GANEX

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Coordinated by CRHEA-CNRS research laboratory, this monthly newsletter is produced by Knowmade with collaboration from the managers of GANEX groups. The newsletter presents a selection of newest scientific publications, patent applications and press releases related to III-Nitride semiconductor materials (GaN, AlN, InN and alloys)

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Selection by III-N French experts

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monthly newsletter

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SCIENTIFIC PUBLICATIONS

Selection of new scientific articles

GROUP 1 - LEDs and Lighting

Group leader: Benjamin Damilano (CRHEA-CNRS)

Information selected by Benjamin Damilano (CRHEA-CNRS)

Application of hexagonal boron nitride to a heat transfer medium of an InGaN/GaN quantum-well green LED

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Group III-nitride light-emitting diodes (LEDs) fabricated on sapphire substrates typically suffer from insufficient heat dissipation, largely due to the low thermal conductivities (TCs) of their epitaxial layers and substrates. In the current work, we significantly improved the heat dissipation characteristics of an InGaN/GaN-quantum-well (QW) green LED by using hexagonal boron nitride (hBN) as a heat transfer medium. Multiple-layer hBN with an average thickness of 11 nm was attached to the back of an InGaN/GaN-QW LED (hBN-LED). As a reference, a LED without the hBN (Ref-LED) was also prepared. After injecting current, heat transfer characteristics inside each LED were analyzed by measuring temperature distribution throughout the LED as function of time. For both LED chips, the maximum temperature was measured on the edge n-type electrode brightly shining fabricated on an n-type GaN cladding layer, and the minimum temperature was measured at the relatively dark-contrast top surface between the p-type electrodes. The hBN-LED took 6 s to reach its maximum temperature (136.1 °C), while the Ref-LED took considerably longer, specifically 11 s. After being switched off, the hBN-LED took 35 s to cool down to 37.5 °C, and the Ref-LED took much longer, specifically 265 s. These results confirmed the considerable contribution of the attached hBN to the transfer and dissipation of heat in the LED. The spatial heat transfer and distribution characteristics along the vertical direction of each LED were theoretically analyzed by carrying out simulations based on the TCs, thicknesses and thermal resistances of the materials used in the chips. The results of these simulations agreed well with the experimental results.

Color-Tunablility in GaN LEDs Based on Atomic Emission Manipulation under Current Injection

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ACS Photonics
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The development of efficient electrically driven color-tunable solid-state light sources will enable new capabilities in lighting and display technologies. Although alternative light sources such as organic light emitting diodes (O-LEDs) have recently gained prominence, GaN-based LEDs remain the most efficient light sources available, making GaN the ideal platform for color-tunable devices. In its trivalent form, Europium is well-known for its red emission at ~620 nm; however, transitions at ~590 and ~545 nm are also possible if additional excited states are exploited. Using intentional codoping and energy-transfer engineering, we show that it is possible to attain all three primary colors due to an emission

originating from two different excited states of the same Eu3+ ion mixed with near band edge emission from GaN centered at ~430 nm. The intensity ratios of these transitions can be controlled by choosing the current injection conditions, such as injection current density and duty cycle under pulsed current injection.

(Ga,In)N/GaN light emitting diodes with a tunnel junction and a rough n-contact layer grown by metalorganic chemical vapor deposition

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AIP Advances
https://doi.org/10.1063/1.5092693

Tunnel junctions (TJs) are envisaged as potential solutions to improve the electrical injection efficiency of nitride emitters in the visible as well as in the UV range. Indeed TJs would solve the issues related to the poor contact with the top p type nitride layer, replacing it by an n type one. But if metal-organic chemical vapor deposition (MOCVD) is chosen to grow the n side of the TJ on a LED, one faces the problem of a potential re-passivation by hydrogen of the underlying p type layer. We propose a TJ epitaxial process whereby low growth temperatures, high growth rates and the type of carrier gas will minimize hydrogen incorporation in the underlying layers. In this view, n++/p++ GaN TJs with and without an (Ga,In)N intermediate layer are grown by MOCVD at varying temperatures (800°C and 1080°C), using N2 as a carrier gas under a very high growth rate of 2.5µm/h on top of blue (Ga,In)N/GaN LEDs. The LEDs made under N2 carrier gas and lower temperature growth conditions are operational without the need for further thermal activation of the Mg acceptors. The light emission intensity from the top surface of the TJ-LEDs is improved compared to the reference LED without TJ: besides the more efficient carrier injection this is also attributable to the larger photon extraction efficiency because of the rough surface of the low temperature grown n-GaN contact layer of the TJ-LEDs.

High performance of AlGaN deep-ultraviolet light emitting diodes due to improved vertical carrier transport by delta-accelerating quantum barrier

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Applied Physics Letters
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AlGaN-based deep-ultraviolet light emitting diodes adopting an embedded delta-AlGaN thin layer with an Al composition higher than that in conventional barriers have been investigated. The experimental result shows that when the current is below 250 mA, the maximum of the external quantum efficiency and light output power for the proposed structure reach severally 1.38% and 10.1 mW, which are enhanced significantly by 160% and 197%, respectively, compared to the conventional ones, showing a tremendous improvement. We attribute that to the inserted delta-thin layer's modulation effect on the energy band, namely, accelerating holes to cross the high barrier with very large kinetic energy, thus increasing the hole injection into the active regions. Meanwhile, the electron concentration within the active regions is enhanced as well because of the accompanying additional effect of the delta-AlGaN thin layer being an electron barrier to block electrons escaping from the active region.

Interwell carrier transport in InGaN/(In)GaN multiple quantum wells

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Applied Physics Letters
https://doi.org/10.1063/1.5092585

Uniform carrier distribution between quantum wells (QWs) of multiple QW light emitting diodes (LEDs) and laser diodes is important for the efficiency of device operation. In lasers, the uniform distribution

ensures that all the QWs contribute to lasing; in LEDs, it enables high power operation with minimal Auger losses and a maximal efficiency. The carrier distribution between the QWs takes place via interwell (IW) transport. In polar GaN-based structures, the transport might be hindered by the strong carrier confinement and the internal electric fields. In this work, we study the IW transport in InGaN/(In)GaN multiple QW structures typical for ultraviolet-emitting devices with different well and barrier parameters. Experiments have been performed by means of time-resolved photoluminescence. We find that the IW transport rate is limited by the hole thermionic emission, which for InGaN/GaN QWs produces long transport times, ~1 ns per well, and a nonuniform IW carrier distribution. However, adding 5% In to the barriers completely changes the situation with the transport time decreasing by a factor of four and the hole thermionic emission energy from 200 meV to 70 meV. This study shows that using InGaN barriers is a promising pathway toward efficient high power InGaN LEDs.

A 225-nm-thick vertical-structure light-emitting diode inhibiting confined waveguide mode

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Applied Physics Express
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An ultrathin vertical-structure light-emitting diode (LED) that inhibits confined optical modes is thought to be an ideal architecture for light extraction in which all emissions will couple to extraction modes. Here, we reduce the vertical-structure LED thickness down to ~225 nm by combining metal-based bonded III-nitride-on-silicon and inductively coupled plasma reactive ion etching without a hard mask. The experimental results confirm that optical waveguide modes confining light are inhibited and all emissions would couple to extraction modes naturally. Moreover, the bottom Ag electrode functions as a reflector to effectively enhance light extraction.

Study on Dislocation Annihilation Mechanism of the High-Quality GaN Grown on Sputtered AlN/PSS and Its Application in Green Light-Emitting Diodes

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IEEE Transactions on Electron Devices
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GaN was grown on the sputtered AlN/patterned sapphire substrate under two growth modes by metal–organic chemical vapor deposition, which was named as "rising tide" and "tsunami" growth modes, respectively, due to different characteristics of the GaN growth process. High-quality GaN epilayer was obtained under "tsunami" growth mode, and the full-width at half-maximums of GaN (002)/(102) high-resolution X-ray diffraction rocking curves were 58/90 arcsec. The green InGaN/GaN light-emitting diodes fabricated on GaN under "tsunami" growth mode exhibited both higher light output power and external quantum efficiency. By monitoring the GaN films at different growth stages using the scanning electron microscope and the transmission electron microscope as well as cathodoluminescence, the dislocation annihilation mechanisms were researched. Under "tsunami" growth mode, GaN grew into the shape of a truncated pyramid that promoted dislocations originated from flat area bend toward the inclined planes, and it was noteworthy that the propagation of dislocations in grains on the conical surface was inhibited. While under "rising tide" growth mode, the dislocations on the conical surface had chances to extend.

Impact of Silver Surface Morphology on the Wall Plug Efficiency of Blue Vertical Light-Emitting Diodes

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IEEE Transactions on Electron Devices
https://doi.org/10.1109/TED.2019.2908965

Due to merits of good thermal conductivity and vertical current distribution, vertical light-emitting diodes (VLEDs) have been widely studied for many years. However, the wall plug efficiency (WPE) remains limited by the light trapping effect in GaN cavity and difficulties to achieve low-resistance ohmic contacts to p-GaN. As one of the solutions, Ni-/Ag-based mirror layers as ohmic contacts have attracted much attention due to the high work function of Ni and high reflectivity of Ag for blue light. In this paper, a Ni/Ag/Ni/Ag/Ti metal stack was deposited separately on the surface of p-GaN. A high WPE of 45.7% for GaN-based blue VLEDs on Si substrates has been achieved at the mean diameter (69 nm) of Ag grains and root-mean-square (rms) surface roughness (2.06 nm) of Ag mirror layers. There are three impacts on VF: formation of NiO, growth of Ag grain, and increases of Ag oxide. The impacts of surface topography on optical properties are investigated by the Mie scattering theory for Ag grains and surface scattering theory for roughness surface of Ag mirror layer. The conclusion shows that: 1) with growth of Ag grain, the absorption of Ag grains is heightened obviously and the intensity distribution of scattering light with scattering angle is changed from uniformity to irregularity and 2) since the magnitudes of specular reflectance are dramatically larger than the scattering about 10^{11} times, the specular reflectance of Ag roughness surface totally covers the attribution of scattering and is only decided by rms values and wavelength of incident light.

A Wirelessly Controllable Optoelectronic Device for Optogenetics

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IEEE Photonics Technology Letters
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The purpose of this paper is to report a new optoelectronic device which consists of a wirelessly controllable driver circuitry and a slender implantable optical probe. Instead of the conventional silicon substrate, the probe is based on GaN material growing on a sapphire substrate. Thin-film blue micro light-emitting diodes (µLEDs) with a total optical power density of 176.9 mW/mm2 at 1 mA are directly fabricated at the probe by semiconductor device fabrication technologies. In a further research, we integrate a yellow µLED on the probe to enable optical stimulation of both excitatory and inhibitory neurons. Besides, we adopt Bluetooth 4.0 wireless communication protocol, therefore, light emitting from the µLEDs can be controlled remotely by a terminal with a distance as far as 20 meters. The driver is also equipped with an accelerometer, a power management module and a System-on-Chip (SoC), they are energized by a rechargeable lithium battery which has up to 10-hour battery life. The whole device is a little bit bigger than a coin, and weighs approximately 6 g. The probe has a length of 1.65 cm and a thickness of 150 µm. These features make the devices suitable for a broad variety of optogenetic experiments.

Active Matrix Monolithic LED Micro-display Using GaN-on-Si Epilayers

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IEEE Photonics Technology Letters
https://doi.org/10.1109/LPT.2019.2910729

An active matrix LED micro-display system was demonstrated with GaN-on-Si epilayers and a custom-designed CMOS backplane using an Au-free

Cu/Sn-based metal bonding method. The blue micro-LED array consists of 64 × 36 pixels with a pitch size of 40 µm × 40 µm and pixel density of 635 pixels per inch (ppi). The Si substrate for the LED growth was removed by reactive ion etching (RIE) using SF6-based gas after flip-chip bonding. Crack-free and smooth GaN layers in the display area were exposed. Images and videos with 4-bit grayscale could be clearly rendered, and light crosstalk was significantly suppressed compared to its counterpart using GaN-on-sapphire epilayers. The demonstration suggests the tremendous potential of the low-cost and large-scale GaN-on-Si epilayers and cost-effective Au-free Cu/Sn-based bonding scheme for micro-display applications.

Improved Epitaxy of AlN Film for Deep-Ultraviolet Light-Emitting Diodes Enabled by Graphene

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Advanced Materials
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The growth of single-crystal III-nitride films with a low stress and dislocation density is crucial for the semiconductor industry. In particular, AlN-derived deep-ultraviolet light-emitting diodes (DUV-LEDs) have important applications in microelectronic technologies and environmental sciences but are still limited by large lattice and thermal mismatches between the epilayer and substrate. Here, the quasi-van der Waals epitaxial (QvdWE) growth of high-quality AlN films on graphene/sapphire substrates is reported and their application in high-performance DUV-LEDs is demonstrated. Guided by density functional theory calculations, it is found that pyrrolic nitrogen in graphene introduced by a plasma treatment greatly facilitates the AlN nucleation and enables fast growth of a mirror-smooth single-crystal film in a very short time of ≈0.5 h (≈50% decrease compared with the conventional process), thus leading to a largely reduced cost. Additionally, graphene effectively releases the biaxial stress (0.11 GPa) and reduces the dislocation density in the epilayer. The as-fabricated DUV-LED shows a low turn-on voltage, good reliability, and high output power. This study may provide a revolutionary technology for the epitaxial growth of AlN films and provide opportunities for scalable applications of graphene films.

AlGaN-based ultraviolet light-emitting diode on high-temperature annealed sputtered AlN template

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Journal of Alloys and Compounds
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We demonstrate 297.5-nm AlGaN-based ultraviolet (UV) light-emitting diodes (LEDs) grown on a high-temperature annealed (HTA) sputtered AlN template upon sapphire substrate. After HTA at 1600 °C, full width at half maximum values of (0002) and (102) planes of the 200-nm sputtered AlN template are significantly improved from 120.7 to 2794.0 arcsec to 82.4 and 352.6 arcsec, respectively, showing comparable threading dislocation densities with the 2-µm AlN template grown by high-temperature metal organic chemical vapor deposition (MOCVD).

Therefore, typical AlN template grown by MOCVD is not necessary in our study. A UV LED grown on this HTA sputtered AlN template reaches light output power of 9.83 mW at 100 mA and external quantum efficiency of 2.77% at 30 mA. Our result indicates that the HTA sputtered AlN template is able to replace the commonly used high-temperature MOCVD AlN templates and thus decrease the growth complexity and cost of AlGaN-based UV LEDs.

High-luminous efficacy green light-emitting diodes with InGaN/GaN quasi-superlattice interlayer and Al-doped indium tin oxide film

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High-luminous efficacy green light-emitting diodes (LEDs) with InGaN/GaN quasi-superlattice (QSL) interlayer and Al-doped indium tin oxide (ITO) current spreading film have been demonstrated. The photoluminescence mapping results revealed that the 2-inch green LED wafer with the QSL interlayer had a longer average peak wavelength as compared to that without the QSL interlayer. In addition, the forward voltage was decreased and the light output power was considerably improved for the green LED chips fabricated from the wafer with the QSL interlayer. Then, an Al-doped ITO film was employed in the green LEDs showing a further improvement in external quantum efficiency. It was mainly ascribed to the increased internal quantum efficiency by analyzing the injection efficiency, light extraction efficiency and X-ray photoelectron spectroscopy spectrum. Finally, at an injected current of 20 mA, a high luminous efficacy of 264.7 lm/W and peak wavelength of 537.2 nm was achieved for the green LEDs with a chip-on-board silicone encapsulation. We determine that the high luminous efficacy was attributed to the improved electrical and light output performance of the LEDs due to the use of the InGaN/GaN QSL interlayer, the Al-doped ITO and the chip packaging structure.

Evidence for defect-assisted tunneling and recombination at extremely low current in InGaN/GaN-based LEDs

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Applied Physics Express
https://doi.org/10.7567/1882-0786/ab10e3

This paper investigates the electroluminescence characteristics of InGaN-based LEDs at extremely low current levels (down to 500 pA), i.e. in and below the region where recombination dynamics are governed by Shockley–Read–Hall recombination. Two different regimes are identified in the current–voltage characteristics, a first one below 100 nA associated to emission at wavelength below midgap, and a second one below 100 μA with a dominant emission at the quantum well wavelength. The experimental findings are interpreted by considering that, at extremely low current, carriers can tunnel towards states deeper than midgap, thus undergoing radiative recombination through defects.

Current Noise and Efficiency Droop of Light-Emitting Diodes in Defect-Assisted Carrier Tunneling from an InGaN/GaN Quantum Well

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Semiconductors
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The current dependences of the spectral noise density and quantum efficiency in green and blue light-emitting diodes with InGaN/GaN quantum wells (QWs) are measured. It is shown that the noise level greatly increases at high currents at which there is a quantum efficiency droop. The mechanism by which the current noise is formed is associated with hopping transport via the deep states of color centers in GaN across the n barrier of an InGaN/GaN QW. The source of the noise is the hopping resistance of the space-charge region, which limits the current of thermally activated electrons into the QW. The efficiency droop and the increase in noise level are attributed to a change in the electric-field direction

near the QW at high injection levels and to an increase in the tunneling leakage of holes from the QW. It is shown that the experimental frequency-related noise spectra having the shape of a Lorentzian spectrum at the working currents are related to the frequency of hopping between deep centers near the InGaN/GaN QW and to Maxwell relaxation in the space-charge region.

Impact of the surface recombination on InGaN/GaN-based blue micro-light emitting diodes

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Optics Express
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In this work, the size-dependent effect for InGaN/GaN-based blue micro-light emitting diodes (μLEDs) is numerically investigated. Our results show that the external quantum efficiency (EQE) and the optical power density drop drastically as the device size decreases when sidewall defects are induced. The observations are owing to the higher surface-to-volume ratio for small μLEDs, which makes the Shockley-Read-Hall (SRH) non-radiative recombination at the sidewall defects not negligible. The sidewall defects also severely affect the injection capability for electrons and holes, such that the electrons and holes are captured by sidewall defects for the SRH recombination. Thus, the poor carrier injection shall be deemed as a challenge for achieving high-brightness μLEDs. Our studies also indicate that the sidewall defects form current leakage channels, and this is reflected by the current density-voltage characteristics. However, the improved current spreading effect can be obtained when the chip size decreases. The better current spreading effect takes account for the reduced forward voltage.

Highly efficient GaN-based high-power flip-chip light-emitting diodes

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Optics Express
https://doi.org/10.1364/OE.27.00A669

High-power flip-chip light-emitting diodes (FCLEDs) suffer from low efficiencies because of poor p-type reflective ohmic contact and severe current crowding. Here, we show that it is possible to improve both the light extraction efficiency (LEE) and current spreading of an FCLED by incorporating a highly reflective metallic reflector made from silver (Ag). The reflector, which consists of an Ag film covered by three pairs of TiW/Pt multilayers, demonstrates high reflectance of 95.0% at 460 nm at arbitrary angles of incidence. Our numerical simulation and experimental results reveal that the FCLED with Ag-based reflector exhibits higher LEE and better current spreading than the FCLED with indium-tin oxide (ITO)/distributed Bragg reflector (DBR). As a result, the external quantum efficiency (EQE) of FCLED with Ag-based reflector was 6.0% higher than that of FCLED with ITO/DBR at 750 mA injection current. Our work also suggests that the EQE of FCLED with the Ag-based reflector could be further enhanced 5.2% by replacing the finger-like n-electrodes with three-dimensional (3D) vias n-electrodes, which spread the injection current uniformly over the entire light-emitting active region. This study paves the way towards higher-performance LED technology.

Micro-photoluminescence mapping of light emissions from aluminum-coated InGaN/GaN quantum wells

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Applied Physics Express
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Micro-photoluminescence (PL) mapping was investigated for Al-coated InGaN/GaN quantum wells (QWs), which showed huge PL enhancement by the surface plasmon (SP) resonance. The obtained images show inhomogeneity at the micro-meter scale; in addition, the region with lower PL intensities tend to have a longer PL wavelength for bare QWs. This correlation changed with an Al coating, positive correlations were observed in an area with a relatively short peak wavelength with blue-shift. Conversely, negative correlations were observed at longer peak wavelengths. These results suggest that the quantum-confined Stark effect (QCSE) was screened by the enhanced electrical-field of the SP resonance.

MOVPE-grown AlGaN-based tunnel heterojunctions enabling fully transparent UVC LEDs

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Photonics Research
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We report on AlGaN-based tunnel heterojunctions grown by metalorganic vapor phase epitaxy enabling fully transparent UVC LEDs by eliminating the absorbing p-AlGaN and p-GaN layers. Furthermore, the electrical characteristics can be improved by exploiting the higher conductivity of n-AlGaN layers as well as a lower resistance of n-contacts. UVC LEDs with AlGaN:Mg/AlGaN:Si tunnel junctions exhibiting single peak emission at 268 nm have been realized, demonstrating effective carrier injection into the AlGaN multiple quantum well active region. The incorporation of a low band gap interlayer enables effective tunneling and strong voltage reduction. Therefore, the interlayer thickness is systematically varied. Tunnel heterojunction LEDs with an 8 nm thick GaN interlayer exhibit continuous-wave emission powers >3 mW near thermal rollover. External quantum efficiencies of 1.4% at a DC current of 5 mA and operating voltages of 20 V are measured on-wafer. Laterally homogeneous emission is demonstrated by UV-sensitive electroluminescence microscopy images. The complete UVC LED heterostructure is grown in a single epitaxy process including in situ activation of the magnesium acceptors.

GROUP 2 - Laser and Coherent Light

Group leader: Bruno Gayral (CEA)

Information selected by Knowmade

Thermal transport of nanoporous gallium nitride for photonic applications

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Recently, nanoporous (NP) GaN has emerged as a promising photonic material in the III-N family. Due to its attractive properties, such as its large refractive index contrast and perfect lattice matching with GaN, as well as its good electrical conductivity, photonic components and devices involving NP GaN have been successfully demonstrated. However, further development of high-performance NP GaN based electrically injected devices, such as vertical-cavity surface-emitting lasers (VCSELs) and edge emitting lasers, requires efficient heat dissipation. Therefore, in this paper, we study thermal conductivity (TC) of NP GaN, especially when incorporated into a practical distributed Bragg reflector (DBR) in a VCSEL device. Through an effective medium model, we study the theoretical effect of NP GaN morphological properties over its TC. We then experimentally measure the TC of NP GaN, with different porosities and pore wall thicknesses, which shows a high agreement with the theoretical model. We also fabricate actual NP GaN DBRs and study the large tunability and interdependence among their TC (1–24 W/m K), refractive index (0.1–1.0), and electrical conductivity (100–2000 S/m) compared to other conventional DBRs. Finally, we perform a finite-element simulation of the heat dissipation within NP GaN-VCSELs, revealing their superior thermal dissipation compared to dielectric DBR based VCSELs. In this regard, this study lays the foundation for nanoscale thermal engineering of NP GaN optoelectronic and photonic devices and paves the way for their successful commercialization.

By-Emitter Analysis of 450-nm Emitting High-Power Diode Laser Bars

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We present an analysis of optical and thermal properties of GaN-based blue-emitting high-power diode laser arrays (bars). Parameters such as emission power and temperature are monitored for each single emitter of arrays consisting of 23 emitters. The obtained data are compared with modeling of the electro-optic properties. In contrast to the well-known infrared bars, the thermal properties in the blue-emitting bars control the individual emitter properties to a very high degree and lead to considerable variations in emitter power, in extreme cases up to 50%. Such extreme cases occur, for example, when emitters fail and thus act as a heat source for their surroundings. Nevertheless these bars reach record output powers and are on the way to becoming major sources of photonic power in the blue spectral range.

Narrow-line InGaN/GaN green laser diode with high-order distributed-feedback surface grating

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Applied Physics Express
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We demonstrate narrow-line green laser emission at 513.85 nm with a linewidth of 31 pm and side-mode suppression ratio of 36.9 dB, operating under continuous-wave injection at room temperature. A

high-order (40th) distributed-feedback surface grating fabricated on multimode InGaN-based green laser diodes via a focused ion beam produces resolution-limited, single-mode lasing with an optical power of 14 mW, lasing threshold of 7.27 kA cm−2, and maximum slope efficiency of 0.32 W A−1. Our realization of narrow-line green laser diodes opens a pathway toward efficient optical communications, sensing, and atomic clocks.

Sub-milliampere-threshold continuous wave operation of GaN-based vertical-cavity surface-emitting laser with lateral optical confinement by curved mirror

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Applied Physics Express
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The continuous wave operation of a gallium-nitride-based vertical-cavity surface-emitting laser (GaN-based VCSEL) that uses boron ion implantation for lateral current confinement and a curved mirror for lateral optical confinement was investigated. The threshold current was 0.25 mA (J th = 3.5 kA cm−2) for a 3 µm diameter current aperture at room temperature and the lasing wavelength was 445.3 nm. This is the lowest threshold current recorded for a GaN-based VCSEL. This result is considered to be a milestone for the further miniaturization of GaN-based VCSELs by the implementation of lateral optical confinement due to the incorporation of a curved mirror.

Screening of quantum-confined Stark effect in nitride laser diodes and superluminescent diodes

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Applied Physics Express
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In the present work we report on the observation of carrier-induced screening of built-in electric fields in (Al, In)GaN laser diodes and superluminescent diodes. We use the emission peak energy as a measure of the quantum-confined Stark effect and its screening by free carriers. For superluminescent diodes we observe a steady increase of screening up to the current density of 10 kA cm−2. This shows that the lasing in nitride laser diodes occurs under high electric fields, far from the flat band conditions.

Top-down fabrication of GaN nano-laser arrays by displacement Talbot lithography and selective area sublimation

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Applied Physics Express
https://doi.org/10.7567/1882-0786/ab0d32

We show that a 4 µm thick GaN layer grown by metal-organic vapour phase epitaxy can be transformed into a well-organized array of GaN nanowires (NWs) using displacement Talbot lithography and selective area sublimation. The optical quality of the GaN NWs obtained by this method is attested by their room temperature photoluminescence and the observation of lasing under optical pumping with a minimum excitation power density threshold of 2.4 MW cm−2.

Strain-free GaN/InAlN chirped short-period superlattice electron-blocking layer for 450 nm InGaN laser diode

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Laser Physics
https://doi.org/10.1088/1555-6611/ab05be

In this study, we optimized the lattice-matched GaN/In0.18Al0.82N chirped short-period superlattice (C-SPSL) electron-blocking layer for a laser diode emitting at 450 nm. The effective bandgap of C-SPSL depends upon the quantum well (QW) and quantum barrier (QB) thickness of C-SPSL. In this study the In0.18Al0.82N QB thickness is constant at 0.5112 nm (1 unit layer (UL) = 1 lattice constant thickness) and the GaN QW thickness is varied as 1 UL, 3 UL, and 5 UL. The estimated effective bandgap for 15 periods of

1 UL GaN/1 UL In0.18Al0.82N SPSL is ~4.2 eV, for four periods of 3 UL GaN/1 UL In0.18Al0.82N SPSL it is ~3.93 eV and for two periods of 5 UL GaN/1 UL In0.18Al0.82N SPSL it is 3.62 eV. Wave-function hybridization and the built-in electric field play an important role in the bandgap behavior of C-SPSL. The electron leakage decreased from 2534.6 A cm−2 to ~14 A cm−2 while hole transportation improved from 7.7 kA cm−2 to 10 kA cm−2 at 10 kA cm−2 injection current density. The light output power per facet improved from 146 mW to 255 mW. Slope efficiency increased from 0.548 W A−1 to 0.924 W A−1 with the C-SPSL design.

GROUP 3 - Power Electronics

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Leakage and breakdown mechanisms of GaN vertical power FinFETs

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Applied Physics Letters
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This work studies the leakage and breakdown mechanisms of 1.2 kV GaN vertical power FinFETs with edge termination. Two competing leakage and breakdown mechanisms have been identified. The first mechanism is dominated by the electric field, with the leakage current dominated by the electric field in the drift region and destructive breakdown voltage by the peak electric field at the edge termination. The second leakage and breakdown mechanism is controlled by an energy (or potential) barrier in the fin channel. This energy barrier suffers from the drain-induced barrier lowering (DIBL) effect and is highly dependent on gate/drain biases, fin geometries, and GaN/oxide interface charges. The electrons injected into the drift region due to the DIBL effect further lead to trap-assisted space-charge-limited conduction, which results in a nondestructive early breakdown. The barrier height in the fin channel determines which mechanism is dominant; the same device could show either destructive or nondestructive breakdown at different gate biases. To enable the normally off power switching, it is important to suppress the leakage from the second mechanism and maintain a sufficiently high energy barrier in the fin channel up to high drain voltages. Finally, the key device parameters determining the energy barrier in the fin channel have been identified. The findings in this work provide critical device understanding and design guidelines for GaN vertical power FinFETs and other "junctionless" vertical high-voltage power transistors.

Design and Simulation of GaN Superjunction Transistors with 2DEG Channels and Fin Channels

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IEEE Journal of Emerging and Selected Topics in Power Electronics
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High-performance two-dimensional-electron-gas (2DEG) channel and sub-micron fin-shaped channel have been recently demonstrated in vertical GaN power transistors. This indicates that, unlike Si and SiC, the inversion-type metal-oxide-semiconductor channel is no longer the 'default option' for future GaN superjunction transistors. This work demonstrates the design and simulation of GaN superjunction transistors with 2DEG and fin channels, i.e. a superjunction current-aperture vertical electron transistor (SJ-CAVET) and a superjunction fin field-effect-transistor (SJ-FinFET). A breakdown voltage over 2.2 kV and a specific on-resistance (Ron,sp) of 0.35 mΩ·cm2 were demonstrated in the simulated GaN SJ-CAVETs and SJ-FinFETs with 10 µm-thick superjunction region. Mixed-mode simulations were used to evaluate their performance in 1.7 kV, 50 A power switching applications. Their Ron,sp and die size are at least 30-to-50-fold smaller than today's best 1.7 kV power transistors. Thanks to the smaller die size, the junction capacitances and switching charges are significantly smaller, allowing for a megahertz practical switching frequency which is at least 10-fold higher than today's 1.7 kV power transistors. The simulations of higher-voltage GaN SJ-CAVETs and SJ-FinFETs up to 10 kV reveal consistent advantages over commercial transistors. These results show the great potentials of GaN SJ-CAVETs

and SJ-FinFETs for future medium-voltage high-frequency power applications.

Enhanced Gate Reliability in GaN MIS-FETs by Converting the GaN Channel into Crystalline Gallium Oxynitride

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We demonstrated the enhanced threshold voltage (VTH) stability and gate reliability of the enhancement-mode (E-mode) GaN-based MIS-FETs under reverse-bias stress (i.e., stress at off-state with high drain voltage), which is achieved by converting the conventional GaN (Eg ∼ 3.4 eV) channel into a crystalline GaOxN1–x (Eg ∼ 4.1 eV) layer. In the MIS-FETs stressed at off-state with a large drain voltage, holes will be generated in the high-electric-field region by impact ionization, and subsequently, degradation of the gate dielectric is caused by the holes passing through the dielectric film. As the valence band offset between the GaOxN1–x and GaN is ∼0.6 eV, an energy barrier for holes will be formed surrounding the gate, which can prevent holes from flowing to the gate side and therefore reduce the hole-induced gate dielectric degradation. The crystalline gallium oxynitride layer converted from GaN could also be a promising method to improve channel reliability for many GaN-based structures and processes.

A review of gallium nitride power device and its applications in motor drive

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CES Transactions on Electrical Machines and Systems
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Wide band-gap gallium nitride (GaN) device has the advantages of large band-gap, high electron mobility and low dielectric constant. Compared with traditional Si devices, these advantages make it suitable for fast-switching and high-power-density power electronics converters, thus reducing the overall weight, volume and power consumption of power electronic systems. As a review paper, this paper summarizes the characteristics and development of the state-of-art GaN power devices with different structures, analyzes the research status, and forecasts the application prospect of GaN devices. In addition, the problems and challenges of GaN devices were discussed. And thanks to the advantages of GaN devices, both the power density and efficiency of motor drive system are improved, which also have been presented in this paper.

Operation Up to 500 °C of Al0.85Ga0.15N/Al0.7Ga0.3N High Electron Mobility Transistors

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IEEE Journal of the Electron Devices Society
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AlGaN channel high electron mobility transistors (HEMTs) are the potential next step after GaN channel HEMTs, as the high aluminum content channel leads to an ultra-wide bandgap, higher breakdown field, and improved high temperature operation. Al 0.85 Ga 0.15 N/Al 0.7 Ga 0.3 N (85/70) HEMTs were operated up to 500 °C in ambient causing only 58% reduction of dc current relative to 25 °C measurement. The low gate leakage current contributed to high gate voltage operation up to +10 V under V ds = 10 V, with ION/IOFF ratios of >2×1011 and 3 ×106 at 25 and 500 °C, respectively. Gate-lag measurements at 100 kHz and 10% duty cycle were ideal and only slight loss of pulsed current at high gate voltages was observed. Low interfacial defects give rise to high quality pulsed characteristics and a low subthreshold swing value of 80 mV/dec at room temperature. Herein is an analysis of AlGaN-channel HEMTs and their potential future for high power and high temperature applications.

Recent development of vertical GaN power devices

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Japanese Journal of Applied Physics
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Gallium nitride (GaN) is an attractive material for high-frequency and high-power devices. Due to the availability of relatively high-quality free-standing bulk GaN substrates, the research and development of vertical GaN devices on GaN substrates has made significant progress in recent years, and various transistors and diodes based on vertical GaN with excellent characteristics have been reported. This paper reviews the current status and recent progress of vertical GaN power device development reported from companies and research institutions, which includes the technological development of our recent research results of Schottky barrier diodes and trench MOSFETs. Key remaining issues for practical applications are also described.

Thermal shock reliability of a GaN die-attach module on DBA substrate with Ti/Ag metallization by using micron/submicron Ag sinter paste

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Japanese Journal of Applied Physics
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This study was carried out to evaluate the reliability of GaN die-attached on a direct bonded aluminum (DBA) substrate with Ag sinter joining in up to 1000 harsh thermal shock cycles over a temperature range from −50 °C to 250 °C. For joining the die-attached structure, metallized Ti/Ag was prepared first on the substrates of DBA and GaN chips. A GaN die and DBA substrate were bonded by a micron/submicron Ag sinter paste in air at 250 °C without pressure. The initial die shear strength of the GaN/DBA joint structure, above 33 MPa, was retained up to 250 cycles and then gradually decreased up to 1000 cycles. Microstructural observation by field-emission scanning electron microscopy and energy-dispersive X-ray spectroscopy showed a crack growing inside the Ag/Al bonding interface during thermal cycles due to the large plastic deformation of the Al layer. In addition, with the aid of simulations based on the finite element method, the damage mechanism is discussed in further detail, including the Al grain boundary effect. This study systematically revealed that the mechanism of thermal shock damage of a GaN/DBA module with an Ag sinter joining structure suggests that it can prevent severe damage during thermal shocks in high-temperature applications.

3D GaN nanoarchitecture for field-effect transistors

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Micro and Nano Engineering
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The three-dimensionality of 3D GaN field-effect transistors (FETs) provides them with unique advantages compared to their planar counterparts, introducing a promising path towards future FETs beyond Moore's law. Similar to today's Si processor technology, 3D GaN FETs offer multi-gate structures that provide excellent electrostatic control over the channel and enable very low subthreshold swing values close to the theoretical limit. Various concepts have been demonstrated, including both lateral and vertical devices with GaN nanowire (NW) or nanofin (NF) geometries. Outstanding transport properties were achieved with laterally contacted NWs that were grown in a bottom-up approach and transferred onto an insulating substrate. For higher power application, vertical FETs based on regular arrays of GaN nanostructures are particularly promising due to their parallel integration capability and large sidewall surfaces, which can be utilized as channel area. In this paper, we review the current status of 3D GaN FETs and discuss their concepts, fabrication techniques, and performances. In addition to the potential benefits, reliability issues and difficulties that may arise in complex 3D processing are discussed, which

need to be tackled to pave the way for future switching applications.

Investigation of post-annealing effects for normally-off GaN metal-oxide semiconductor heterojunction field-effect transistors with thin AlN barrier layer

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Japanese Journal of Applied Physics
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The effects of post-annealing processes for normally-off GaN metal-oxide semiconductor heterojunction field-effect transistors (MOS-HFETs) with a thin AlN barrier layer are investigated. These annealing processes are post-deposition annealing (PDA) after oxide deposition, post-metallization annealing (PMA) after gate metallization, and positive-bias annealing (PBA) after wafer processes. PMA and PBA are effective in enhancing the drain current density and threshold voltage shift. The most effective method is PBA and the obtained threshold voltage and drain current density are +3.0 V and 0.7 A mm−1, respectively. This is attributed to improvements in interfacial trap states which is confirmed by an investigation of the frequency dependence of capacitance–voltage characteristics.

A variable nanotrench structure for electric field modulation in AlGaN/GaN devices

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Japanese Journal of Applied Physics
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The surface electric field (E-field) optimization of AlGaN/GaN devices is very important because the two-dimensional electron gas channel is extremely close to the surface. In this work, a novel variable nanotrench (VNT) structure for E-field modulation in AlGaN/GaN devices is proposed and demonstrated. The effectiveness of the VNT-structure in optimizing the surface E-field is investigated by the technology computer aided design simulation. Single step dry etching is developed to fabricate the VNT-structure. Benefitting from the VNT-anode, the fabricated lateral AlGaN/GaN Schottky barrier diode exhibits improved performance including reduced leakage current, increased breakdown voltage, and suppressed electron trapping under reverse bias.

High-performance lateral GaN Schottky barrier diode on silicon substrate with low turn-on voltage of 0.31 V, high breakdown voltage of 2.65 kV and high-power figure-of-merit of 2.65 GW cm−2

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Applied Physics Express
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We demonstrate high-performance AlGaN/GaN lateral Schottky barrier diodes (SBDs) with Mo anode and low turn-on voltage of 0.31 V. AlGaN/GaN SBDs with anode to cathode spacing of 6/10/15/20/25 µm achieve a breakdown voltage (BV) of 0.83/1.23/1.62/2.46/2.65 kV, yielding a power figure-of-merit (FOM) of 1.53/1.82/1.77/2.65/2.12 GW cm−2. The power FOM of 2.65 GW cm−2 and BV of 2.65 kV are the best results of AlGaN/GaN SBDs on silicon substrate. Combined with the good dynamic performance with only 10% R on increase when switched from a −600 V stress for 10 ms, GaN SBDs verify their great promise for future power electronic applications.

Demonstration of fully-vertical GaN-on-Si power MOSFETs using regrowth technique

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Electronics Letters
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The authors are reporting for the first time the fabrication of GaN-based fully-vertical high-power metal-oxide-semiconductor field effect transistors on Si. The electrical measurements of the fabricated device exhibited both vertical and lateral modes of

operation. The transfer characteristics of the device in vertical mode showed a peak trans-conductance of 23.6 mS/mm with a threshold voltage (Vth) of −19.6−19.6 V. The maximum current drain density of 249.3 mA/mm was observed with ON-resistance (RON) of 44.2 ΩΩ -mm. The electrical results obtained in the vertical mode were also compared with the laterally oriented devices. The comparison of the electrical results indicates a relatively higher ON-resistance of the device in the vertical configuration, due to the contribution of the series resistance of the buffer layers in the epi-structure.

Extraction of Packaged GaN Power Transistors Parasitics Using S-Parameters

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IEEE Transactions on Electron Devices
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In order to better predict the high-frequency switching operation of transistors in power converters, parasitic elements of these devices such as resistances, inductances, and capacitances must be accurately evaluated. This paper reports on the characterization of a gallium nitride (GaN) packaged power transistor using S-parameters in order to extract the device parasitics. Because the transistor is packaged, a calibration technique is carried out using specific test fixtures designed on FR4 printed circuit board (PCB) in order to get the S-parameters in the transistor plane from the measurement. The proposed method is suitable for a wide range of power devices. In this paper, it is applied to an enhancement-mode GaN high electron mobility transistor (HEMT). The impact of junction temperature on drain and source resistances is also evaluated. According to characterization results, equation-based modeling is proposed for the nonlinear parameters. The extracted parasitic elements are compared with reference values given by the device manufacturer.

Characterization of Deep and Shallow Traps in GaN HEMT using Multi-frequency C-V Measurement and Pulse-mode Voltage Stress

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IEEE Transactions on Device and Materials Reliability
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In this work, the influence of interface traps at the SiN/GaN interface and Carbon-related buffer traps on GaN high electron mobility transistor (HEMT) on silicon substrate has been studied using high-frequency capacitance-voltage (HFCV) and quasi-static C-V (QSCV) measurement. The correlation between dynamic resistance degradation and trap density distribution subjected to pulse stress conditions has been examined. Deeper-level traps from the hole-emission process of Carbon-related buffer layer are activated by high drain voltage during off-state stress and shallow-level traps at the SiN interface are enhanced by an increase in gate voltage during on-state stress. Two-dimension device simulations have been carried out to probe the physical insight into the dynamic resistance degradation. Good agreement between experimental data and simulated results is obtained while taking into account of shallow-level and deeper-level traps.

Positive Threshold Voltage Shift in AlGaN/GaN HEMTs and E-Mode Operation by $Al_xTi_{1-x}O$ Based Gate Stack Engineering

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IEEE Transactions on Electron Devices
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In this paper, for the first time, we have experimentally demonstrated enhancement mode (e-mode) AlGaN/GaN high-electron-mobility transistor (HEMT) operation by integrating p-type high-κ $Al_xTi_{1-x}O$ based gate stack. Concentration of Al in Al-Ti-O system was found to be a tuning parameter for the threshold voltage of GaN HEMTs. The high-κ

properties of $Al_xTi_{1-x}O$ as a function of Al % are studied. Superiority of AlTiO over other p-oxides such as CuO and NiO_x is proven statistically. Using the high-κ and p-type AlTiO, in conjunction with a thinner AlGaN barrier under gate, 600-V e-mode GaN HEMTs are demonstrated with superior on-state performance (Ion ~ 400 mA/mm and Ron =8.9 Ω-mm) and gate control over channel (Ion/Ioff = 10^7, SS = 73 mV/dec, and gate leakage < 200 nA/mm), beside improved safe operating area reliability.

Enhancement-Mode Tri-Gate Nanowire InAlN/GaN MOSHEMT for Power Applications

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IEEE Electron Device Letters
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This study demonstrates a novel enhancementmode tri-gate nanowire InAlN/GaN MOSHEMT with ultrasonic spray pyrolysis deposition (USPD) deposited Al2O3 as the gate dielectric layer. The proposed device reveals a threshold voltage (VTH) of +2.3 V and a maximum drain current (ID, max) of 705 mA/mm. It also exhibits superior electrical performances, including a high on-state/off-state current (Ion/Ioff) ratio of 109-1010, a steep subthreshold swing (SS) of 65 mV/decade, and a large breakdown voltage (BV) of 800 V with a leakage current of 0.7 μA/mm while keeping a low specific on-resistance (Ron, sp) of 1.04 mΩ·cm2. This novel E-mode device presents great potential for power device applications.

A Test Circuit for GaN HEMTs Dynamic Ron Characterization in Power Electronics Applications

IEEE Journal of Emerging and Selected Topics in Power Electronics
https://doi.org/10.1109/JESTPE.2019.2912130

Wide bandgap devices such as GaN HEMTs are a promising technology in the field of Power Electronics. Due to the physical properties of the Gallium nitride and the device design, they can outperform their Silicon counterparts for the design of highly efficient power switching converters. However, its design should face certain effects that can diminish its performance. One of such effect is the degradation mechanism known as dynamic onresistance (dynamic RON,), being its mitigation one of the main objectives in the design of the device. In this paper, a circuit is proposed for assessing if this effect is present in GaN transistors in power electronics applications. The circuit allows testing the GaN HEMTs with different stress voltages and times maintaining the desired current level, and allows for repeating the test in successive switching pulses, with adjustable switching frequency and duty cycle, always with the same current, mimicking a real power electronics application.

High performance enhancement-mode HEMT with 3DEG to conduct current and 3DHG as back barrier

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Superlattices and Microstructures
https://doi.org/10.1016/j.spmi.2019.04.024

A novel enhancement-mode (E-mode) high electron mobility transistor (HEMT) with three-dimensional electron gas (3DEG) and three-dimensional hole gas (3DHG) is presented. It features a GaN-top layer, a positive graded AlGaN barrier layer (GAL), and a negative graded AlGaN back barrier layer (GABL) (wherein the positive/negative doping gradient is defined with respect to the growth direction), with a vertical conduction channel aside a MIS trench gate. The 2DHG is formed at the interface between the GaN-top layer and GAL. The 3DEG and 3DHG are formed due to the polarization induced by linearly grading Aluminum (Al) composition from 0 to xAl in GAL and 0.4 to 0 in GABL, respectively. The source and drain locate at the same side of the MIS trench gate, and the source contacts with the gate. Firstly, 2DHG blocks the electron current conduction path between the source and 3DEG so as to achieve E-mode. Secondly, the high-sheet density 3DEG in GAL greatly increases the on-state current. Thirdly, the leakage current effectively is reduced by the 3DHG in GABL, improving the breakdown voltage. Fourthly, a high breakdown voltage (BV) is obtained because the

polarization junction formed by the polarization charges in GAL and GABL improves the electric field distribution in the drift region. The BV of the proposed HEMT increases to 1080 V from 47 V of the conventional MIS HEMT at the same length of the drift region, and specific on-resistance (Ron,sp) decreases to 0.29 mΩ cm2 from 0.64 mΩ cm2 in simulation.

Design and Fabrication of GaN p-n Junction Diodes with Negative Beveled-Mesa Termination

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IEEE Electron Device Letters
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We report on homoepitaxial GaN p-n junction diodes with a negative beveled-mesa termination. The electric field distribution in a beveled-mesa was investigated using TCAD simulation, the devices were designed using currently available GaN growth techniques. Shallow-angle (ca. 10.) negative bevel GaN p-n junction diodes were fabricated with various Mg acceptor concentrations in the p-layers. The suppression of electric field crowding and improvement of the breakdown voltage were observed as the Mg concentration was decreased. The parallel plane breakdown field of 2.86 MV/cm was obtained for a device with the breakdown voltage of 425 V.

Reliability concern of quasi-vertical GaN Schottky barrier diode under high temperature reverse bias stress

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Superlattices and Microstructures
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In this paper, the reliability of quasi-vertical GaN Schottky barrier diodes under high temperature reverse bias (HTRB) stress has been investigated. The test results indicate that the stress applied on the devices makes reverse leakage current decrease, but the forward performance, capacitance and reverse recovery performance show negligible changes. With the help of experiments and T-CAD simulations, it is demonstrated that there is trapping process of hot electrons along vertical sidewall of the device under high reverse voltage stress, which leads to the decrease of reverse leakage current. An empirical model can be used to predict the variations and good coincidences can be observed based on the acquired experiment data. Moreover, long time over voltage stress on the device leads to the direct failure. By using the infrared thermography analysis and T-CAD simulations, the failure mechanism has been also illustrated.

A Demonstration of Nitrogen Polar Gallium Nitride Current Aperture Vertical Electron Transistor

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IEEE Electron Device Letters
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We report the first demonstration of Nitrogen polar GaN current aperture vertical electron transistor with a blocking electric field over 2.9MV/cm. The devices were grown by metalorganic chemical vapor deposition on a cplane sapphire substrate. The fabrication involved a maskless planar regrowth of a very thin AlN layer above the current blocking layer which induced a two-dimensional electron gas in the channel, and also prevented the out-diffusion of activated Mg ions into the GaN channel layer. The alloyed source and drain ohmic contacts on the regrown n+-GaN layer offered low contact resistance of 0.18 mY.cm2 (0.22 Y.mm). The device displayed a maximum drain current of 1.68 kA/cm2, with a low RON,SP of 2.48 mY.cm2. With just about 200nm drift layer, a 3-terminal breakdown voltage of 58V was achieved. Output characteristics were free of dispersion under pulsed measurements with 80 ls and 500 ns pulse widths. Npolar current aperture

vertical electron transistors show fundamentally significant advantages in favor of using Mg2+-implanted GaN as current blocking layers compared to Gapolar counterparts.

Mg implantation dose dependence of MOS channel characteristics in GaN double-implanted MOSFETs

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Applied Physics Express
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Lateral GaN double-implanted MOSFETs (DIMOSFETs) on Mg ion implanted GaN layers with different Mg ion implantation doses have been evaluated to investigate the impact of Mg dose on MOS channel properties. It is demonstrated that the threshold voltage (Vth) and the field effect mobility (μ fe) depend on the Mg dose. A maximum μ fe of 173 cm2 V−1 s−1 has been obtained with a V th of 2.2 V on the Mg implantation layer with a dose of 4.2 × 1013 cm−2. The obtained results indicate that the channel characteristics of a GaN DIMOSFET can be designed by p-type ion implantation.

Normally-off p-GaN/AlGaN/GaN high-electron-mobility transistors using oxygen plasma treatment

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Applied Physics Express
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We propose a method of oxygen plasma treatment to realize normally-off p-GaN/AlGaN/GaN high-electron-mobility transistors. The fabricated device features an oxide surface passivation layer and a high-resistivity GaN cap layer at the access region, both transformed from p-GaN by the oxygen plasma treatment technique. With optimized treatment conditions, a low sheet resistance of 682 Ω/squ has been successfully obtained and the fabricated device shows high performance with a positive threshold voltage of +1.02 V, a maximum drain current of 301 mA mm−1, a high on/off ratio of ~108, a breakdown voltage of 660 V, and low current collapse.

Implantation-and etching-free high voltage vertical GaN p–n diodes terminated by plasma-hydrogenated p-GaN: revealing the role of thermal annealing

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Applied Physics Express
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Low-damage, low-temperature, and easy-to-implement hydrogen-plasma-based termination is attractive for fabricating implantation- and etching-free GaN power p–n diodes. This work investigates in detail the hydrogenation process and unveils the critical role of thermal annealing. A subsequent thermal annealing is key to thermally driving down hydrogen to fully hydrogenate p-GaN to form the termination. The devices showed a specific on-resistance of 0.4 mΩ cm2 and a breakdown voltage (BV) of ~1.4 kV. They also exhibited improved BV compared with mesa-etched devices. High temperature performance was also investigated. These results can serve as important references for future developments of GaN power electronics.

On the Baliga's Figure-Of-Merits (BFOM) Enhancement of a Novel GaN Nano-Pillar Vertical Field Effect Transistor (FET) with 2DEG Channel and Patterned Substrate

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Nanoscale Research Letters
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A novel enhancement-mode vertical GaN field effect transistor (FET) with 2DEG for reducing the on-state resistance (RON) and substrate pattern (SP) for enhancing the breakdown voltage (BV) is proposed in this work. By deliberately designing the width and height of the SP, the high concentrated electric field (E-field) under p-GaN cap could be separated without dramatically impacting the RON, turning out an enhanced Baliga's Figure-Of-Merits (BFOM, BV2/RON). Verified by experimentally calibrated ATLAS simulation, the proposed device with a 700-nm-long and 4.6-µm-width SP features six times higher BFOM in comparison to the FET without patterned substrate. Furthermore, the proposed pillar device and the SP inside just occupy a nano-scale area, enabling a high-density integration of such devices, which renders its high potential in future power applications.

GROUP 4 - Advanced Electronics and RF

Group leader: Jean-Claude Dejaeger (IEMN)

Information selected by Jean-Claude Dejaeger (IEMN) and Yvon Cordier (CRHEA-CNRS)

A unified static-dynamic analytic model for ultra-scaled III-nitride high electron mobility transistors

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Journal of Applied Physics
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This paper presents an analytic model to calculate nodal charges and their corresponding internodal capacitances in ultra-scaled III-nitride high electron mobility transistors (HEMTs) in which carrier transport is expected to be quasiballistic. The dynamic model is combined with our previously published static model [K. Li and S. Rakheja, J. Appl. Phys. 123, 184501 (2018)] to provide a unified physical description of the HEMT. In the dynamic model, the position-dependent channel charge is obtained using a realistic potential profile in the channel, obtained from the solution of the Poisson equation. The effect of electric field lines penetrating from the ungated access regions into the channel (gated region) is included. Fringing electric field lines from the gate to the channel, which are especially critical in the off-region of the device, are included in the charge description. The channel charges are obtained self-consistently with the transport model and introduce 16 additional input parameters, which are necessary to explain the bias dependence of internodal capacitances in the off-state and in the off-to-on transition region of the device. Using the model, we elucidate the difference in the capacitance-voltage behavior of drift-diffusive and quasiballistic devices. The sensitivity of channel charges to the specific formulation of the potential profile is also examined. The unified model is applied to the experimental capacitance-voltage data of 42-nm and 105-nm gate-length InAlN/GaN HEMTs with an InGaN backbarrier. Additionally, the model is validated against hydrodynamic simulations of a 50-nm gate-length AlGaN/GaN HEMT with significant Joule heating. The model yields an excellent agreement with the measured and simulated data sets over a broad range of bias and temperature conditions. The model is also used to elucidate the role of contact resistance, Joule heating, and nodal capacitances on the RF performance, i.e., cut-off frequency, third-order intermodulation current, and the input third-order intercept point, of scaled III-nitride HEMTs.

Terahertz emission from biased AlGaN/GaN high-electron-mobility transistors

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We report on the results of a comprehensive study of THz emission from a set of dedicated AlGaN/GaN high-electron-mobility transistors. We find that voltage-biased transistors indeed emit in the THz frequency range, as reported in the literature; however, our data let us conclude that this radiation cannot be directly attributed to plasmonic instability phenomena. Instead, two other distinct mechanisms are identified. One is based on high-frequency self-oscillations originating from positive feedback within the frequency range where the transistor provides gain. Such oscillations are especially facilitated by the integration of antenna structures and cease to exist after taking specific measures for circuit stabilization. Another mechanism is identified for the case of broadband emission from multifinger transistors fabricated without any specific antenna. In contrast to the predictions of the plasmonic instability picture, the spectra of this emission depend on the gate and drain biasing conditions and on the bias modulation frequency. This emission can be understood as a combination of thermal emission from the heated material and from thermally excited plasmons and trap states.

A Planar Distributed Channel AlGaN/GaN HEMT Technology

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IEEE Transactions on Electron Devices
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This brief presents AlGaN/GaN high electron mobility transistor (HEMT) devices with improved thermal and dc current–voltage I-V performance using a novel method of obtaining a distributed channel device, i.e., the total semiconductor area between the ohmic contacts comprise conducting and nonconducting regions. A novel oxygen (O 2) plasma treatment technique is used to realize the inactive or nonconducting regions. Multifinger devices with 1-mm gate periphery exhibit extremely low gate leakage currents below 0.2 um/mm at a gate voltage of −20 V and an increase in the saturated output current by 14% at 20-V drain voltage. Moreover, performed dc I-V measurements at various ambient temperatures show that the proposed method not only increases the saturated output currents by over 10% for 1x100 um2 gate devices but also significantly reduces their knee walkout voltage from 6 to 3 V at 300 K. These results show that this device design approach can exploit further the potential of the GaN material system for transistor applications.

Bayesian Inference-Based Behavioral Modeling Technique for GaN HEMTs

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IEEE Transactions on Microwave Theory and Techniques
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A new, frequency-domain, behavioral modeling methodology for gallium nitride (GaN) high-electron-mobility transistors (HEMTs), based on the Bayesian inference theory, is presented in this paper. Several different probability distribution (kernel) functions are examined for the Bayesian-based modeling architecture, with the optimal kernel function identified through experimental testing. These results are compared to an alternative approach based on the artificial neural networks (ANNs), with the data showing that the proposed approach demonstrates improved accuracy, while at the same time, alleviating the well-known ANN overfitting issue. Model verification is performed at the fundamental and harmonic frequencies using the identified optimal kernel, through comparisons with simulated data from a reference nonlinear circuit model, and with experimental data from separate 2- and 10-W GaN HEMT devices, over a wide range of load conditions. The models can predict accurately the optimal area of the fundamental output power on the Smith chart and the area of optimal power efficiency. Furthermore, the ability of the model to interpolate across input power levels and input frequencies is also tested, with excellent fidelity to the simulated and measured data obtained.

Neutron irradiation effects on the electrical properties of previously electrically stressed AlInN/GaN HEMTs

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IEEE Transactions on Nuclear Science
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This paper analyses the neutron irradiation impact on the electrical performances of unstressed, on-state, off-state and Negative Gate Bias (NGB) stressed AlInN/GaN HEMTs. These irradiations have resulted in the creation of electron traps that are causing a decrease in the drain current and an increase in the access resistance of the unstressed, on-state or off-state stressed AlInN/GaN devices. These degradations have been correlated with gamma

spectrometry measurements and transmutation reactions occurred during the thermalized neutron irradiation have been highlighted. Despite these phenomena, a rise in drain current and a reduction in access resistance have been observed when NGB stressed AlInN/GaN HEMTs were irradiated with a fluence of 1.2x1012 neutrons/cm2. The differences between the electrical behaviors of unstressed, on-state, off-state, and NGB stressed devices observed after the neutron bombardment are related to the presence of electron traps in these device structures.

Simulation of the RF Power Performance of a GaN HFET and Comparison to Experiment

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IEEE Transactions on Electron Devices
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The large-signal RF power performance of an AlGaN/GaN heterostructure field-effect transistor (HFET) is simulated by technology computer-aided design (TCAD) software, and compared to measurement. A clear procedure for extraction of the simulation physical parameters is described. Trapping effects are included, but temperature effects are not. Good agreement between simulation and measurement is demonstrated, paving the way for efficiency optimization of GaN HFETs using TCAD.

First demonstration of RF N-polar GaN MIS-HEMTs grown on bulk GaN using PAMBE

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Semiconductor Science and Technology
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Nitrogen polar (N-Polar) GaN high-electron mobility transistors (HEMT) targeting high efficiency in millimeter wave power amplification applications were fabricated on epitaxial layers grown by plasma assisted molecular beam epitaxy (PAMBE) on on-axis semi-insulating bulk GaN substrates. On-state current density of ~1 A mm−1 was observed on transistors with L G = 0.75 µm, L GS = 0.5 µm and L GD = 3.75 µm. In a deep class AB mode of operation, devices fabricated on epitaxial structures with these substrates demonstrated 60% higher electron channel mobility compared to devices fabricated with a similar epitaxial structure grown on sapphire substrates using metal-organic chemical vapor deposition. As the first demonstration of N-polar GaN-on-GaN MISHEMT for power amplifier applications, the devices discussed in this letter bridge a path towards achieving higher power gain and efficiency for millimeter-wave N-polar GaN HEMTs.

Ku-band GaN 100-W internally matched amplifier using accurate large signal model

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International Journal of Numerical Modelling: Electronic Networks, Devices and Fields
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This paper describes a Ku-band 100-W gallium nitride (GaN) internally matched power amplifier using an accurate large signal Angelov model. The large gate-periphery GaN devices on SiC substrate are used for achieving the large power output and high efficiency. For designing exactly the power amplifier, the large signal GaN model is founded using measured pulse I-V and S parameters of different bias conditions. The foundation impedance and harmonic impedance are matched simultaneously in the matching circuit based on the large signal model. The power amplifier efficiency is promoted, and the input and output matching circuit with the GaN chips are integrated in a 13 × 21 mm ceramic package. Using two 12 mm GaN transistors, the amplifier finally has the pulse output power of over 100 W and the linear gain of 8 dB across the band of 13 to 15 GHz, the efficiency is over 40% under the pulse drain bias voltage (Vds) of 32 V, and the duty is 10% with the pulse width of 100 microseconds. The results show that the character of realized amplifier is consistent with the simulation data information, which fully indicates the veracity of the developed model. And

this is the first paper proposed of a 100 W power amplifier achieved in such a small package in Ku band.

GaN-on-Si HEMTs for wireless base stations

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Materials Science in Semiconductor Processing
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Gallium Nitride, in the form of epitaxial HEMTs (High Electron Mobility Transistor), is now almost universally acknowledged as the replacement for silicon bipolar and power LDMOS (Laterally Diffused Metal Oxide Semiconductor) devices as the primary active element for linear power amplification in RF (Radio Frequency), microwave, and mmW (Millimeter Wave) base station applications. This is particularly true for GaN-on-SiC (Silicon Carbide) discrete HEMT devices and MMIC's (Monolithic Microwave Integrated Circuits) which enable the state-of-the-art high frequency performance and bandwidth required for sub-6 GHz frequency bands covering both 4G and 5G systems as well as able to be extended into Ku-Band and Ka-Band applications.

A Millimeter-wave AlGaN/GaN HEMT Fabricated with Transitional-Recessed-Gate Technology for High-Gain and High-Linearity Applications

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IEEE Electron Device Letters
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A high-linearity and high-gain AlGaN/GaN HEMTs with a 100 nm gate was demonstrated. The device employs transitional recessed gate (TRG) along the gate width for millimeter wave power application. The gradually changing gate recess depth was created using transitional dosed photoetching. Accurate etching ensured the FET-elements have a continued Vts offset in the local equivalent threshold voltage (Vth) in different areas. The device exhibits a high Id,max of 1.12 A/mm and a high peak extrinsic gm of 374 mS/mm with an improved gate swing > 2.6V, much higher than that of Fin-HEMT. Excellent RF performance was shown, including fT/fmax = 61.8/148.8 GHz, Gas/Glinear = 9.98 / 12dB at 30GHz. To the best of our knowledge, this is the best associated gain and linearity performance reported to date for AlGaN/GaN HEMTs. This work has great potential for high gain and linearity millimeter wave power applications, which are needed for future communication systems.

Dynamic Performance and Characterization of Traps Using Different Measurements Techniques for the New AlGaN/GaN HEMT of 0.15-µm Ultrashort Gate Length

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IEEE Transactions on Microwave Theory and Techniques
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In this paper, we characterize the signature of traps existing in the new AlGaN/GaN HEMT of 0.15-µm ultrashort gate length and 8 x 50 µm² gate width (GH15) through three different measurement techniques which are low frequency (LF) S-parameters, drain-current deep level transient spectroscopy (I-DLTS), and LF drain noise characterization. These three different measurements techniques were performed for varying chuck temperatures (Tchuck) ranging between 25 °C and 125 °C and for the same biasing condition. All measurements ensure approximatively the extraction of the same signature of traps [apparent activation energy (Ea) and cross section (σn)] existing in the UMS device. Furthermore, we have characterized the thermal resistance (RTH) using pulsed I-V measurement and a two-step calibration process. The determination of RTH is important to evaluate the device and to know precisely the signature of traps Ea and σn defined by the Arrhenius equation. A large signal measurements using an unequally spaced multitone (USMT) signal were done in order to evaluate the performance of GH15 transistor around the optimum load impedance in terms of efficiency (max PAE ~ 55%). The leakage

current which measured before and after all measurements for VGS = -6, -7 V and for VDS varying from 0 to 10 V was lower than 100 µA/mm. To our knowledge, results on charge-trapping and large-signal performance are reported for the first time in 0.15-µm technology.

GaN-on-Diamond HEMT Technology with T AVG = 176 °C at P DC,max = 56 W/mm Measured by Transient Thermoreflectance Imaging

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IEEE Electron Device Letters
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Record DC power has been demonstrated in AlGaN/GaN high electron mobility transistors fabricated using a substrate replacement process in which a thick diamond substrate is grown by chemical vapor deposition following removal of the original Si substrate. Crucial to the process is a ~30 nm thick SiN interlayer that has been optimized for thermal resistance. The reductions obtained in self-heating have been quantified by transient thermoreflectance imaging and interpreted using 3D numerical simulation. With a DC power dissipation level of 56 W/mm, the measured average and maximum temperatures in the gate-drain access region were 176 °C, and 205 °C, respectively.

Ku- and K-band high-efficiency GaN MMIC HPA chipset for satellite communications

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Electronics Letters
https://doi.org/10.1049/el.2018.7179

A GaN monolithic microwave-integrated circuit (MMIC) driver and high power amplifier (HPA) chipset solution are presented for two commonly utilised satellite communications frequency bands. The MMICs represent first pass designs utilising Qorvo's recently released 0.15 µm GaN on SiC process featuring slot via devices.

Dynamic Dual-Gate Bias Modulation for Linearization of a High-Efficiency Multistage PA

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IEEE Transactions on Microwave Theory and Techniques
https://doi.org/10.1109/TMTT.2019.2909878

This paper investigates the linearization of high-efficiency multistage PAs through gate bias modulation derived from the envelope of the RF input signal. We show that separate control of the driver- and power-stage gate bias voltages allows for independent linearization of gain and phase. An iterative algorithm determines signal-dependent gate voltage functions that minimize amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) distortion, and is demonstrated on a 10-W high-efficiency X-band GaN monolithic microwave integrated circuit (MMIC) PA with a custom-designed hybrid dual-gate bias modulator. The noise power ratio (NPR) of a 5-MHz-wide signal is improved by as much as 9.4 dB compared to the PA with a static bias, without degradation in power-added efficiency (PAE) and gain. The measured average PAE improves from 19.9 % at 9.8-dB backoff by 0.8 points, with a saturated gain increase of 0.2 dB at 9.7 GHz. A long-term evolution (LTE) signal with different envelope statistics and a 10.6-dB peak-to-average power ratio (PAPR) is amplified with an adjacent channel power ratio (ACPR) improvement of up to 7.9 dB.

Multi-channel AlGaN/GaN Lateral Schottky Barrier Diodes on Low Resistivity Silicon for Sub-THz Integrated Circuits Applications

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IEEE Electron Device Letters
https://doi.org/10.1109/LED.2019.2912910

This work presents novel multi-channel RF lateral Schottky-barrier diodes (SBDs) based on AlGaN/GaN on Low Resistivity (LR) (σ = 0.02 Ω.cm) silicon substrates. The developed technology offers a reduction of 37 % in onset voltage, VON (from 1.34 to

0.84 V), and 36 % in ON-resistance, RON (1.52 to 0.97 to Ω.mm) as a result of lowering the Schottky barrier height, φn, when compared to conventional lateral SBDs. No compromise in reverse-breakdown voltage and reverse-bias leakage current performance was observed as both multi-channel and conventional technologies exhibited VBV of (VBV > 30 V) and IR of (IR < 38 μA/mm), respectively. Furthermore, a precise small-signal equivalent circuit model was developed and verified for frequencies up to 110 GHz. The fabricated devices exhibited cut-off frequencies of up to 0.6 THz, demonstrating the potential use of lateral AlGaN/GaN SBDs on LR silicon for high-efficiency high-frequency Integrated Circuits applications.

Scalable Modeling of Transient Self-Heating of GaN High-Electron-Mobility Transistors Based on Experimental Measurements

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IEEE Transactions on Electron Devices
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This paper details an extraction procedure to fully model the transient self-heating of transistors from a GaN HEMT technology. Frequency-resolved gate resistance thermometry (f-GRT) is used to extract the thermal impedance of HEMTs with various gate widths. A fully scalable analytical model is developed from the experimental results. In the second stage, transient thermoreflectance imaging (TTI) is used to bring deeper insights into the HEMTs' temperature distribution by individually extracting the transient self-heating of each finger. TTI results are further used to successfully validate the f-GRT results and the modeling of the thermal impedance. Overall, f-GRT is demonstrated to be a fast and robust method for characterizing the transient thermal characteristics of a GaN HEMT. For the first time to the authors' knowledge, a scalable model of the thermal impedance is extracted fully from experimental results.

Analysis of Class-F Power Amplifiers with a Second-Harmonic Input Voltage Manipulation

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IEEE Transactions on Circuits and Systems II: Express Briefs
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In this paper, analysis of class-F high-efficiency power amplifiers (PAs) when adding a second-harmonic input voltage to the gate node of the transistor is derived. The theoretical formulations of the drain current, output power and drain efficiency are elaborated for this case. Based on them, the maximum output power and drain efficiency can be obtained from the closed-form solution set of the initial amplitude and phase of second-harmonic input voltage component. Calculations show that, with a proper second harmonic voltage adding to the input of the transistor, the performance of class-F PAs can be improved evidently. Besides, to validate the theoretical analysis, a simulation using a real GaN transistor has been presented. The relative errors of drain efficiency and output power between the results of theory and simulation are only 1.3% and 2.4%, respectively. To the best knowledge of the author, this is the first full theory to illustrate the performance enhancement of class-F PAs with a second-harmonic input voltage manipulation.

Design of Concurrent Dual-Band Continuous Class-J Mode Doherty Power Amplifier with Precise Impedance Terminations

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IEEE Microwave and Wireless Components Letters
https://doi.org/10.1109/LMWC.2019.2909024

In this letter, a novel methodology for designing concurrent dual-band continuous class-J mode Doherty power amplifier (DPA) with precise impedance terminations is presented. First, the required impedance condition of the carrier amplifier which operates in continuous class-J mode at the back-off region is analyzed in detail. Based on the proposed theory, the fundamental impedance is realized by taking advantage of the noninfinity output

impedance of the peaking stage, then the second harmonic impedance is realized with a harmonic tuning postmatching network. A 1.8-/2.6-GHz dual-band DPA employing commercial GaN devices is designed and implemented to validate the proposed method. The fabricated DPA can achieve 68.5% and 75% drain efficiencies (DEs) for saturated power level at 1.8 and 2.6 GHz, respectively. For the 6-dB back-off region, the measured DEs are 64% and 63% at the two designed frequencies.

Wideband High-Efficiency Power Amplifier Using D/CRLH Bandpass Filtering Matching Topology

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A wideband and high-efficiency power amplifier (PA) based on a bandpass filtering (BPF) matching network is presented. Composite right-/left-handed (CRLH) cell and dual-CRLH (D-CRLH) cell are employed to realize the wideband BPF matching network with an absorbed bias circuit. The equivalent circuit model of the proposed BPF matching network is given and a synthesized design method is introduced. Furthermore, one wideband gallium nitride (GaN) PA with high efficiency is achieved by using the proposed BPF matching network accordingly. The measured S-parameters of the wideband PA reveal bandpass response from 1.2 to 2.3 GHz with ± 1.2-dB gain flatness and one transmission zero (TZ). For large signal performance from 1.25 to 2.4 GHz, the experimental results show that the measured drain efficiency (DE) is between 64.3% and 77.5%, and verifying the validity of the design strategies for the proposed wideband high-efficiency PA. Due to the compact feature of the CRLH and D-CRLH (D/CRLH) matching network, the proposed PA achieves the smallest area in terms of core circuit compared with other published works. The results demonstrate the advantages of the D/CRLH BPF structure for designing wideband high-efficiency PAs.

Experimental and modeling insight for fin-shaped transistors based on AlN/GaN/AlN double barrier heterostructure

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Solid-State Electronics
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The exploitation of the two-dimensional electron gas (2DEG) channel of an AlN/GaN/AlN double barrier heterostructure, for High Electron Mobility Transistors (HEMTs) with metal-oxide-semiconductor (MOS) tri-gate around a fin-shaped channel (MOS-FinHEMTs), has been investigated by combining fabrication, dc I-V measurements and simulations of single-fin MOS-FinHEMT devices. The dependence of the threshold voltage (Vth) and the maximum drain-source current (Ids,max) on the fin width (Wfin), as well as the effects of ohmic contact resistance, gate-drain and source-gate distance and of the Al2O3 gate dielectric thickness (tox), have been addressed. Fabricated single-fin MOS-FinHEMT devices with tox= 20 nm, exhibited a positive shift of Vth, in comparison to a reference planar-gate device, ranging from +0.8 V for Wfin = 650 nm to +3.4 V for Wfin = 200 nm, due to lateral depletion of the channel by the gate contacts on the fin sidewalls. Simulations reproduced the experimental Vth values and also predicted the Vth of devices with narrower fins, down to Wfin=10 nm. The boundary for normally-off operation (Vth=0 V) was determined at Wfin = 17 nm that may increase up to 31 nm if the tensile strain of the top AlN barrier in the fin nanostructure is elastically relaxed. A reduction of maximum drain-source current per top gate width (Ids,max/Wg) with decreasing Wfin in the range of 200-650 nm may result from increased ohmic contact resistance. However, for narrower fins, Ids,max/Wg is predicted to decrease significantly with decreasing Wfin, due to the lateral field of the sidewall gates. The Ids,max/Wg will also decrease with increasing distance between the source, gate and drain contacts for any Wfin. Finally, the Vth and Ids,max/Wg values were calculated for Al2O3 thickness in the range of 5 to 40 nm.

Gate Current Reduction and Improved DC/RF Characteristics in GaN-Based MOS-HEMTs Using Thermally Grown TiO_2 as a Dielectric

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IEEE Transactions on Electron Devices
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This paper demonstrates a reduction in the gate leakage current and improvement in transistor characteristics in thermally grown TiO_2/AlGaN/GaN heterostructure-based metal-oxide-semiconductor high-electron-mobility transistors (MOS-HEMTs). In contrast to the conventional AlGaN/GaN HEMTs, thermionic field emission through gate is not the dominant current transport mechanism for the thermally grown TiO_2/AlGaN interface. The gate current is greatly affected by the properties of the oxide material and oxide-semiconductor interface in addition to the property of the barrier layer. The MOS-HEMTs with a 3.4-nm-thick TiO_2 gate insulator exhibits a low gate leakage current of 10^{-8} Acm^{-2}, which leads to superior device performances in terms of saturation drain current, peak transconductance, subthreshold swing, and unity gain frequency of 620 mA/mm, 158 mS/mm, 75 mV/decade, and 7 GHz, respectively, for a 400-nm gate length device. This is further augmented by an increase in on/off ratio to $5x10^8$ and a large reduction in the subthreshold leakage current by at least two orders of magnitude in comparison to that of a control HEMT. Trap-assisted tunneling (TAT) and Poole-Frenkel (PF) emission are found to be the dominant current mechanisms for gate leakage at high temperatures and moderate electric field. The activation energy of traps in PF emission is found to be 0.49 eV, and the extracted trap energy levels for the TAT are found to be in the range of 1.7-2.2 eV. The reverse bias current is found to saturate at high voltages when the field across the diode also saturates. The transistor characteristics improvement is largely ascribed to an increase in 2-D electron gas (2DEG) density.

GROUP 5 – MEMS and Sensors

Group leader: Marc Faucher (IEMN)

Information selected by Knowmade

Design and Demonstration of Tunable Amplified Sensitivity of AlGaN/GaN High Electron Mobility Transistor (HEMT)-Based Biosensors in Human Serum

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Analytical Chemistry
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We have developed a swift and simplistic protein immunoassay using aptamer functionalized AlGaN/GaN high electron mobility transistors (HEMTs). The unique design of the sensor facilitates protein detection in a physiological salt environment overcoming charge screening effects, without requiring sample preprocessing. This study reports a tunable and amplified sensitivity of solution-gated electric double layer (EDL) HEMT-based biosensors, which demonstrates significantly enhanced sensitivity by designing a smaller gap between the gate electrode and the detection, and by operating at higher gate voltage. Sensitivity is calculated by quantifying NT-proBNP, a clinical biomarker of heart failure, in buffer and untreated human serum samples. The biosensor depicts elevated sensitivity and high selectivity. Furthermore, detailed investigation of the amplified sensitivity in an increased ionic strength environment is conducted, and it is revealed that a high sensitivity of 80.54 mV/decade protein concentration can be achieved, which is much higher than that of previously reported FET biosensors. This sensor technology demonstrates immense potential in developing surface affinity sensors for clinical diagnostics.

Adsorption of toxic gas molecules on pristine and transition metal doped hexagonal GaN monolayer: A first-principles study

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Vacuum
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Using the first-principles calculations based on density functional theory (DFT-D2 method), we systematically study the structural, energetic, electronic and magnetic properties of toxic gas molecules (H2S, NH3 and SO2) adsorbed on pristine and transition metal (TM) atom (Fe, Mn) doped GaN monolayer (GaN-ML). The results show that the H2S and NH3 are physisorbed on pristine GaN-ML with small adsorption energy, charge transfer, and long adsorption distance. While chemical adsorption character of SO2 on GaN-ML can be obtained, which means that the pristine GaN-ML is sensitive to SO2. We find that the adsorption ability of pristine GaN-ML can be improved by introducing TM dopants. TM (Fe, Mn) doping can increase adsorption energy and charge transfer of the adsorbed systems, except for SO2 adsorbed Fe doped GaN-ML. The enhancing interaction between adsorbed molecules and the TM doped GaN-ML can dramatically induce electrical conductivity changes. Therefore, the TM doped GaN-ML is more suitable for gas molecules detection compared with the pristine GaN-ML. These present properties of gas molecules adsorbed on the pristine and TM doped GaN-ML will help to guide scientists to develop better two-dimensional GaN-based gas sensors in the future.

High-Gain Silicon-Based InGaN/GaN Dot-in-Nanowire Array Photodetector

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ACS Photonics
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The characteristics of visible (λ = 550 nm) InGaN/GaN disk-in-nanowire array photoconductive detectors have been measured and analyzed. The nanowire arrays are grown on (001) silicon substrates by plasma-assisted molecular beam epitaxy. Single, elongated quantum dots are formed in the disk regions by strain relaxation. The spectral photocurrent response of the device has been measured as a function of bias and temperature (T ≥ 300 K) and is characterized by multiple distinct peaks, which are believed to arise from electron–hole bound state transitions in the quantum dots. The bias-dependent gain is very large and ∼103, mainly due to a component resulting from the modulation of the conduction volume of the nanowires upon screening of the surface state charge on the walls by photoexcited holes. The temporal photoconductive response of the device has been measured and is characterized by slow (∼seconds) rise and decay times. The measured photocurrent spectra and transient response have been analyzed by appropriate models.

In Situ Growth of Leakage-Free Direct-Bridging GaN Nanowires: Application to Gas Sensors for Long-Term Stability, Low Power Consumption, and Sub-ppb Detection Limit

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Nano Letters
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Direct-bridge growth of aligned GaN nanowires (NWs) over the trench of GaN-coated sapphire substrate was realized in which the issues of parasitic deposition and resultant bypass current were resolved by combining the novel shadowing effect of the deep trench with the surface-passivation effect of the SiO2 coating. Due to the robust connection and the absence of a contact barrier in bridging NWs, the intrinsic sensing properties of the NW itself can be obtained. For the first time, the gas-sensing properties (e.g., NO2) of the bridging GaN NWs were studied. With the assistance of UV light, the detection limit was improved from 4.5 to 0.5 ppb at room temperature, and the corresponding response time was reduced from 518 to 18 s. This kind of sensor is promising for high sensitivity (detection of less than parts per billion), low power consumption (capable of room-temperature operation), high stability (variation in resistance of <0.8% during 240 days), and in situ monolithic integration.

Transverse spurious mode compensation for AlN Lamb wave resonators

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Lamb wave modes with type I dispersion characteristics exhibit strong affinity toward multi transverse modes behavior above resonance frequency (fr) in the AlN Lamb wave resonators (LWRs), especially the high-transduction-efficiency modes: S0 and S1 mode. For conventional interdigital transducer (IDT) design, the IDT aperture and IDT gap are the two main factors impacting the transverse mode placements and strengths, according to the wave vector analysis and finite element method (FEM) simulation. Moreover, the convex slowness curve of the Lamb wave modes propagating in AlN platelets allows the wave guiding and weak lateral leakage into busbars by the high-velocity IDT gap region. Apodization, the standard technique to suppress the transverse modes for IDT-excited resonators, suffers from drawbacks such as additional loss and reduction of the effective coupling coefficient (k2eff). Type I Lamb wave modes in AlN show positive slope in the dispersion branch, so that a border region of lower eigen-resonance frequency

is required to form Piston mode structure for transverse spurious mode suppression and lateral leakage reduction. Based on dispersion calculations and 2.5D FEM simulations, we demonstrate that by designing the low-velocity border region, such as simply changing the IDT layout, the guiding can be improved and a Piston mode can be obtained for the type I Lamb wave modes.

Linear and Circular AlGaN/AlN/GaN MOS-HEMT-based pH Sensor on Si Substrate: A Comparative Analysis

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IEEE Sensors Letters
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In this article, sensitivity enhancement of undoped AlGaN/AlN/GaN HEMT for pH detection by using dielectric (10 nm Al 2 O 3)-based MOS-gated structure is demonstrated. Linear and circular MOS-HEMT (L-MOSHEMT and C-MOSHEMT, respectively) with similar dimensions are fabricated on Si substrate. Novel sensing metric g d /I DS (drain conductance to current ratio) is introduced, and C-MOSHEMT attains the highest sensitivity of 1.74 mA/pH and 58 mV −1 /pH when change in drain current (I DS) and g d /I DS are taken as the sensing metrics, respectively.

On the Ammonia Sensing Performance and Transmission Approach of a Platinum/Nickel Oxide/GaN-Based Metal-Oxide-Semiconductor Diode

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IEEE Journal of the Electron Devices Society
https://doi.org/10.1109/JEDS.2019.2908419

New platinum (Pt)/nickel oxide (NiO)/GaN-based metal-oxide-semiconductor (MOS) diode-type ammonia sensor was fabricated and studied. In addition, a new grey polynomial differential recovery (GPDR) model was developed for the application of data transmission. The studied Pt/NiO/GaN-based MOS diode shows good ammonia sensing performance at relatively high temperatures (≥423 K). A very high sensing response of 244.2 under 1000 ppm NH 3 /air gas and a low detecting level of 2 ppm NH 3 /air are obtained at 423 K. The studied device also shows operating flexibility in the applied forward and reverse voltages, and good reversibility in ammonia sensing. In order to expand the practical application of ammonia sensing, a GPDR model was developed to effectively reduce data redundancy by 64.22% and achieve a recovery rate of 99.79% compared with the original data. Therefore, the studied sensor device provides promise for ammonia sensing applications.

Effect of torsional beam length on acoustic functionalities of bio-inspired piezoelectric MEMS directional microphone

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IEEE Sensors Journal
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In MEMS, the vibrations of torsionally supported diaphragms largely depend on the torsional beam specifications. An amiss selection of the beam parameters can lead to significant imperfection in the microphone functionalities, like, modal frequency, sensitivity, directionality, signal-to-noise ratio (SNR), and input referred noise floor. Here, we present two piezoelectric MEMS directional microphones inspired by the ear anatomy of fly Ormia ochracea with a prime focus to identify the effect of torsional beam dimensions on their acoustic functionalities. The dimensions of both diaphragms and the width of the torsional beams are identical for both microphones, the only difference between these two microphones lies in the torsional beam length. The microphones are fabricated by a commercially available micromachining process; PiezoMUMPs. To convert the mechanical vibrations into the electronic signal, a

unique piezoelectric sensing scheme is developed comprising of aluminium nitride (AlN) and D33 transducer mode. The performances of both microphones are carried out by theoretical analysis and simulation and further verified with the experimental measurements. It is found from all analyses that the microphone having a shorter length of the torsional beam is better in terms of sensitivity, noise floor, and SNR regarding its low propagation delay.

Enhancement mechanism of H2 sensing in metal-functionalized GaN nanowires

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Applied Surface Science
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We use density functional theory to evaluate the metals adsorption on the surface of Gallium Nitride (GaN) nanowire (NW) and propose a model to explore H2 sensing enhancement mechanism of metal-functionalized GaN nanowire in theory. The adsorption energy is negative when the metal atoms move closed to the surface of GaN NWs, which reflect the feature of exothermic reaction. Moreover, the simulation indicate the metal-functionalized GaN have much stronger sensing to H2 by forming chemisorption between H2 molecules and metal atoms on the surface, rather than the conventional van der Waals forces between H2 molecules and the pure GaN surface. The latter can only lead to a poor response to H2 since the weak interactions. Comparing with Au, Ag and Cu-functionalized surface, H2 molecules are adsorbed at Pt-functionalized surface, with the lowest adsorption energy, which indicate it is expect to be the most suitable for H2 detection. It should be originated from the largest band gap change and most significantly surface charge reconstruction of Pt-functionalized surface. Our results present an enhancement mechanism of gas sensing from the reduction of the surface potential by the metals effect, which can be applied to design and advance gas-sensing materials.

High-performance nanoporous-GaN metal-insulator-semiconductor ultraviolet photodetectors with a thermal oxidized β-Ga2O3 layer

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Optics Letters
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We report on the high-performance nanoporous (NP) GaN-based metal-insulator-semiconductor (MIS) ultraviolet (UV) photodetectors (PDs) with a thermal oxidized β-Ga2O3insulating layer. The devices show a high responsivity of 4.5×105 A/W and maximum external quantum efficiency of 1.55×108% at 360 nm under a 10 V applied bias, which are attributed to the trap-assisted tunneling induced internal gain mechanism. Correspondingly, a specific detectivity of 8.27×1015 Jones and excellent optical switching repeatability are also observed in our fabricated PDs. The NP-GaN/β-Ga2O3 MIS UV PD may act as an excellent candidate for the application in UV photodetection due to the high performance and simple fabrication process.

Electro-mechanical properties of multilayered aluminum nitride and platinum thin films at high temperatures

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Sensors and Actuators A: Physical
https://doi.org/10.1016/j.sna.2019.04.036

In this study, the electro-mechanical properties of multilayered thin films consisting of 10 bi-layers of 7 nm aluminum nitride (AlN) and 3 nm platinum (Pt)

are investigated in the as deposited state and after different post deposition annealing steps. The multilayers are deposited using direct current magnetron sputtering on thermally oxidized silicon wafers or sapphire substrates and are annealed in Ar atmosphere at 800, 900 and 1000 °C up to 24 h. The electro-mechanical properties are characterized from room temperature up to 500 °C using Van-der-Pauw as well as gauge factor measurements. Furthermore, transmission electron microscopy and energy dispersive X-ray analyses are used to investigate the microstructure and the chemical composition of the multilayers before and after thermal loading. The influence of the annealing on the crystalline structure is examined by X-ray diffraction analyses. Annealing in this high temperature range causes an intermixture of the individual Pt and AlN sub-layers as well as a recrystallization of the Pt thin films. Annealing the multilayered thin film system at 900 °C for 1 h in Argon atmosphere results in a multilayer which is electrically stable up to 500 °C in air and which exhibits a 3 times lower temperature coefficient of resistance at a similar gauge factor when compared to pure Pt thin films.

The investigation of integrated SAW strain sensor based on AlN/TC4 structure

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Sensors and Actuators A: Physical
https://doi.org/10.1016/j.sna.2019.04.012

This paper reports a novel strain sensor integrated on metal component. High-performance SAW strain sensor is embed on the layered AlN/TC4(Ti-6Al-4 V) structure by lift-off photolithography techniques, while the AlN film is directly deposited on the TC4 metal beam without bonding materials. The strain characteristics of the integrated sensor have been simulated and experimental investigated. The finite element modeling (FEM) simulation reveals that the strain transfer ratio (STR) of the sensor reaches 0.992 at 20 °C. The experimental results show that the strain sensitivity of the sensor reaches 1.61 ppm/με with a deviation of 0.56%. The strain hysteresis error of the SAW devices is about 0.32% at 25 °C. The temperature behavior in strain sensitivity and hysteresis errors have also been studied. Though negative effects caused by increasing of operation temperature on its strain response, the integrated SAW sensor shows better performance than the reported one in a wide range of operation temperature. The prepared layered SAW sensor integrated with TC4 alloy has great potential applications in high temperature harsh environment.

Performance Modulation for Back-illuminated AlGaN Ultraviolet Avalanche Photodiodes Based on Multiplication Scaling

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IEEE Photonics Journal
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Back-illuminated ultraviolet avalanche photodiodes (APDs) of various multiplication widths were fabricated on AlN templates with a separate absorption and multiplication structure. The impacts of increased multiplication scale on device performance were investigated. The avalanche breakdown voltage was found to increase as the multiplication layer thickness (MLT) increases. The APD with 230-nm-MLT achieved a superior maximum multiplication gain of 5.4×104 , higher than that obtained in devices with 150-nm- and 300-nm-MLT. Theoretical simulations demonstrated that the critical electric field intensity in avalanche region would decrease as the rising of MLT, indicating the modulating ability of multiplication scaling on the AlGaN APD performance. In addition, APDs fabricated on different AlN templates were employed to study the effects of crystalline quality on device properties.

Sensitivity enhanced temperature sensor: one-port 2D surface phononic crystal resonator based on AlN/sapphire

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Semiconductor Science and Technology
https://doi.org/10.1088/1361-6641/ab0a82

According to the structure of a one-port surface acoustic wave (SAW) resonator, a one-port surface phononic crystal (SPC) resonator is designed. Both one-port SAW resonator and one-port SPC resonator are fabricated on AlN/Sapphire. Frequency responses and quality factors are studied. The one-port SAW resonator has a fundamental resonance mode at 693.07 MHz. Unlike the one-port SAW resonator, the one-port SPC resonator has two distinct resonance modes at 680.28 MHz and 698.91 MHz, respectively. From the simulation results by finite element method (FEM), these two resonance modes may come from the two cavities of the one-port SPC resonator. Frequency-versus-temperature behaviors of these two resonators are investigated. The results show that the frequencies of resonance modes of these two resonators are decreased linearly with the increased temperature. A new kind of temperature sensor is proposed by using frequency difference between these two resonance modes of the one-port SPC resonator. The eventual temperature coefficient of frequency (TCF) value of the temperature sensor is -99.30 ppm °C−1 which is twice more than that of the one-port SAW resonator. All results prove that temperature sensitivity is enhanced by using two mode characters of one-port SPC resonator based on AlN/Sapphire.

GROUP 6 - Photovoltaics and Energy harvesting

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First-principles modeling of GaN(0001)/water interface: Effect of surface charging

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The Journal of Chemical Physics
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The accumulation properties of photogenerated carriers at the semiconductor surface determine the performance of photoelectrodes. However, to the best of our knowledge, there are no computational studies that methodically examine the effect of “surface charging” on photocatalytic activities. In this work, the effect of excess carriers at the semiconductor surface on the geometric and electronic structures of the semiconductor/electrolyte interface is studied systematically with the aid of first-principles calculations. We found that the number of water molecules that can be dissociated follows the “extended” electron counting rule; the dissociation limit is smaller than that predicted by the standard electron counting rule (0.375 ML) by the number of excess holes at the interface. When the geometric structure of the GaN/water interface obeys the extended electron counting rule, the Ga-originated surface states are removed from the bandgap due to the excess holes and adsorbates, and correspondingly, the Fermi level becomes free from pinning. Clearly, the excess charge has a great impact on the interface structure and most likely on the chemical reactions. This study serves as a basis for further studies on the semiconductor/electrolyte interface under working conditions.

Achieving High Quality Factor without Vacuum Packaging by High Density Proof Mass Integration in Vibration Energy Harvesters

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Journal of Microelectromechanical Systems
https://doi.org/10.1109/JMEMS.2019.2910228

This paper presents a simple approach to control fluidic damping, and thereby improve the mechanical quality factor at ambient pressure, of AlN-based piezoelectric resonant energy harvesters by using high density proof masses. Using models adapted from the literature, and accounting for the simultaneous transverse and rotational motion of the cantilever beam, scaling laws are extracted for the fluidic quality factor, Qf, as a function of the fluid damping regime, either due to drag or squeeze film forces. Subsequently, we demonstrate the utility of the scaling laws by characterizing silicon-based devices and tungsten tip masses. By accounting for other damping sources and the device operating frequency, we achieve close to an order of magnitude improvement on Qf with this strategy, going from 398 to 4193. Beside potential for footprint reductions and higher power outputs, these results suggest that high density proof mass integration can be an alternative to vacuum packaging for MEMS based vibration energy harvesting.

Ultra-Energy-Efficient Photoelectrode Using Microstriped GaN on Si

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ACS Photonics
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A prototype photoelectrode with a unique design has been fabricated using GaN microstripes grown on a patterned Si substrate. The photoelectrode has demonstrated a record-high photocurrent density of 11 mA/cm2 upon one sun illumination and a H2 generation rate of up to 2.67 mL·cm–2·h–1. This performance with a step-change has been achieved due to the contribution from both the GaN and the silicon substrate, as such a combination covers a wide spectral region (from the ultraviolet region due to the GaN bandgap to the infrared region due to the silicon bandgap). Unlike conventional GaN grown on a silicon substrate, where a thick AlN layer is required to separate GaN from the silicon in order to avoid the well-known Ga melt-back issue, a GaN/silicon heterojunction in our photoelectrode can be formed as a result of a weak Ga melt-back reaction, which is due to the specially designed configuration of our photoelectrode grown using the microstripes. Two reference photoelectrodes have been fabricated for comparison in order to support our conclusion. The results presented may pave the way for the fabrication of ultra-energy-efficient GaN-on-Si-based photoelectrodes or even photovoltaics devices.

Tunable electronic and optical properties of new two-dimensional GaN/BAs van der Waals heterostructures with the potential for photovoltaic applications

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Chemical Physics Letters
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First-principle calculations have been executed to examine the optical and electronic properties of two-dimensional GaN/BAs heterostructures with three possible stacking orders. It has been disclosed that these heterostructures are semiconductors and dynamically stable. Also, it should be accentuated that AB and BB stackings have indirect band gaps of about 1.71 and 1.685 eV, respectively. Most importantly, AA stacking exhibit a direct band gap of 0.676 eV pointing out that it is helpful to photocatalysis. Owing to special optical and electronic properties of GaN/BAs vdW heterostructures, it is ratiocinated that these heterostructures can be congenial for the solar cell applications.

GaN nanowire arrays for photocatalytic applications II: influence of a dielectric shell and liquid environments

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Applied Physics B
https://doi.org/10.1007/s00340-019-7187-y

GaN nanowires (NWs) are promising candidates for photocatalytic devices due to their large surface-to-volume ratio and their waveguide character. Protective coatings and nanoparticle co-catalysts are widely used to improve the stability and the photocatalytic activity of semiconductors in liquid electrolytes. Here, we present a systematic experimental study of the influence of a dielectric shell and liquid environments on the interaction of light with GaN NW arrays related to photocatalytic applications. Transmission measurements on bare GaN NWs and core–shell NWs with varying shell thickness and refractive index of the shell reveal a shift of the transmission minima that originate from the coupling of light to various waveguide modes supported within the NWs. This shift is a result of the shift of the dispersion relations of the modes for core–shell NWs. The transmission spectra of GaN NWs in liquid environments show a spatial and spectral shift. These results are explained by the dependence of both, the waveguide properties of the single NWs and the photonic crystal characteristics of the NW array, on the refractive index of the environment. A comparison of the experimental findings with numerical simulations shows a good agreement.

Photoelectric Properties of GaN Layers Grown by Plasma-Assisted Molecular-Beam Epitaxy on Si(111) Substrates and SiC/Si(111) Epitaxial Layers

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Semiconductors
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The photoelectric properties of GaN/SiC/Si(111) and GaN/Si(111) heterostructures grown by plasma-assisted molecular-beam epitaxy under the same growth conditions on identical silicon substrates, but with different buffer layers, are experimentally investigated. The GaN/SiC/Si(111) structure is formed on a Si substrate with the SiC buffer layer grown by a new atom-substitution technique and the GaN/Si(111) structure, on a Si substrate subjected to pre-epitaxial plasma nitridation. The significant effect of carbon-vacancy clusters contained in the SiC layer on the growth of the GaN layer and its optical and photoelectric properties is found. It is experimentally established that the GaN/SiC/Si(111) heterostructure has a higher photosensitivity than the GaN/Si(111) heterostructure. In the GaN/SiC/Si(111) heterostructure, the coexistence of two oppositely directed p–n junctions is observed. One p–n junction forms at the SiC/Si interface and the other, at the GaN/SiC interface. It is shown that the occurrence of an electric barrier in the GaN/Si(111) heterostructure at the GaN/Si(111) heterointerface is caused by the formation of a thin silicon-nitride transition layer during pre-epitaxial plasma nitridation of the Si(111) substrate.

Theoretical study of the effect of polarization matching layers on the Shockley–Read–Hall recombination-induced dark current density in InGaN/GaN heterostructure solar cells

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Journal of Computational Electronics
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The physical effects of the polarization-induced charge density on the losses due to Shockley–Read–Hall (SRH) recombination in InGaN/GaN solar cells under conditions of low p-GaN doping density (~ 5 × 1017 cm−3) are discussed. Theoretical studies are performed for four p-i-n InxGa1−xN/GaN heterostructures (with x = 0.10, 0.15, 0.20, and 0.25) to analyze the effect of the polarization-induced interface charges on the built-in field present across the absorption region of the cell, which is otherwise responsible for the extraction of photogenerated charge carriers. Furthermore, the role of polarization matching layers, strategically placed at the i-InGaN/p-GaN interface, in countering the SRH recombination-induced dark current density is discussed based on simulations performed using APSYS software from Crosslight. The simulation results are validated using a mathematical model.

GROUP 7 - Materials, Technology and Fundamental

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NANO

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Determining GaN Nanowire Polarity and its Influence on Light Emission in the Scanning Electron Microscope

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Nano Letters
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The crystal polarity of non-centrosymmetric wurtzite GaN nanowires is determined non-destructively in the scanning electron microscope using electron backscatter diffraction (EBSD). The impact of the nanowire polarity on light emission is then investigated using cathodoluminescence (CL) spectroscopy. EBSD can determine polarity of non-centrosymmetric crystals by interrogating differences in the intensity distribution of bands of the EBSD pattern associated with semi-polar planes. Experimental EBSD patterns from an array of GaN nanowires are compared with theoretical patterns produced using dynamical electron simulations to reveal whether they are Ga or N-polar or, as in several cases, of mixed polarity. CL spectroscopy demonstrates the effect of the polarity on light emission, with spectra obtained from nanowires of known polarity revealing a small but measureable shift (≈28 meV) in the band edge emission energy between those with Ga and N polarity. We attributed this energy shift to a difference in impurity incorporation in nanowires of different crystal polarity. This approach can be employed to non-destructively identify polarity in a wide range of non-centrosymmetric nanoscale material systems and provide direct comparison with their luminescence.

InGaN Platelets: Synthesis and Applications toward Green and Red Light-Emitting Diodes

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Nano Letters
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In this work, we present a method to synthesize arrays of hexagonal InGaN submicrometer platelets with a top c-plane area having an extension of a few hundred nanometers by selective area metal–organic vapor-phase epitaxy. The InGaN platelets were made by in situ annealing of InGaN pyramids, whereby InGaN from the pyramid apex was thermally etched away, leaving a c-plane surface, while the inclined {10$\bar{1}$1} planes of the pyramids were intact. The as-formed c-planes, which are rough with islands of a few tens of nanometers, can be flattened with InGaN regrowth, showing single bilayer steps and high-quality optical properties (full width at half-maximum of photoluminescence at room temperature: 107 meV for In0.09Ga0.91N and 151 meV for In0.18Ga0.82N). Such platelets offer surfaces having relaxed lattice constants, thus enabling shifting the quantum well emission from blue (as when grown on GaN) to green and red. For single InGaN quantum wells grown on the c-plane of such InGaN platelets, a sharp interface between the quantum well and the barriers was observed. The emission energy from the quantum well, grown under the same conditions, was shifted from 2.17 eV on In0.09Ga0.91N platelets to 1.95 eV on In0.18Ga0.82N platelets as a result of a thicker quantum well and a reduced indium pulling effect on In0.18Ga0.82N platelets. On the basis of this method, prototype light-emitting diodes were demonstrated with green emission on

In0.09Ga0.91N platelets and red emission on In0.18Ga0.82N platelets.

Polarity conversion of GaN nanowires grown by plasma-assisted molecular beam epitaxy

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Applied Physics Letters
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It is demonstrated that the N-polarity of GaN nanowires (NWs) spontaneously nucleated on Si (111) by molecular beam epitaxy can be reversed by intercalation of an Al- or a Ga-oxynitride thin layer. The polarity change has been assessed by a combination of chemical etching, Kelvin probe force microscopy, cathodo- and photoluminescence spectroscopy, and transmission electron microscopy experiments. Cathodoluminescence of the Ga-polar NW section exhibits a higher intensity in the band edge region, consistent with a reduced incorporation of chemical impurities. The polarity reversal method we propose opens the path to the integration of optimized metal-polar NW devices on any kind of substrate.

High-Gain Silicon-Based InGaN/GaN Dot-in-Nanowire Array Photodetector

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ACS Photonics
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The characteristics of visible (λ = 550 nm) InGaN/GaN disk-in-nanowire array photoconductive detectors have been measured and analyzed. The nanowire arrays are grown on (001) silicon substrates by plasma-assisted molecular beam epitaxy. Single, elongated quantum dots are formed in the disk regions by strain relaxation. The spectral photocurrent response of the device has been measured as a function of bias and temperature ($T \geq 300$ K) and is characterized by multiple distinct peaks, which are believed to arise from electron–hole bound state transitions in the quantum dots. The bias-dependent gain is very large and ~103, mainly due to a component resulting from the modulation of the conduction volume of the nanowires upon screening of the surface state charge on the walls by photoexcited holes. The temporal photoconductive response of the device has been measured and is characterized by slow (~seconds) rise and decay times. The measured photocurrent spectra and transient response have been analyzed by appropriate models.

Enhanced uniformity of III-nitride nanowire arrays on bulk metallic glass and nanocrystalline substrates

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Journal of Vacuum Science & Technology B
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Nanowires possess unique strain relieving properties making them compatible with a wide variety of substrates ranging from single crystalline semiconductors, amorphous ceramics, and polycrystalline metals. Flexible metallic foils are particularly interesting substrates for nanowires for both flexible optoelectronics and high throughput manufacturing techniques. However, nanowires grown on polycrystalline metals exhibit grain-dependent morphologies. As an alternative route, the authors demonstrate the growth of highly uniform III-Nitride nanowires on bulk metallic glass (amorphous metal) and nanocrystalline Pt metal films using molecular beam epitaxy. Nanowire arrays on metallic glass substrates show uniformity over length scales >100 µm. The quality of these nanowires is explored by photoluminescence spectroscopy. The electrical characteristics of individual nanowires are measured via conductive

atomic force microscopy, and mesoscale light-emitting diodes (LEDs) are fabricated. Nanowires grown on nanocrystalline Pt films showed an increase in output power by a factor of up to 32, and an increase in the overall LED efficiency by up to 13× compared with simultaneously grown nanowire LEDs on bare Si.

3D GaN nanoarchitecture for field-effect transistors

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Micro and Nano Engineering
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The three-dimensionality of 3D GaN field-effect transistors (FETs) provides them with unique advantages compared to their planar counterparts, introducing a promising path towards future FETs beyond Moore's law. Similar to today's Si processor technology, 3D GaN FETs offer multi-gate structures that provide excellent electrostatic control over the channel and enable very low subthreshold swing values close to the theoretical limit. Various concepts have been demonstrated, including both lateral and vertical devices with GaN nanowire (NW) or nanofin (NF) geometries. Outstanding transport properties were achieved with laterally contacted NWs that were grown in a bottom-up approach and transferred onto an insulating substrate. For higher power application, vertical FETs based on regular arrays of GaN nanostructures are particularly promising due to their parallel integration capability and large sidewall surfaces, which can be utilized as channel area. In this paper, we review the current status of 3D GaN FETs and discuss their concepts, fabrication techniques, and performances. In addition to the potential benefits, reliability issues and difficulties that may arise in complex 3D processing are discussed, which need to be tackled to pave the way for future switching applications.

High-aspect-ratio single-crystalline AlN nanowires: Free-catalytic PVT growth and field-emission studies

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Journal of Alloys and Compounds
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Nanowires (NWs) with high aspect ratios (HARs) have great advantages for the fabrication of nanodevices. Herein, a high-efficiency and simple physical vapor transport (PVT) method is utilized to synthesize the uniform HAR aluminum nitride (AlN) NWs on a tungsten substrate without any catalysts. Synergistic effect of high surface energy of (0001), low saturated vapor pressure and large axial temperature gradient leads to the growth of HAR AlN NWs, which provides new insight for the growth of low-dimensional AlN nanostructures. The as-obtained AlN NWs with super HAR have hexagonal wurtzite structure, the diameters are about 100 nm and the lengths are over 200 μm. The AlN NWs have an intensive deep ultraviolet (DUV) absorption peak at 5.94 eV and exhibit a relatively high electrical conductivity (1.29 × 10−3 Ω−1 cm−1), low turn-on field (6.2 V μm−1) and threshold field (8.5 V μm−1). These results indicate that PVT method is efficient to fabricate HAR AlN NWs and the AlN NWs not only play an important role in DUV photoelectric devices but also have tremendous potential as a candidate for field-emission nanodevices.

GaN nanowire arrays for photocatalytic applications II: influence of a dielectric shell and liquid environments

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Applied Physics B
https://doi.org/10.1007/s00340-019-7187-y

GaN nanowires (NWs) are promising candidates for photocatalytic devices due to their large surface-to-volume ratio and their waveguide character. Protective coatings and nanoparticle co-catalysts

are widely used to improve the stability and the photocatalytic activity of semiconductors in liquid electrolytes. Here, we present a systematic experimental study of the influence of a dielectric shell and liquid environments on the interaction of light with GaN NW arrays related to photocatalytic applications. Transmission measurements on bare GaN NWs and core–shell NWs with varying shell thickness and refractive index of the shell reveal a shift of the transmission minima that originate from the coupling of light to various waveguide modes supported within the NWs. This shift is a result of the shift of the dispersion relations of the modes for core–shell NWs. The transmission spectra of GaN NWs in liquid environments show a spatial and spectral shift. These results are explained by the dependence of both, the waveguide properties of the single NWs and the photonic crystal characteristics of the NW array, on the refractive index of the environment. A comparison of the experimental findings with numerical simulations shows a good agreement.

NON/SEMI POLAR

Information selected by Knowmade

Crystal growth of a MnS buffer layer for non-polar AlN on Si (100) deposited by radio frequency magnetron sputtering

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Japanese Journal of Applied Physics
https://doi.org/10.7567/1347-4065/aafd8e

The growth conditions of MnS thin film on a Si (100) substrate deposited by the RF-magnetron sputtering method were investigated. The MnS is a buffer layer for the epitaxial growth of non-polar AlN thin film on the Si (100) substrate. The 4°-off-Si (100) substrate and the insertion of MnS film grown at room temperature (RT-MnS) improved the crystallinity and the surface roughness of the MnS film. In particular, the 20 nm thick RT-MnS showed a reduction of surface roughness of the MnS layer deposited at 550 °C. The root mean square value of the MnS layer was 0.23 nm, which is in the same range as that of the Si substrate. X-ray photoelectron spectroscopy measurements revealed that RT-MnS insertion with a thickness over 10 nm reduced the sulfur vacancy formation in the MnS film deposited on RT-MnS, and the MnS was thermally stable at the growth temperature of AlN.

Overgrowth and characterization of (11-22) semi-polar GaN on (113) silicon with a two-step method

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Semiconductor Science and Technology
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A two-step approach has been developed for the growth of semi-polar (11–22) GaN on patterned (113) silicon substrates, which effectively eliminates Ga melt-back etching at a high temperature, one of the most challenging issues. A (113) Si substrate is patterned into groove trenches by means of using a standard photolithography technique and then anisotropic chemical etching, forming (111) facets with an inclination angle of 58˚ with respect to c-axis in addition to the un-etched (113) facets. A thick AlN layer is subsequently epitaxially grown on the patterned silicon to cover all the facets ensuring to eliminate the melt-back, followed by selectively depositing SiO2 masks on the (113) facets only. Further GaN overgrowth is performed only on the exposed (111) facets, forming (11–22) semi-polar GaN with high crystal quality along the vertical direction. Stimulated emission at room temperature has been observed with a low threshold. Low-temperature photoluminescence measurements confirm a significant reduction in basal stacking faults density. This method provides a promising approach to effectively suppress the Ga melt-back etching issue, which is particularly important for Al(Ga)N growth on semi-polar GaN that requires a high growth temperature. The presented results are crucially important for developing monolithic on-

chip integration of electronics and photonics on silicon.

Characterization and optimization of AlN nucleation layer for nonpolar a-plane GaN grown on r-plane sapphire substrate

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Superlattices and Microstructures
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Nonpolar (11–20) a-plane GaN films with AlN nucleation layer were grown on (10–12) r-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD). The crystalline and surface qualities of a-plane GaN were found to closely depend on the growth conditions of AlN nucleation layer. With decreasing AlN growth temperature, the AlN grains became larger and sparser, which significantly reduced the defects density of a-plane GaN films. The growth time of the low temperature AlN layer was further optimized, and a-plane GaN films with reduced anisotropy in the crystalline quality, surface morphology and in-plane strains were achieved. It was found that the lateral growth lengths along different directions of GaN could be modulated by the growth time of AlN nucleation layer, thus changing the anisotropy of a-plane GaN films.

Effect of Surfactant Based Abrasive Free Slurry on CMP Polishing Rate and Planarization of Semi-Polar (11–22) GaN Surface

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ECS J. Solid State Sci. Technol.
https://doi.org/10.1149/2.0171905jss

An abrasive free slurry has been formulated using ionic and non-ionic surfactants with KMnO4 as an oxidiser. Subsequently, the effect of these surfactants on the material removal rate (MRR) and surface planarity of semi-polar (11–22) GaN surface have been studied using chemical mechanical planarization (CMP) process. The formulated polishing slurries were characterized for their rheological properties such as shear thickening, thinning and viscosity as a function of shear rate. It was found that the polishing rate and surface planarity depend on the type of surfactant and its concentration. The estimated MRR values of various surfactants are seen to decrease from anionic to cationic to non-ionic in the order SDS>CTAB>TX-100 and the maximum MRR has been found to be 2.58µm/hr for 0.5 wt% SDS surfactant containing slurry, under optimized conditions of other CMP parameters. In compared to the cationic (CTAB) and non-ionic surfactants (TX-100), anionic surfactant (SDS) offered relatively good surface planarity with a remarkable root-mean-square (rms) surface roughness (Rq) of 2 Å over a scan area of 1 × 1 µm.2

MATERIAL / CHARACTERIZATION / EQUIPMENT / NUMERICAL SIMULATION

Information selected by
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AlN/InAlN thin-film transistors fabricated on glass substrates at room temperature

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Scientific Reports
https://doi.org/10.1038/s41598-019-42822-6

In this study, InAlN was grown on glass substrates using pulsed sputtering deposition (PSD) at room temperature (RT) and was applied to thin-film transistors (TFTs). The surface flatness of the InAlN films was improved by reducing the growth temperature from 350 °C to RT. Further, the electron mobility and concentration of the InAlN film that was grown at RT were observed to be strongly dependent on the In composition. It was also observed that the electron concentration could be reduced during the introduction of Al atoms into InN, which could most likely be attributed to the

reduction in the position of the Fermi level stabilization energy with respect to the conduction band edge. Further, InAlN-TFT was fabricated, and successful operation with a field-effect mobility of 8 cm2 V−1 s−1 was confirmed. This was the first demonstration of the operation of TFTs based on the growth of InAlN on an amorphous substrate at RT.

Observation of single optical site of Eu and Mg codoped GaN grown by NH3-source molecular beam epitaxy

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Journal of Applied Physics
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Eu-doped GaN (GaN:Eu) is a promising solid-state material for quantum information devices owing to its ideal quantum levels. However, a decrease of Eu concentration and the unification of optical sites are required for these devices to access an Eu ion. In this article, the effect of Eu concentration on the optical properties of Mg-codoped GaN:Eu was evaluated. The photoluminescence intensity from Eu ions increased linearly with increasing Eu concentration up to 1 × 1019 cm−3, beyond which the intensity saturated. This resulted from the increase of the sharp luminescence line at 620.5 nm (site A), which has a large excitation cross section, with increasing Eu concentration in the range of low Eu concentrations; an excess Eu concentration leads to the formation of other types of optical sites with a low transfer efficiency or inactive sites. For a low Eu concentration of 3 × 1018 cm−3, all optical sites except a specific optical site corresponding to site A disappeared, and the unification of optical sites was suggested. This result is expected to be valuable to realize quantum information devices.

Effect of Ge doping on growth stress and conductivity in AlxGa1-xN

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Applied Physics Letters
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Silicon (Si) is a common n-type donor in AlxGa1-xN; however, it induces bending of edge-type threading dislocations which can generate tensile stress in the film leading to the formation of channeling cracks in thick layers. Germanium (Ge) has previously been investigated as an alternative to Si for n-type doping of GaN, but its impact on film stress in AlxGa1-xN has not been investigated in detail. In this study, we employ in situ wafer curvature measurements combined with postgrowth characterization to investigate Ge doping of AlxGa1-xN (x = 0–0.62) layers grown on 6H-SiC by metalorganic chemical vapor deposition. It was found that Ge doping (n ∼ 1.6 × 1019 cm−3) of Al0.30Ga0.70N does not induce tensile stress during growth in contrast to that observed with a similar level of Si doping. In addition, the average inclination angle of edge dislocations was similar for undoped and Ge doped films indicating that Ge does not promote surface-mediated dislocation climb. High n-type doping was achieved in Ge doped AlxGa1-xN for lower Al fraction range (x < 0.5), but resistivity increased and carrier density decreased significantly for higher Al fractions. The results demonstrate Ge doping as a viable alternative to Si doping of AlxGa1-xN (x < 0.5) for achieving thick, crack-free layers.

Solving the problem of gallium contamination problem in InAlN layers in close coupled showerhead reactors

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Applied Physics Express
https://doi.org/10.7567/1882-0786/ab0bbb

Gallium contamination is a well-known problem for InAlN layers grown in close coupled showerhead metal-organic vapor phase epitaxy reactors, and we have previously suggested a model explaining this gallium incorporation and the associated reduction in indium [Mrad, J. Cryst. Growth 507, 139 (2019)]. Here we propose the hypothesis that increasing the showerhead face temperature during GaN growth should encourage the growth of more stable GaN rather than metallic gallium, and reduce the reactions between tri-methyl indium and gallium on the showerhead. Using a hot deposition shield on the showerhead, we have confirmed this, to grow for the first time almost entirely gallium free InAlN layers in a showerhead reactor.

Gate length effect on trapping properties in AlGaN/GaN high-electron-mobility transistors

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Semiconductor Science and Technology
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A comparative study was performed to assess the gate length effect on trapping properties in AlGaN/GaN metal-oxide-semiconductor channel high-electron-mobility transistors. Deep level transient spectroscopy and electrical simulations were used to investigate the deep levels response in two devices with the same gate surface area but with gate lengths of 15 and 1 µm. Results reveal that the repartition of equipotential lines depends on the gate length and impacts trapping phenomena. We demonstrated that the concentration of the defects localized beneath the gate electrode and associated with etching induced damage is reduced with a short gate length. Furthermore, for a negative gate voltage, the depletion region is less extended toward the buffer layers with a gate length of 1 µm, meaning that the trapping effects are reduced. Finally, this work indicates that it is better to design transistors with a short gate length to moderate the effect of trapping phenomena.

Epitaxial growth of (111) BaTiO3 thin films on (0002) GaN substrates with SrTiO3/TiN buffer layers

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High-quality perovskite (111) BaTiO3 (BTO) ferroelectric thin films were epitaxially grown on wurtzite (0002) GaN substrates with the rationally designed SrTiO3 (STO)/TiN buffer layers by pulsed laser deposition. Particularly, TiN thin films with excellent conductivity could also be served as the bottom electrodes. The epitaxial relationship of the BTO/STO/TiN/GaN heterostructures was proved to be (111)[1 1^{-} 0] BTO//(111)[1 1^{-} 0] STO//(111)[1 1^{-} 0] TiN//(0002)[11 2^{-} 0] GaN by reflection high-energy electron diffraction and high resolution X-ray diffraction. Furthermore, the detailed interface structure and epitaxial relationship of the BTO/STO/TiN/GaN heterostructures were identified on atomic scale by high resolution transmission electron microscopy. The epitaxial (111) BTO ferroelectric thin films on GaN substrates exhibited the favorable ferroelectric properties with the remnant polarization of 12.97 µC cm−2. The high-quality epitaxial integration of perovskite BTO thin films on wurtzite GaN substrates could promote the potential applications in the advanced GaN-based integrated ferroelectric devices.

Electron transport in N-polar GaN-based heterostructures

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Applied Physics Letters
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Electron transport in N-polar GaN-based high-electron-mobility transistor (HEMT) structures with a combination of In0.18Al0.82N-AlN as the barrier was studied via temperature-dependent van der Pauw Hall and Shubnikov de Haas measurements. In contrast to Ga-polar HEMT structures, no persistent photoconductivity could be detected. In a sample with 10 nm thick InAlN, only one oscillation frequency was observed, demonstrating that a single sublevel is present. From the oscillations, a two-dimensional electron gas carrier density of 8.54×1012 cm−2 and a mobility of 4970 cm2/V s were extracted at 1.7 K. This sample was further investigated using ionic liquid gating. The charge density was varied from 7.5×1012 cm−2 to 9.6×1012 cm−2. The electron mobility significantly declined with decreasing charge density. This is in contrast to Ga-polar HEMT structures, where the electron mobility typically increases slightly as the charge density decreases.

Physical and electrical properties of ALD-Al2O3/GaN MOS capacitor annealed with high pressure water vapor

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Japanese Journal of Applied Physics
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High pressure water vapor annealing (HPWVA) was performed on GaN metal/oxide semiconductor capacitor with Al2O3 film prepared using atomic-layer deposition. The fixed charge density and interface trap density are significantly improved by applying HPWVA (0.5 MPa at 400 °C for 30 min). These results are mainly related to a reaction of the Al2O3/GaN structure with the diffused active H2O monomer derived from HPWVA. It was found that the oxidation and Al–OH formation occurred in the Al2O3 film and thin gallium oxide was formed at the Al2O3/GaN interface.

Unusual step meandering due to Ehrlich-Schwoebel barrier in GaN epitaxy on the N-polar surface

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Applied Surface Science
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The stability of the Nitrogen-polar (000-1) surface of single-crystal bulk GaN substrates is studied for layers grown by plasma-assisted molecular beam epitaxy (PAMBE) in Nitrogen-rich conditions at 730 °C. It is shown that smooth GaN layers with parallel atomic steps are obtained for substrates when the surface crystal miscut angle is larger than 2o, revealing a highly stable epitaxial growth regime on single crystals. A step meandering pattern is observed on layers grown on lower miscut angle substrates. The meandering periodicity is found to have an inverse dependence on growth rate and miscut angle. This is opposite to what is observed for epitaxy on the Ga-polar surface. Combining analytic modeling and kinetic Monte Carlo simulations, it is shown that the existence of an Ehrlich-Schwoebel Barrier (ESB) in the PAMBE growth of GaN in nitrogen-rich conditions on (000-1) GaN reproduces the experimentally observed periodicity of step meandering. Assuming that ESB height depends on interactions between diffusing adatoms, all experimental phenomena are reproduced.

Influence of substrate misorientation on carbon impurity incorporation and electrical properties of p-GaN grown by metalorganic chemical vapor deposition

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Applied Physics Express
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The influence of substrate misorientation angle on carbon impurity incorporation and electrical properties of p-GaN grown at a low temperature of 900 °C has been explored. Secondary ion mass spectrometry results reveal that the concentration of unintentionally incorporated carbon impurity decreases remarkably (from 2 × 1017 cm−3 to 7 × 1016 cm−3) with the increasing misorientation angle. The step motion model is introduced to explain the reason for decreasing carbon concentration with increasing misorientation angle. It has also been found the hole concentration of p-GaN increases and the resistivity of p-GaN decreases with the increasing misorientation angle since carbon acts as compensating donor in p-GaN.

Non-edge-triggered inversion from Ga polarity to N polarity of c-GaN domains on an SiO2 mask during epitaxial lateral overgrowth

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It was previously reported that N-polar c-GaN domains nucleated in window openings on c-plane sapphire were inverted to Ga-polar domains at the edge of an SiO2 mask during epitaxial lateral overgrowth, but it was asserted that polarity inversion of N-polar GaN domains could not occur beyond the edge of the SiO2 mask. However, that assertion was demonstrated only in the case of a-facet-exposed GaN. It is reported here that polarity inversion from Ga polarity to N polarity of m-facet-exposed c-GaN domains occurred during epitaxial lateral overgrowth on the flat region beyond the edge of a circular-patterned SiO2 mask. An increased flow rate of NH3 during the epitaxial lateral overgrowth is thought to induce this type of non-edge-triggered polarity inversion. Further investigation reveals that non-edge-triggered polarity inversion is also possible when the a-facet is exposed at the lateral growth front of Ga-polar GaN domains.

Can we always control the thickness layer in the MBE method with atomic precision? Analysis of the problem on the MQWs GaN/AlN example

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Japanese Journal of Applied Physics
https://doi.org/10.7567/1347-4065/ab10c2

The GaN/AlN multiple-quantum-wells (MQWs) structures were studied using high resolution scanning transmission electron microscopy simulations (HR STEM) and the experimental data from HR STEM measurements. GaN/AlN MQWs were synthesized by plasma-assisted molecular beam epitaxy (PAMBE). The electron microscopy methods were used to examine both interfaces. It was shown that AlN /GaN interfaces are sharp while the GaN/AlN are diffuse over two atomic layers. The latter diffusional disorder is not related to the basic limitation of the PAMBE method, but to the chemical growth properties of GaN. The three cases were investigated: sharp interface, diffuse single monolayer (ML) and diffusive two MLs.

Extraction of stress and dislocation density using in-situ curvature measurements for AlGaN and GaN on silicon growth

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We have analyzed the in-situ measurements of bow and reflectance during growth of GaN on silicon layers for HEMT based devices, varying the quality of the layers by changing the AlN nucleation layer. By fitting the curves and applying the Stoney equation, we were able to extract stress profiles in the layers, and convert these into out of plane strain profiles. This allowed us to simulate X-Ray Diffraction profiles which matched well with measured data, confirming the validity of our data extraction. Finally, we see that we incorporate less stress with a higher dislocation density in the GaN layers, and so for a given set of growth conditions, we can infer the dislocation density by looking at the relaxation rate.

PRESS RELEASE

Technical and economic information selected by Knowmade

ELECTRONICS

Qorvo to acquire programmable analog/mixed-signal power IC firm Active-Semi

SemiconductorToday

Qorvo Inc of Greensboro, NC, USA (which provides core technologies and RF solutions for mobile, infrastructure and defense applications) has agreed to acquire Active-Semi International Inc of Dallas, TX, USA, a private fabless supplier of programmable analog/mixed-signal power management and intelligent motor drive ICs.

Qorvo says that Active-Semi's technologies are positioned to intersect multiple long-term secular growth opportunities in 5G, industrial, data-center, automotive and smart home applications by addressing the increased demand for efficient power solutions. The firm will become part of Qorvo's Infrastructure and Defense Products (IDP) group.

"With the acquisition of Active-Semi, Qorvo will expand IDP's product offerings for existing customers and extend our reach into new high-growth power management markets," says Qorvo's president & CEO Bob Bruggeworth. "We see significant opportunities to accelerate adoption of Active-Semi's innovative analog/mixed-signal solutions across multiple markets by leveraging Qorvo's global scale, sales channel and customer relationships."

Power efficiency is increasingly a core requirement in electronic applications in IDP's existing markets, including 5G base stations, active phased arrays for defense, automotive, and Internet of Things (IoT). Active-Semi's programmable mixed-signal power solutions provide simplicity, efficiency and design flexibility – resulting in smaller footprints, lower bill of material costs and reduced time to market, says Qorvo.

"The combination of Active-Semi's programmable analog power solutions with Qorvo's leading product and technology portfolio opens up vast opportunities to accelerate revenue, develop more highly integrated system solutions and target new high-growth markets, like 5G infrastructure," comments Active-Semi's CEO Larry Blackledge.

Qorvo expects the acquisition to be accretive to non-GAAP gross margin and non-GAAP EPS in the first year. The acquisition is subject to regulatory approval and customary closing conditions and is expected to close in Qorvo's fiscal first-quarter 2019 (ending 29 June).

First demonstration of RF N-polar GaN metal-insulator-semiconductor HEMT

SemiconductorToday

University of California Santa Barbara (UCSB) in the USA has reported the first radio frequency (RF) nitrogen-polar gallium nitride-on-gallium nitride (GaN-on-GaN) metal-insulator-semiconductor high-electron-mobility transistor (MISHEMT) [Shubhra S Pasayat et al, Semicond. Sci. Technol., vol34, p045009, 2019]. Using GaN substrates enabled the dislocation density to be reduced, minimizing carrier scattering at the low charge densities typical for transistors used in AB-mode amplification.

The researchers are keen to develop solutions for millimeter-wave RF applications in sensing and communication that variously employ frequency bands in atmospheric absorption and transmission windows. The N-polar orientation reverses the usual Ga-polar structure. In particular, the channel layer of mobile charges is induced by a back-barrier rather than a top barrier. N-polar devices tend to have higher power output, but reduced efficiency.

AB-mode amplification biases transistors towards pinch-off when channel carrier densities are low. AB operation reduces dissipation losses and higher efficiency is obtained when the bias is towards the B-mode rather than A-mode end of the trade-off, so-called 'deep' AB biasing. In N-polar devices, such biasing suffers from a degradation in electron mobility that apparently arises from scattering off the back-barrier. By contrast, in Ga-polar devices deep AB biasing pushes the electrons away from the top barrier interface.

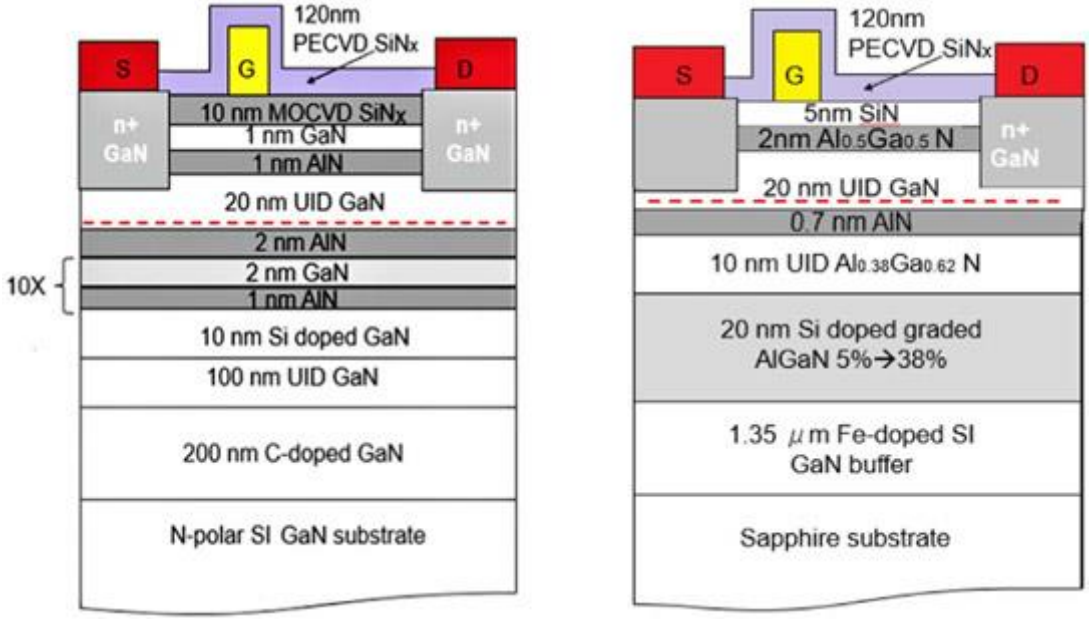


Figure 1: (a) N-polar HEMT device PAMBE structure and fabrication cross-section. (b) Conventional MOCVD grown N-polar GaN HEMT.

The epitaxial structure for the device (FIgure 1) was grown by plasma-assisted molecular beam epitaxy (PAMBE) on on-axis semi-insulating bulk GaN. The carbon (C) doping of the 200nm GaN buffer continued the semi-insulating character of the substrate. The back-barrier was prepared with 100nm of unintentionally doped (UID) material, followed by 10nm of n-GaN, which was used to control the position of the Fermi level in the overlying structure.

The barrier itself consisted of a 10-period super-lattice of 1nm/2nm AlN/GaN, and capped with 2nm of AlN. This structure induced a two-dimensional electron gas in the 20nm UID GaN channel layer. The 2nm AlN layer reduced barrier interface scattering.

The researchers explain why they used the super-lattice structure: "Due to a lag between the rate of aluminium cell temperature change in PAMBE and the optimum growth rate for N-polar AlGaN/GaN structure, an interruption-free linearly graded AlGaN growth was not possible."

The epitaxial material was completed with 1nm/1nm AlN/GaN. The super-lattice was designed to have an effective 33% Al content, while the cap had an effective 50% Al content. The channel mobility was 800cm2/V-s, about 60% higher than for a GaN-on-sapphire structure.

Further PAMBE was used to selectively deposit n+-GaN contacts through a silicon dioxide mask. Further transistor fabrication included metal-organic chemical vapor deposition (MOCVD) of silicon nitride gate dielectric, reactive-ion mesa etching, source/drain contact titanium/gold ohmic metal electrode deposition, and gate and contact pad deposition of titanium/gold. A 120nm plasma-enhanced chemical vapor deposition (PECVD) silicon nitride layer provided passivation.

The gate had two wings of 25µm width (2x25µm) and 0.75µm length. The gate was placed at 0.5µm distance from the source contact. The source-drain distance was 5µm. With the gate at 0V relative to the source (VGS), the on-resistance was ~2Ω-mm. The maximum drain current was 1.1A/mm at almost 5V VDS. The peak transconductance was ~200mS/mm with the gate at -4.2V and the drain at 4V.

The current was slightly higher under pulsed operation, suggesting a self-heating effect. In many GaN-based transistors there is significant current collapse/dispersion where the charge flow is lower under pulsed operation. There was no such dispersion/collapse observed with the UCSB device.

Frequency cut-offs (Figure 2) were determined with the device biased at -4.5V VGS and 8V VDS: 14.6GHz for maximum oscillation/power gain (fmax) and 8.9GHz for current gain (ft). The biasing produced a drain current of 0.598A/mm. The cut-off values were determined without pad de-embedding.

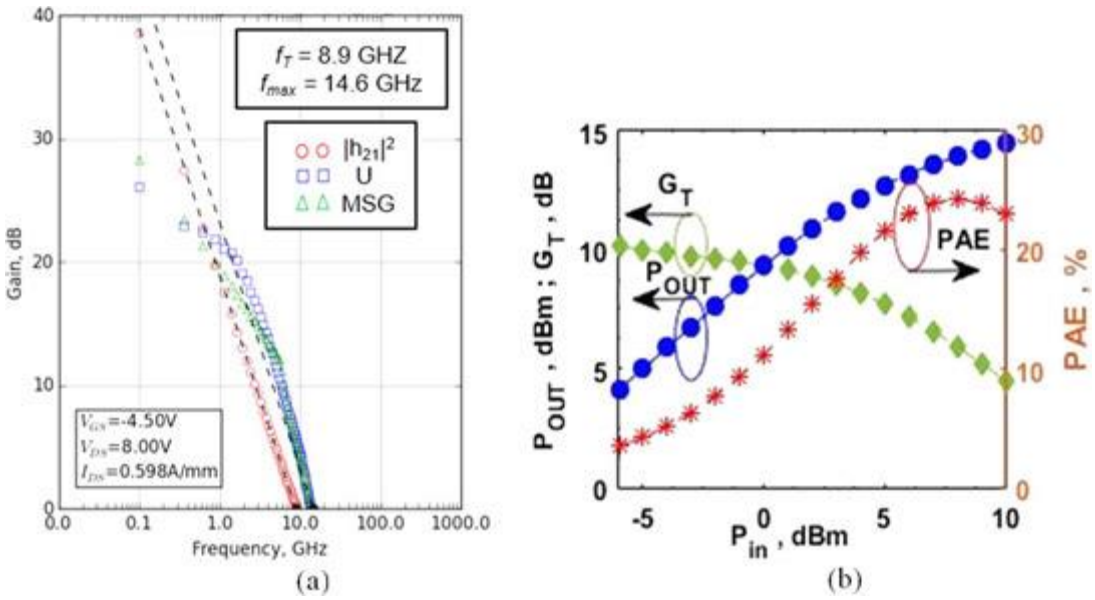


Figure 2: (a) Small-signal gain data for simultaneous peak ft and fmax and (b) 4GHz load-pull power sweep.

Load-pull measurements at 4GHz were performed to assess large-signal performance. Class AB biasing was used with the drain current at 270mA/mm, about a quarter of the maximum (-6V VGS, 5V VDQ,Q). This optimized power-added efficiency (PAE) at 4GHz in its trade-off with gain. The output power density reached 0.56W/mm. The maximum PAE was 24%.

The researchers hope to achieve deep AB biasing in future scaled and optimized devices. For example, the gate-to-drain breakdown voltage of ~15V needs to be increased to enable increased gain and PAE at low charge density.

EPC adds 80V eGaN FET to AEC Q101-qualified product family for high-resolution LiDAR

SemiconductorToday

Efficient Power Conversion Corp (EPC) of El Segundo, CA, USA – which makes enhancement-mode gallium nitride on silicon (eGaN) power field-effect transistors (FETs) for power management applications – has announced AEC Q101 qualification of the 80V EPC2214 eGaN FET, which is designed for light detection & ranging (LiDAR) systems in the automotive industry and other harsh environments.

eGaN technology has been in mass production for over nine years, accumulating billions of hours of field experience in automotive applications, such as LiDAR and radar for autonomous cars, 48V – 12V DC-DC converters used in data-center computers, ultra-high-fidelity infotainment systems, and high-intensity headlamps for trucks, notes EPC. The new device has completed rigorous automotive AEC Q101 qualification testing and will be followed with several more discrete transistors and integrated circuits designed for the harsh automotive environment.

As an 80V, 20mΩ, eGaN FET with a 47A pulsed current rating in a 1.8mm2 footprint, the EPC2214 is suited to use for firing the lasers in LiDAR systems because the FET can be triggered to create high current with extremely short pulse widths. The short pulse width leads to higher resolution, and the higher pulse current allows the LiDAR system to discern objects at greater distances. These two characteristics, along with their small size and low cost, make eGaN FETs suuitable for radar and ultrasonic sensors in addition to LiDAR in demanding automotive applications, says EPC.

To complete AEC Q101 testing, the eGaN FETs underwent rigorous environmental and bias-stress testingncluding humidity testing with bias (H3TRB), high-temperature reverse bias (HTRB), high-temperature gate bias (HTGB), temperature cycling (TC), as well as several other tests. EPC says that its wafer-level chip-scale (WLCS) packaging passed all the same testing standards created for conventional packaged parts, demonstrating that the superior performance of chip-scale packaging does not compromise ruggedness or reliability. The eGaN devices are produced in facilities certified to the Automotive Quality Management System Standard IATF 16949.

“This new automotive product is the most recent in what will be a constant stream of EPC transistors and integrated circuits designed to enable autonomous driving and improve fuel economy and safety,” says CEO & co-founder Alex Lidow. “Our eGaN technology is faster, smaller, more efficient, lower cost and more reliable than the aging silicon power MOSFET used in today’s vehicles,” he adds.

Priced at $0.72 each in 2500-unit/reel quantities, the EPC2214 eGaN FET is available for immediate delivery from distributor Digi-Key Corp.

Global 5G smartphone shipments to grow from just 5 million in 2019 to 1 billion in 2025

SemiconductorToday

Global 5G smartphone shipments will reach a modest 5 million units in 2019 as early models will be expensive and available in limited volumes, forecasts market research firm Strategy Analytics in its Insight report ‘5G Smartphones: From Zero to a Billion’.

“Less than 1% of all smartphones shipped worldwide will be 5G-enabled this year,” says Ken Hyers, director at Strategy Analytics. “Global 5G smartphone shipments are tiny for now, due to expensive device pricing, component bottlenecks, and restricted availability of active 5G networks,” he adds.

"Samsung will be the early 5G smartphone leader in the first half of 2019, due to initial launches across South Korea and the United States," notes senior analyst Ville Petteri-Ukonaho. "We predict LG, Huawei, Xiaomi, Motorola and others will follow later in the year, followed by Apple iPhone with its first 5G model in second-half 2020. The iPhone looks set to be at least a year behind Samsung in the 5G smartphone race and Apple must be careful not to fall too far behind," he adds.

"The short-term outlook for 5G smartphones is weak, but the long-term opportunity remains huge," comments Neil Mawston, executive director at Strategy Analytics. "We forecast 1 billion 5G smartphones to ship worldwide per year by 2025. The introduction of 5G networks, by carriers like Verizon or China Mobile, opens up high-speed, ultra-low-latency services such as 8K video, streaming games, and augmented reality (AR) for business. The next big question for the mobile industry is how much extra consumers are really willing to pay, if anything, for those emerging 5G smartphones and services."

MACOM and Goertek forming JV to supply GaN-on-Si products for China's 5G build out

SemiconductorToday

MACOM Technology Solutions Holdings Inc of Lowell, MA, USA (which makes semiconductors, components and subassemblies for analog RF, microwave, millimeter-wave and photonic applications) has agreed to establish a joint venture company with Goertek Inc, a multi-billion-dollar electronic components company based in Shandong, China. The joint venture will be based in Hong Kong and will supply, market and distribute gallium nitride on silicon (GaN-on-Si)-based RF power components into China's base-station market.

Goertek focuses mainly on R&D, manufacturing and sales of components (acoustics, sensor, optoelectronic etc) and finished products (for VR/AR/MR, wearable, hearable, home applications etc). Viewing semiconductors as a strategic focus, Goertek has developed capabilities covering chip design, packaging, testing, algorithm and system integration, and has developed large-scale production capacity for MEMS products.

Goertek will provide a total of up to $134.6m to MACOM, including $30m up front. MACOM will further be entitled to royalties and dividend preferences in the joint venture. Goertek and MACOM will each contribute $25m in working capital to the JV. MACOM retains rights to sell GaN-on-Si products outside China, Hong Kong and Macau.

"This joint venture is a capstone to MACOM's strategy to become a scale player within the multi-billion-dollar 5G base-station market in China, which in turn enables us to further invest in US-based innovation," says MACOM's president & CEO John Croteau. "We are pleased to be able to leverage our existing design capabilities and resources in China by aligning with a JV partner of the caliber of Goertek. They perfectly complement our GaN-on-Si based RF power component products with high-volume manufacturing expertise, well-connected sales and proven supply-chain management into China's top OEMs and service providers," he adds.

"Leveraging MACOM's superior GaN-on-Si technology, we will provide world-leading RF components to the 5G market in China, as well as enriching our RF capabilities," comments Goertek's CEO Long Jiang.

The transaction is subject to certain closing conditions (including receipt of approval from China's State Administration for Market Regulation) and is expected to close in second-half 2019.

ROHM acquiring Panasonic Semiconductor's diode and transistor business

SemiconductorToday

ROHM of Kyoto, Japan is acquiring part of the diode and transistor business of Kyoto-based Panasonic Semiconductor Solutions Co Ltd, a group company of Panasonic Corp of Osaka, Japan that was founded in 2014. The transfer is scheduled for October.

Established in 1958, ROHM's Semiconductor business has been developing, producing and selling semiconductor devices since the 1960s as a core business of the ROHM Group and claims to have the largest shares of the global markets for small-signal transistors and diodes. Looking ahead, given the strong prospects of continuous growth in the automotive electronics, industrial equipment and other markets, ROHM will be expanding its business in bipolar transistors, circuit-protective Zener diodes, TVS diodes and other products. As a part of that, ROHM is investing in a wide range of business resources in order to strengthen product lineups, further enhance product quality and ensure stable supplies. By acquiring the Panasonic business, ROHM aims to further expand its market share.

To ensure a smooth transition and stable supply to customers, ROHM will outsource production to Panasonic and maintain the same supply structure as before until the transfer is complete.

Going forward, both companies will be jointly preparing for the transfer of business, including obtaining all necessary approvals and permits.

GaN Systems exhibits highest-current-rated 650V GaN power transistors at PCIM

SemiconductorToday

In booth 9-507 at PCIM Europe 2019 (Power Conversion and Intelligent Motion) in Nuremberg, Germany (7-9 May), GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of gallium nitride-based power switching semiconductors for power conversion and control applications) is demonstrating its 650V, 150A GaN power transistor (claimed to be the highest-current 650V GaN power transistor). The GS-065-150 device has 100 times lower switching losses than comparable silicon-based insulated-gate bipolar transistors (IGBTs) it is reckoned, yielding a 99% reduction in switching losses. In addition, a wide range of new products, devices and systems from customers and partners (with many now in production) is also on display.

Recently introduced products at the booth include the GS-065 low-current (3.5-11A) transistor line with EZDrive circuit compatibility. The combination of a smaller, next-generation design and the EZDrive circuit (which eliminates the need for a discrete driver) significantly reduces bill of materials cost and improves performance, says the firm.

Reference tools being shown include the new 50W wireless power amplifier, a small-size, low-cost, and high-efficiency evaluation board suitable for wireless power transfer and charging applications; 1.5kW and 3kW bridgeless totem-pole power factor correction (PFC) reference designs using GaN Systems' 650V power transistors; and high-performance insulated metal substrate (IMS) half-bridge thermal mounting solutions, which provide design flexibility and scalability with three power level configurations up to 1.5kW, 3kW and 6kW.

Customer demonstrations span industrial, solar, consumer and transportation applications including innovative AC/DC and DC/DC power supplies, energy storage systems, laptop AC chargers as well as high-power wireless charging systems for drones, robots, scooters and 5G applications. The latest innovations in the automotive space include an electric vehicle (EV) onboard charger, traction inverter, and a 480W, 4-channel LiDAR laser-driver.

Mission Microwave supplying high-power X-, Ku- & Ka-band BUCs worth over $12m for SATCOM terminals

SemiconductorToday

Mission Microwave Technologies LLC of Santa Fe Springs, CA, USA, which manufactures gallium nitride (GaN)-based solid-state power amplifiers (SSPAs) and block up-converters (BUCs), has received orders from multiple government contractors to provide X-, Ku- and Ka-band block upconverters as components of complex SATCOM terminals in support of the warfighter. The combined value of the orders was over $12m in first-quarter 2019.

"Mission Microwave's value proposition of smaller, lighter and more efficient high-power amplifiers is enabling our customers to create highly portable, higher-throughput terminals with lower power consumption than previous options," says president & CEO Francis Auricchio. "Our customers rigorously evaluated our products and chose Mission Microwave to support their customers' demanding requirements for reliability, performance and delivery."

Mission's Stinger, Javelin and Titan products have been designed into families of terminals across X-, Ku- and Ka-band frequencies. Their common form factor and interfaces allow designers to create flexible platforms, eliminating the need to re-engineer the implementation when missions change.

The products delivered by Mission Microwave for these programs include high-performance commercial-off-the-shelf (COTS) amplifiers for X-, Ku- and Ka-band terminals. They rely on Mission's patented GaN amplifier and BUC designs to support customers operating in harsh environments while reducing the size, weight and power (SWaP) burden on the remote users. Mission Microwave has supplied the satellite terminal industry by shipping high power X, Ku and Ka-band amplifiers and BUCs for mobile applications in ground, maritime and other applications in both government and commercial industry sectors that require reliability, performance and efficiency.

Diamond thermal management boosts gallium nitride transistor power

SemiconductorToday

A team of researchers mainly based at the US Naval Research Laboratory (NRL) claim record DC power density from aluminium gallium nitride (AlGaN) barrier high-electron-mobility transistors (HEMTs) [Marko J. Tadjer et al, IEEE Electron Device Letters, published online 11 April 2019]. Other researchers in the team were variously from Southern Methodist University, TMX Scientific, University of California Los Angeles (UCLA) and Akash Systems Inc in the USA.

The high power was achieved by replacing the silicon substrate on which the III-nitride device layers were grown with diamond to allow enhanced thermal management.

The team targets the high frequency and high power density needed for commercial and military electronics. Diamond has previously been used to manage the high temperatures generated in such applications, due to its very high thermal conductivity. One technique for this is wafer bonding, but an attractive alternative is to grow diamond directly on the backside of the device layers.

Building on previous work, the NRL-led team inverted the GaN/Si substrate and removed the silicon substrate. Etching of the exposed N-polar III-N nucleation layers left some 700nm of GaN buffer. A 30nm silicon nitride (SiN) barrier was applied before chemical vapor deposition (CVD) of a thick polycrystalline diamond layer at Element Six Technologies (E6, part of the De Beers Group).

E6 specializes in synthetic diamond and tungsten carbide growth processes. In addition to thermal management, applications for these 'supermaterials' cover sectors such as oil and gas extraction, automotive and aerospace parts, mining and construction, consumer electronics, optics, and wear reduction in mechanical systems. The company claims employment of 1900 people with production facilities in UK, Ireland, Germany, South Africa and the USA. E6 traces its history back to 1946.

The NRL device structure was completed with a 20nm Al0.2Ga0.8N barrier layer, mesa plasma etch, titanium/aluminium/nickel/gold ohmic source-drain contact deposition and annealing, nickel/gold Schottky gate deposition, titanium/gold contact pad overlay, and plasma-enhanced chemical vapor deposition (PECVD) silicon nitride passivation. The device fabrication was carried out both before and after the silicon substrate replacement with diamond. The silicon nitride passivation was optimized for avoiding current collapse under pulsed operation.

The researchers report: "Room-temperature Hall measurements and DC current-voltage characteristics indicated that the substrate-side process did not significantly influence the mobility and sheet carrier density, and thus the on-resistance of the HEMTs. Additionally, only minimal effects on threshold voltage and transconductance were observed."

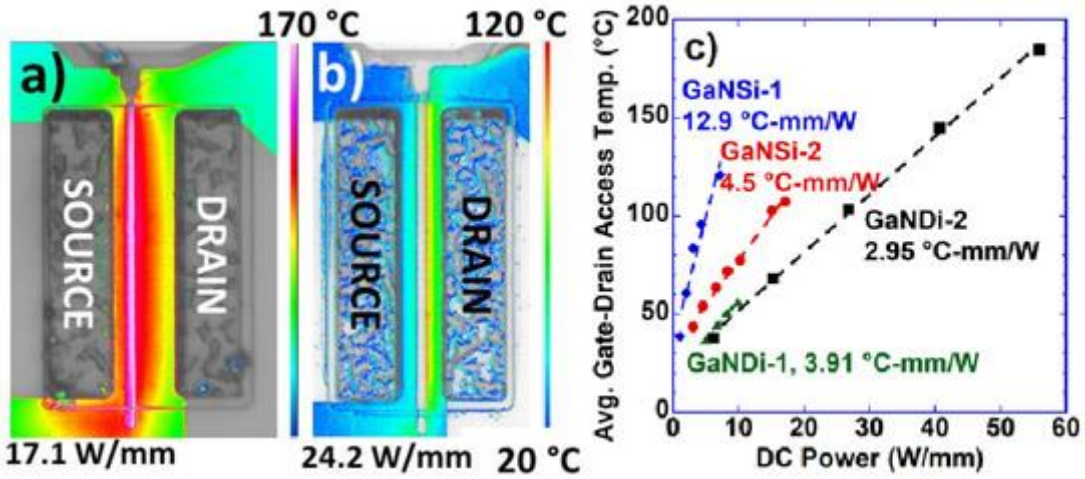


Figure 1: Steady-state thermoreflectance maps of AlGaN/GaN HEMTs before and after backside diamond deposition process measured at 365nm illumination as function of DC output power: (a) silicon-based sample GaNSi-2; (b) diamond-based ample GaNDi-2; and (c) average temperature in gate-drain access region as function of DC power (IDS xVDS) for range of AlGaN/GaN HEMTs.

Thermoreflectance imaging (TRI) showed temperature increases near contacts beyond 150°C under 15W/mm power density direct current (DC) operation of HEMTs on silicon (Figure 1). By contrast, the device on diamond demonstrated no significant temperature increase with 24.2W/mm power density. Above 24.2W/mm, the temperature did increase, largely due to gate leakage current. Even so, the temperature did not exceed 176°C in the access/contact region with the power density at 56W/mm. The maximum temperature of 205°C was seen in the gate region at the drain edge.

The diamond-based GaN HEMT (GaNDi-2) achieved a thermal resistance as low as 2.95°C-mm/W. A device from an earlier version of the diamond replacement (GanDi-1) process had a higher thermal resistance of 3.91°C-mm/W. The higher value was attributed to defects at the interface with the diamond substrate. Transmission electron micrography (TEM) showed nanometer-sized voids in the GaNDi-1 sample's 30nm silicon nitride layer and at the GaN interface (Figure 2). The GaNDi-2 sample, by contrast, achieved "a sharp GaN-diamond interface

and lower thermal resistance". The thermal resistance was significantly higher for GaN HEMTs on the original silicon substrates (GaNSi-1&2).

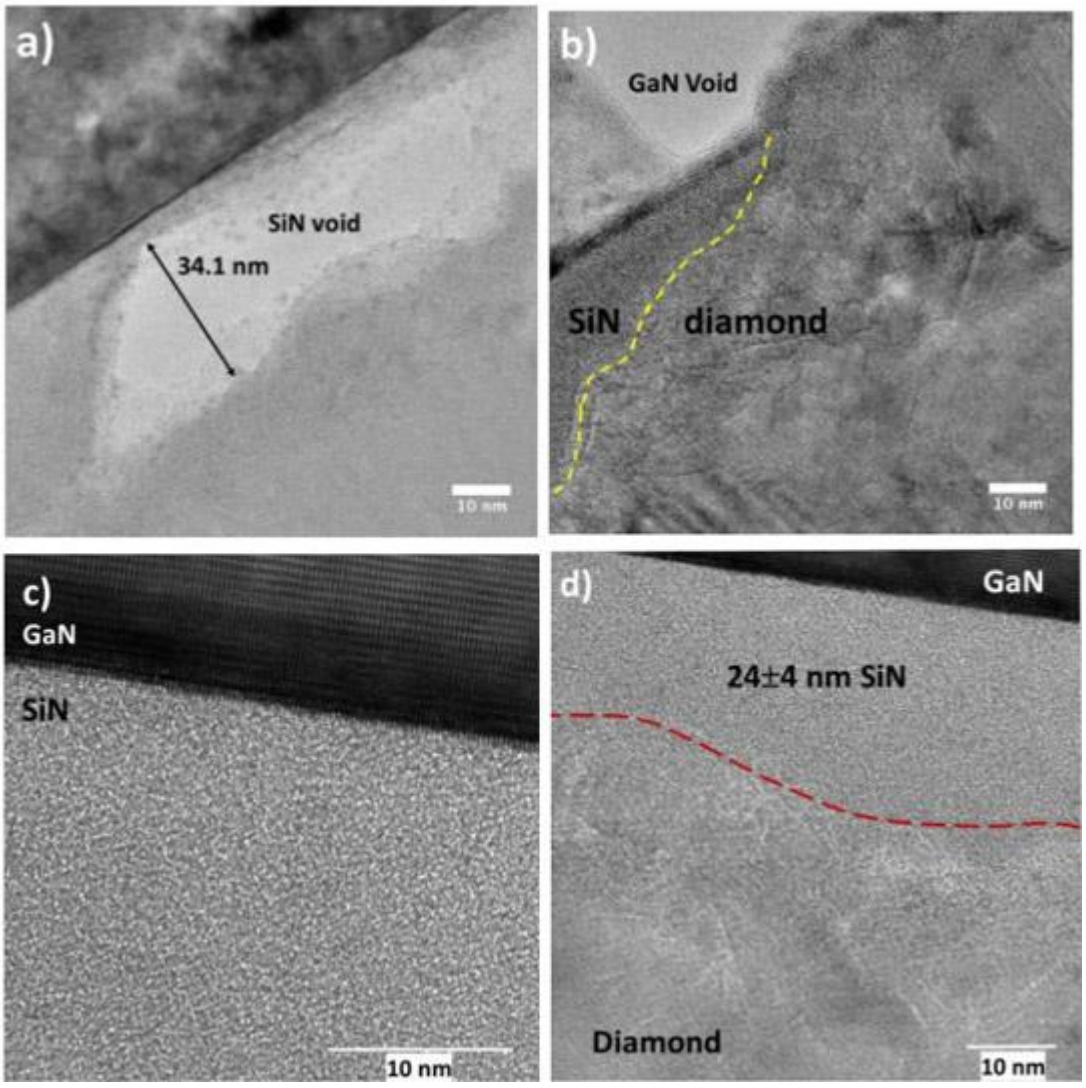


Figure 2: High-resolution TEM image of GaN/SiN/diamond interface of (a) sample GaNDi-1 showing void in SiN, (b) sample GaNDi-1 showing void in N-polar side of GaN caused by H-plasma etching during diamond CVD, (c) sharp, void-free interface between amorphous SiN and crystalline GaN for sample GaNDi-2, and (d) SiN/polycrystalline diamond substrate interface for sample GaNDi-2 (delineated by dashed red line).

The researchers suggest that thinning or eliminating the silicon nitride barrier layer could decrease the thermal resistance by up to 48%. However, such a process would need also eliminate voids from the interface.

WiBotic and GaN Systems partner on high-power wireless charging for drones and autonomous robots

SemiconductorToday

Partnering with GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of gallium nitride-based power switching semiconductors for power conversion and control applications), WiBotic of Seattle, WA, USA is providing off-the-shelf high-power wireless charging solutions for the rapidly growing robotics ecosystem to deliver the power levels and increased antenna range that both drones and robots demand.

The partnership aims to advance the capabilities of mobile industrial robots, freeing them from limitations imposed by existing restricted charging methods that allow for continuous operation. For mobile robots to work

efficiently, flexibly and without interruption, they need to achieve autonomy with wireless charging stations rather than requiring an operator to make a physical connection, note the firms.

GaN power semiconductors enable the autonomous wireless charging that these conditions require by operating at a high switching frequency, delivering high-power capability with the spatial freedom (large air gaps) needed in the design of charging systems that require no human intervention.

WiBotic's off-the-shelf, fully automatic, intelligent wireless power system includes components that incorporate GaN Systems' technology to enable very high efficiency levels. The systems allow:

- rapid charging at hundreds of watts and greater;
- autonomous charging at multiple locations and multiple times per day without having to spend time docking;
- greater robot uptime (so fewer robots are needed to complete the same amount of work); and
- no cords and moving parts (so there is no limit on the number of charge cycles a system can deliver).

"GaN provides high reliability and, when coupled with wireless power systems from WiBotic, the technologies provide an extremely robust and reliable system that never wears out," says WiBotic's CEO & co-founder Ben Waters. "We chose GaN Systems as a strategic partner because of its unique and best-in-class GaN technology. The result of this partnership is new wireless power solutions that offer higher power delivery across a wide range of applications," he adds.

"GaN power semiconductors, operating at high frequency, are enabling several wireless charging advantages from higher power capability to significant level of spatial freedom that are needed in multiple industries," comments CEO Jim Witham.

Fraunhofer IAF enhances functionality of GaN power ICs with integrated sensors as part of GaNIAL project

SemiconductorToday

Fraunhofer Institute for Applied Solid State Physics (IAF) of Freiburg, Germany says that it has significantly enhanced the functionality of gallium nitride (GaN) power ICs for voltage converters by integrating current and temperature sensors onto a GaN-based chip, along with power transistors, freewheeling diodes and gate drivers. The development could pave the way for more compact and efficient on-board chargers in electric vehicles.

For vehicles with electric drive to become a lasting presence in society, there needs to be greater flexibility in charging options, says Fraunhofer IAF. To make use of charging stations using alternating current, wall charging stations or conventional plug sockets where possible, users are dependent on on-board chargers. As this charging technology is carried in the vehicle, it must be as small and lightweight as possible, and also cost-efficient. It therefore requires extremely compact yet efficient power electronics systems such as voltage converters.

Several components on a single chip

Fraunhofer IAF has been conducting research on monolithic integration in power electronics for several years. This requires several components such as power components, the control circuit and sensors to be combined on a single chip. The concept makes use of gallium nitride. In 2014, Fraunhofer IAF integrated intrinsic freewheeling

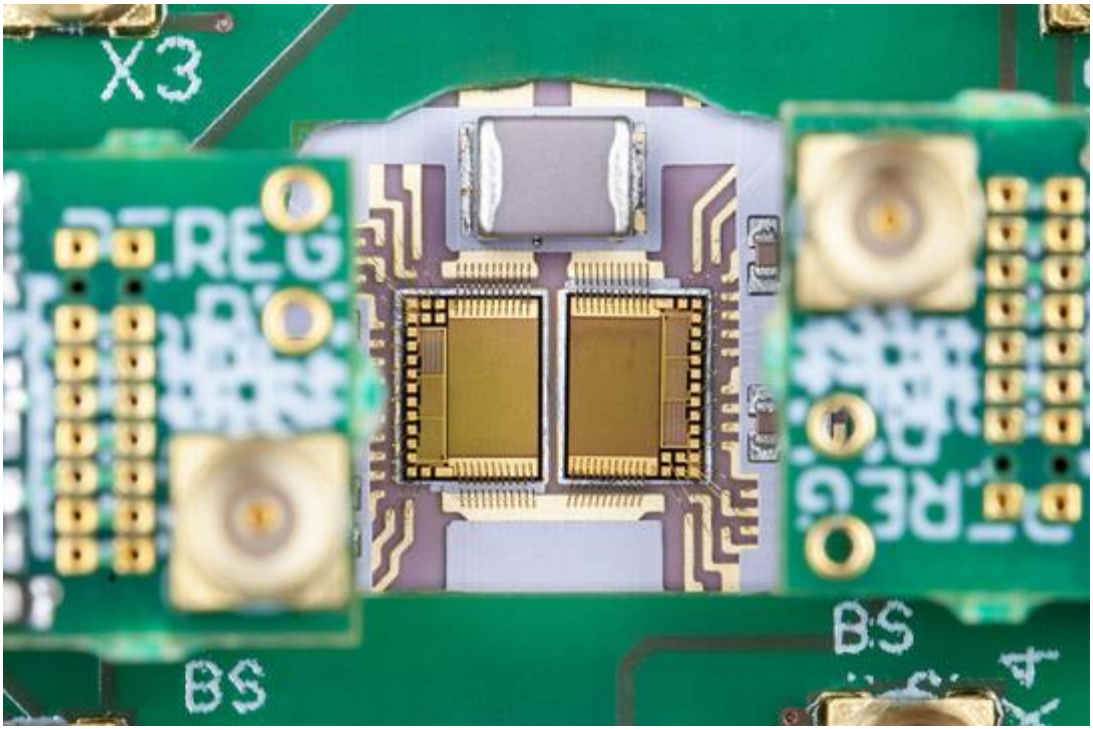
diodes and gate drivers on a 600V-class power transistor. In 2017, a monolithic GaN half-bridge was then operated at 400V for the first time.

The latest research results combine current and temperature sensors and 600V-class power transistors with intrinsic freewheeling diodes and gate drivers in a GaN power IC for the first time. As part of the project GaNIAL ('Integrated and efficient power electronics based on gallium nitride'), the researchers have provided functional verification of full functionality in a GaN power IC, achieving what is reckoned to be a breakthrough in the integration density of power electronics systems. "By additionally integrating sensors on the GaN chip, we have succeeded in significantly enhancing the functionality of our GaN technology for power electronics," says GaNIAL's project manager Dr Patrick Waltereit, deputy head of the Power Electronics business unit at Fraunhofer IAF.

The GaNIAL project is funded by Germany's Federal Ministry of Education and Research (BMBF). Since 2016, this collaboration between Fraunhofer IAF and the BMW Group, Robert Bosch GmbH, Finepower GmbH and the University of Stuttgart has been working to develop powerful, compact GaN-based components for electromobility.

Integrated sensors for direct control

Compared with conventional voltage converters, the new circuit simultaneously not only enables higher switching frequencies and a higher power density but also provides for fast and accurate condition monitoring within the chip itself. "Although the increased switching frequency of GaN-based power electronics allows for increasingly compact designs, this results in a greater requirement for their monitoring and control," says Stefan Mönch, a researcher in the Power Electronics business unit. "This means that having sensors integrated within the same chip is a considerable advantage."



Picture: GaN power ICs with integrated transistors, gate drivers, diodes and current and temperature sensors for condition monitoring.

Previously, current and temperature sensors were implemented externally to the GaN chip. The integrated current sensor now enables feedback-free measurement of the transistor current for closed-loop control and short-circuit protection, and saves space compared to the customary external current sensors. The integrated temperature sensor enables direct measurement of the temperature of the power transistor, mapping this thermally critical point considerably faster and more accurately than previous external sensors, as the distance and resulting temperature difference between the sensor and the point of measurement is eliminated by the monolithic integration.

"The monolithic integration of the GaN power electronics with sensors and control circuit saves space on the chip surface, reduces the outlay on assembly and improves reliability," says Mönch, who designed the integrated circuit for the GaN chip. "For applications that require lots of very small, efficient systems to be installed in limited space, such as in electromobility, this is crucial," he adds. Measuring just 4mm x 3mm, the GaN chip is the basis for the further development of more compact on-board chargers.

Exploiting GaN's unique characteristic

For the monolithic integration, the research team utilized the gallium nitride deposited on a silicon substrate. The unique characteristic of GaN-on-Si power electronics is the lateral nature of the material: the current flows parallel to the surface of the chip, so all connections are located on the top of the chip and connected via conductor paths. This lateral structure of the GaN components allows for the monolithic integration of several components, such as transistors, drivers, diodes and sensors, on a single chip. "Gallium nitride has a further crucial market advantage compared to other wide-bandgap semiconductors, such as silicon carbide: GaN can be deposited on cost-efficient, large-area silicon substrates, making it suitable for industrial applications," says Mönch.

Exagan opens Power Solutions Center to extend applications support and market reach

SemiconductorToday

Continuing its progress in accelerating the adoption of gallium-nitride (GaN)-on-silicon semiconductors in power markets, gallium nitride technology start-up Exagan of Grenoble and Toulouse, France (founded in 2014 with support from CEA-Leti and Soitec) has opened a new Power Solutions Center in Toulouse to extend its applications support and market reach in wide-ranging, customer-specific end products. The opening of the facility, which is operating in close collaboration with technology partner CEA Tech, follows the launch of Exagan's first GaN applications center in Taipei, Taiwan last October.

The Toulouse facility provides customers with new application-development and product-validation capabilities using highly specialized electronic equipment. It also enables Exagan to master new architectures for GaN solutions while also boosting power-conversion efficiencies in current topologies.

Exagan says that its technology and products are designed to offer value in device performance, robustness and ease of integration with existing platforms. G-FET power transistors can be fabricated in existing 200mm CMOS wafer fabs, enabling a multi-source supply, easy scalability and optimal cost/performance benefits.

With its fab-lite business model, Exagan offers control of GaN technology integration from starting materials to full implementation in end products, enabling product optimization and volume manufacturing. The firm's product portfolio covers a wide range of power levels and applications, from small fast-charging systems, data centers and onboard automotive chargers up to fast-charging stations for electric vehicles.

"Building on a robust GaN technology and product portfolio, Exagan is now deploying GaN Power Solutions Centers in Europe and Asia to work closely with customers," says president & CEO Frédéric Dupont. "Our goal is to deliver the best functionality and value by optimizing GaN devices' industry-leading balance of power density, power efficiency, reliability and system costs," he adds.

The market for GaN in power electronics is projected to increase at a compound annual growth rate (CAGR) of 93% by 2023, according to market research firm Yole Développement.

Exagan is exhibiting its GaN-based product portfolio – including G-FET power transistors, G-DRIVE intelligent system-in-a-package (SiP) solutions and evaluation modules – in booth #637 (Hall 9) at PCIM Europe 2019 in Germany. Specifically, the firm is showcasing the performance of its G-FET power transistors in applications such as 65W USB PD 3.0 power chargers and power factor correction (PFC) ranging from 300W up to 1.5kW for next-generation data centers.

Imec demos fully monolithical co-integration of GaN half-bridge with drivers

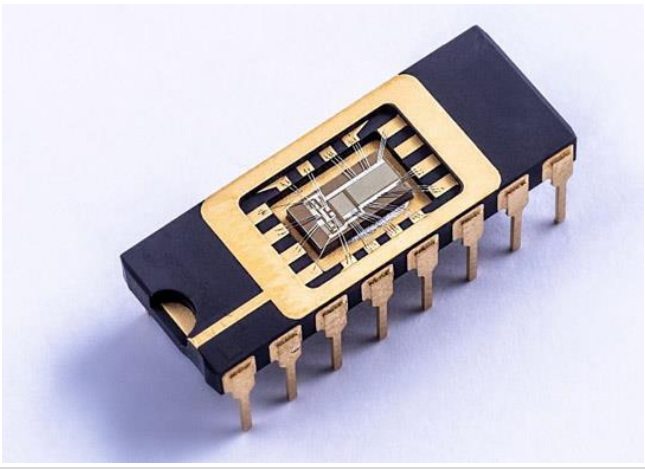
SemiconductorToday

At PCIM (Power Conversion Intelligent Motion) Europe 2019 in Nuremberg, Germany (7-9 May), nanoelectronics research centre imec of Leuven, Belgium is demonstrating a functional GaN half-bridge monolithically integrated with drivers. Mounted on a buck-convertor test board, the chip converts an input voltage of 48V to an output voltage of 1V, with a pulse width modulation signal of 1MHz. The achievement leverages imec's gallium nitride on silicon (GaN-on-Si) and GaN-on-QST technology platforms, reducing parasitic inductance and boosting commutation speed.

GaN power electronics is currently dominated by off-the-shelf discrete components. Half-bridges – common subcircuits in power systems – are fabricated from separate discrete components, either in separate packages or integrated in one package, especially for the higher-voltage ranges. A challenge, especially at high voltages, is that on-chip half-bridges designed on GaN-on-Si technology are limited in performance by a back-gating effect that negatively affects the high-side switch of the half-bridge, as well as by switching noise that disturbs the control circuits.

To unlock the full potential of GaN power technology, imec monolithically co-integrated a half-bridge and drivers in one GaN-IC chip. Complemented by low-voltage logic transistors, a suite of passive components for low-ohmic and high-ohmic resistors, and a MIM-capacitor, high-end integrated power systems can be realized on a single die.

Imec's solution builds on imec's GaN-on-SOI and GaN-on-QST technology platforms that allow for galvanic isolation of the power devices, drivers and control logic, by the buried oxide and oxide-filled deep trench isolation. This isolation scheme not only eliminates the detrimental back-gating effect that negatively affects the high-side switch of the half-bridge, but also reduces the switching noise that disturbs the control circuits. With the design of a co-integrated level shifter for driving the high-side switch, a dead-time controller to avoid overlapping gate input waveforms, and an on-chip pulse-width modulation circuit, highly integrated buck and boost convertors can be fabricated.



"Someone might think that by using SOI or QST wafers instead of silicon wafers will result in more expensive technology. However, with GaN-on-Si several discrete devices need to be individually packaged (with advanced packages to take advance of the GaN fast switching performance) and connected to their drivers and other elements at the board or packaged level," says business development manager Denis Marcon. "Instead, with imec's GaN-IC technology, the full converter including drivers and analog blocks etc is on-chip, which can then be packaged with simple package technology (as the frequency sensitive components are already connected on-chip). This dramatically saves on the cost of the final power system."

To further boost the performance of these monolithic integrated power systems, imec aims to extend its platform with additional co-integrated components, such as Schottky diodes and depletion-mode HEMTs.

"With the aim to further foster innovation in the GaN power electronics, this GaN-IC platform is available for prototyping through our multi-project-wafer (MPW) service," notes Stefaan Decoutere, program director GaN power electronics at imec. "The possibilities for high-end power systems with unprecedented performance, either in switching speed, operating frequency or energy efficiency, with reduced inductive parasitics and unseen reduction of the form-factors, will further boost the use of GaN for power supplies in the consumer and re-useable energy market segments," he believes.

Navitas' GaNFast power ICs enable 2x shrink and 75% more emergency lighting

SemiconductorToday

Navitas Semiconductor Inc of El Segundo, CA, USA says that its GaNFast power integrated circuits are enabling HotSpot Plus FHSAC1-UNV-70S, a high-reliability 70W normal + 7W emergency back-up lighting power system made by Fulham Co Inc of Hawthorne, CA, USA (which makes commercial lighting components and electronics for commercial general lighting, parking structure, signage, horticultural, UV and other applications). Gallium nitride (GaN) power IC technology powers both the main LED luminaire and charges the on-board LiFePO4 battery to provide everyday lighting and up to 90 minutes of emergency runtime.

Founded in 2014, Navitas introduced what it claimed to be the first commercial GaN power ICs. The firm says that its proprietary 'AllGaN' process design kit (PDK) monolithically integrates GaN power field-effect transistors (FETs) with GaN logic and analog circuits, enabling faster charging, higher power density and greater energy savings for mobile, consumer, enterprise, eMobility and new energy markets.

New, high-speed GaN power ICs are said to have up to 20x the performance of silicon chips. By operating at high frequency and simultaneously increasing efficiency, GaNFast power ICs reduce the size, weight and cost of components such as transformers, heatsinks and printed-circuit boards. GaNFast's 3–4x increase in power density enables a 2-to-1 reduction in LED hardware and leaves room to expand battery size to 14.4Whr and increase emergency lighting by 75% for increased safety compared with similar-sized 4W emergency-only systems, it is reckoned.

The Hotspot Plus 70S was developed for original equipment manufacturers (OEMs) looking for a highly reliable, universal LED driver that would meet state and city safety requirements in a single, compact, all-in-one emergency/LED driver. Suitable for luminaires where LED driver space is limited, the HotSpot Plus 70S has the smallest form-factor available (424mm x 30mm x 25mm), it is claimed, and features universal 120–277VAC input with a maximum of 70W (programmable constant current output of 350–2400mA/11–55VDC) normal and up to 7W emergency output, so customers can stock a single LED driver for a broad range of fixtures.

"With the HotSpot Plus 70S, our goal was to provide an LED driver + Emergency LED driver with integrated batteries in the same size as a single-function non-emergency LED driver, and the Navitas GaNFast power ICs

enabled us to reach this goal," says Alvaro Garcia, senior director, product management, at Fulham. "This significant achievement is an industry first, which will enable our customers to design smaller more cost-effective LED lighting systems," he reckons.

"Fulham joins a rapidly growing list of mobile and consumer brands in high-volume production with GaN power ICs that are setting a new standard in energy savings and power density," says Navitas' CEO Gene Sheridan.

Cree investing $1bn to expand SiC materials production and power & RF fab capacity by up to 30-fold

SemiconductorToday

As part of its long-term growth strategy, Cree Inc of Durham, NC, USA is to invest up to $1bn over five years in expanding its silicon carbide capacity with the development of an automated 200mm silicon carbide fabrication facility ($450m) and a materials mega factory ($450m) at its US campus headquarters in Durham (toghether with $100m in other investments associated with growing the business), marking the firm's largest investment to date in fueling its Wolfspeed silicon carbide (SiC) and gallium nitride on silicon carbide (GaN-on-SiC) business.

Upon completion in 2024, the facilities will substantially increase the firm's silicon carbide materials capability and wafer fabrication capacity, targeting wide-bandgap semiconductor solutions that are enabling the technology shifts underway within the automotive, communications infrastructure and industrial markets.

"We continue to see great interest from the automotive and communications infrastructure sectors to leverage the benefits of silicon carbide to drive innovation. However, the demand for silicon carbide has long surpassed the available supply," says CEO Gregg Lowe. "We are announcing our largest-ever investment in production to dramatically increase this supply and help customers deliver transformative products and services to the marketplace," he adds. "This investment in equipment, infrastructure and our workforce is capable of increasing our silicon carbide wafer fabrication capacity up to 30-fold and our materials production by up to 30-fold compared to Q1 of fiscal year 2017, which is when we began the first phase of capacity expansion. We believe this will allow us to meet the expected growth in Wolfspeed silicon carbide material and device demand over the next five years and beyond."

The plan will deliver additional capacity for its Wolfspeed silicon carbide business through the build out of an existing structure as a 253,000ft2, 200mm power & RF wafer fabrication facility as an initial step to serve the projected market demand. The new North Fab is designed to be fully automotive qualified and will provide nearly 18 times more surface area for manufacturing than exists currently, opening initially with the production of 150mm wafers. The firm will convert its existing Durham fabrication and materials facility into a materials mega factory.

"These silicon carbide manufacturing mega-hubs will accelerate the innovation of today's fastest-growing markets by producing solutions that help extend the range and reduce the charge times for electric vehicles, as well as support the rollout of 5G networks around the world," says Lowe. "This represents the largest capital investment in the history of silicon carbide and GaN technologies and production with a fiscally responsible approach," he believes. "By using existing facilities and installing a majority of refurbished tools, we believe we will be able to deliver a state-of-the-art 200mm-capable fab at approximately one-third of the cost of a new fab."

The expanded campus will also create high-tech job opportunities and serve as an advanced manufacturing workforce development initiative. Cree plans to partner with state and local community and four-year colleges to develop training programs to prepare its workforce for the long-term employment and growth opportunities that the new facilities will present.

Positive threshold in GaN transistors with p-type aluminium titanium oxide

SemiconductorToday

The Indian Institute of Science claims the first enhancement-mode (e-mode) operation of aluminium gallium nitride/gallium nitride (AlGaN/GaN) high-electron-mobility transistors (HEMTs) using p-type aluminium titanium oxide (AlTiO) gate insulation [Sayak Dutta Gupta et al, IEEE Transactions on Electron Devices, published online 16 April 2019].

The metal-oxide-semiconductor (MOS) gate stack combined the high-k dielectric properties of TiO2 (k greater than 60) with the p-type properties supplied by Al2O3 doping (k ~9). The Al2O3 substitutes the 2Als on Ti sites and the 3Os have a deficit of one vacancy that is doubly positively charged. The charged O vacancy can release two holes, which can subsequently be reabsorbed by uncharged O vacancies. The compensating negative charges on the 2 Al sites are fixed.

The researchers comment: "The ON-state performance of e-mode HEMTs in this paper with p-type AlTiO was found to be on par with the best reports till date."

GaN HEMTs are being developed as power switches, where enhancement-mode as opposed to depletion-mode is desired for low power loss and fail-safe performance. Enhancement-mode devices are in the low-current OFF-state when the gate potential is at 0V. By contrast, depletion-mode operation has the current on with 0V gates and requires a (negative) potential to pinch off the electron flow.

Unfortunately, simple GaN HEMTs are depletion-mode and special extra processing is required to push threshold voltages in a positive direction to give enhancement-mode, normally off performance. The placing of p-type materials, such as magnesium-doped p-GaN, under the gate is one such method for moving to enhancement-mode devices. Recessing the gate into the barrier also pushes the threshold positive, but removing all the barrier material increases on-resistance due to etch damage of the GaN channel surface.

High-k dielectrics give increased electrostatic control of current under the gate with sharper turn-on (low subthreshold swing), while reducing gate leakage, compared with Schottky gate HEMTs.

Metal-organic chemical vapor deposition (MOCVD) on 6-inch (111) silicon substrates produced epitaxial structures with 150nm AlN nucleation, 1µm AlGaN transition, 3µm GaN buffer/channel, 22nm Al0.22Ga0.78N barrier, and 40nm in situ silicon nitride cap.

Fabricated transistors (Figure 1) consisted of annealed titanium/aluminium/nickel/gold source-drain contacts, plasma-etched mesa isolation, atomic layer etching (ALE) of the AlGaN barrier for gate recessing, surface treatment and deposition of gate oxide, and nickel/gold gate metal formation and low-temperature annealing.

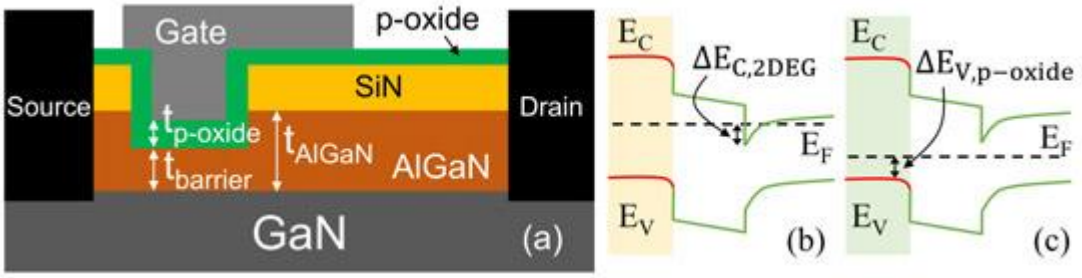


Figure 1: (a) Cross-sectional view of HEMT with p-type metal oxide gate and partially recessed AlGaN barrier. Energy-band sketch of AlGaN/GaN HEMTs with (b) conventional dielectric and (c) p-type oxide: p-type oxide shifts Fermi level (EF) beneath conduction band (EC) in two-dimensional electron gas (2DEG) channel.

The gate oxide was applied using BENEQ atomic layer deposition (ALD) equipment. Water (H2O) was used as precursor for oxygen in both the TiO2 and Al2O3 components. The titanium was sourced from titanium tetraisopropoxide (TTIP), and aluminium from trimethylaluminium (TMA). The oxide was built up from cycles of Al2O3 and TiO2 layers.

Hall measurements on Al0.52T0.48O showed p-type conductivity with a majority hole concentration at 1.4x1014/cm3. The Al0.52T0.48O material was compared as a p-type gate oxide against MOS-HEMT structures incorporating pure TiO2, sputtered copper oxide or electron-beam evaporated nickel oxide.

Pure TiO2 gate insulation resulted in depletion-mode operation with a threshold voltage at -4V. With 52% Al in the TiO2, the threshold shifted in a positive direction to -0.2V. Post-deposition annealing also pushed the threshold positively as the temperature increased, but the effect became less pronounced for higher Al contents of the AlTiO. The more positive effect at lower contents is due to greater activation of the Al, it is thought. At 52% Al, the number of Ti sites where Al can be activated is limited.

Copper oxide gave a smaller threshold shift than AlTiO. In addition, the gate leakage was increased by up to four orders of magnitude. With nickel oxide, the gate leakage was even worse.

Thinning the barrier by recessing the gate enabled positive threshold voltages to be attained. With the barrier thickness at 8nm, the threshold was +0.5V. The resulting transistor operated in enhancement-mode with the device in the OFF-state at 0V gate potential. The thinner barrier also improved channel control with lower OFF-state current (100x lower) and improved/lower subthreshold swing at 73mV/decade (Figure 2).

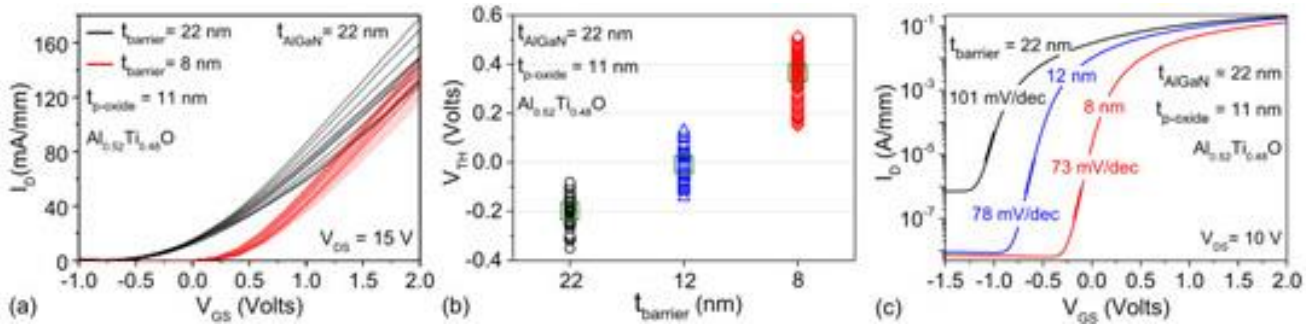


Figure 2: (a) Transfer characteristics of HEMTs with optimized p-oxide and different barrier thicknesses. (b) Shift in threshold (VTH) from negative to positive when barrier thickness under the gate was scaled. (c) Logarithmic plot of transfer characteristics and derived subthreshold swing (SS) values.

The threshold voltage hysteresis for drain current-gate voltage dual sweeps was ~30mV and ~40mV with the drain bias at 0.1V and 15V, respectively.

A device with 3µm gate length and 17.5µm source-drain spacing achieved a drain current ~400mA/mm at +4V gate potential. The on-resistance was 8.9Ω-mm, while the on/off current ratio was 107. Gate leakage was less than 200nA/mm.

The OFF-state three-terminal breakdown voltage was more than 600V with the substrate grounded. Catastrophic failure was seen in the mesa isolation, not as usual in the gate-drain region. The researchers expect an increased breakdown voltage from improved mesa isolation processes.

The researchers believe that the threshold can be pushed beyond +1V with optimization of the p-oxide gate insulation.

OPTOELECTRONICS

AquiSense and OASIS partner on UV-C LED-based clean drinking water systems

SemiconductorToday

Nikkiso Group company AquiSense Technologies LLC of Erlanger, KY, USA (which designs and manufactures water, air and surface disinfection systems based on UV-C LEDs) has announced an exclusive new product platform for OASIS International, which designs, manufactures and distributes clean drinking water systems (water coolers and point-of-use filtration equipment) to over 80 countries via several brand names. The partnership provides OASIS with AquiSense's patented ultraviolet light-emitting diode (UV-C LED) water treatment technology for cleaner, safer water directly at the point of dispense.

AquiSense and OASIS have been engaged in close cooperation for over a year in a detailed joint development effort to deliver the QUASAR, a unique, highly integrated UV LED solution. The QUASAR platform offers a high-level microbial disinfection barrier directly at the point of discharge for multiple OASIS products, including water coolers, fountains, bottle fillers, and point-of-use dispensers. The solution has been third-party validated to show over 99.99% (4-log) pathogen reduction, in addition to long-term customer field trials.

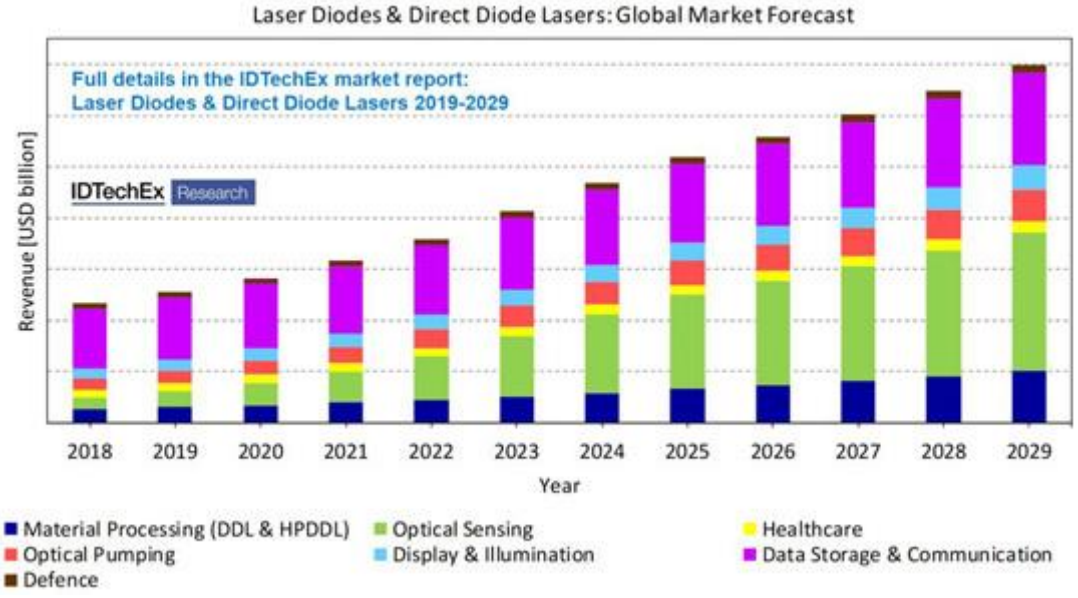
"This partnership signifies a step change from regional product integration, to widely available, global product availability for UV-C LED technology," says AquiSense's CEO Oliver Lawal. "We are happy to provide the latest chemical-free water treatment technology to OASIS customers," he adds.

"The QUASAR integrates into our electronic bottle filler products, which provides clean drinking water," says Lou Busick, OASIS International's VP innovation & new product development.

Laser diode and direct-diode laser market to grow to $13.985bn by 2029

SemiconductorToday

The market for laser diodes and direct-diode lasers will grow to $13.985bn by 2029, comprising $11.952bn for laser diodes and $2.033bn for direct-diode lasers, according to the report 'Laser Diodes & Direct Diode Lasers 2019-2029' by market research and technology consulting firm IDTechEx of Cambridge, UK.



Picture: Laser diodes and direct-diode lasers market forecast by IDTechEx.

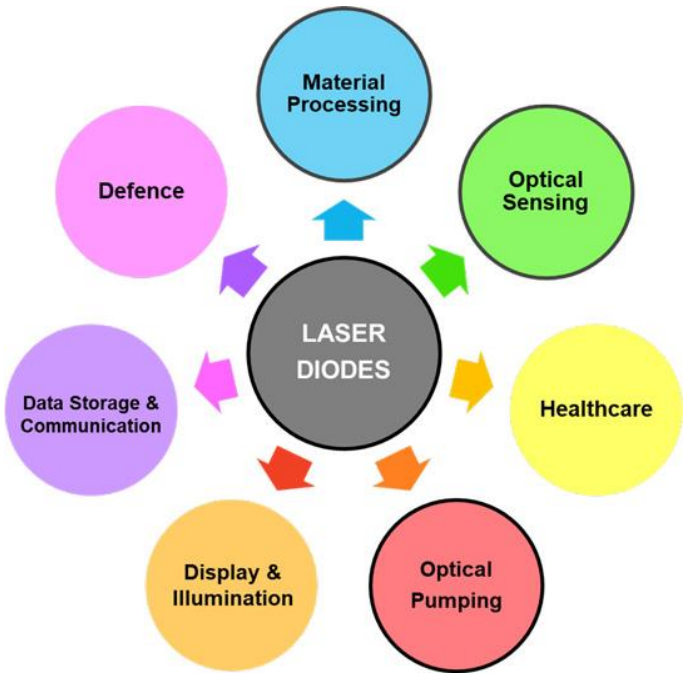
Emerging semiconductor laser technologies are revolutionizing the industrial material processing and optical sensing markets, while the automotive and electronics industries are benefiting greatly from advances in laser manufacturing, 3D sensing and imaging, LiDAR, and industrial machine vision. Notably, the optical sensing market segment should grow by an order of magnitude during 2019-2029.

Unlike light-emitting diodes (LEDs), laser diodes produce a coherent beam of monochromatic (single-wavelength) light, which remains collimated at long distance (as observed with common laser pointers). Laser diodes also have a higher radiance (brighter) and are more energy efficient compared with LEDs.

The power output of a single laser diode can range from milliwatt to multi-watt levels. Individual emitters can be used alone or combined to form more complicated lasers with different properties and applications. Multiple laser diodes can form a laser diode bar for the optical pumping (energy input) of solid-state lasers. Laser diodes integrated into modules with beam-shaping optics and control electronics are useful for many applications.

Direct-diode lasers for industrial materials processing

During the past three decades, the average power of laser diodes has increased exponentially, while their average price has decreased exponentially. These advances in semiconductor laser technology have enabled the development of direct-diode lasers (DDLs), including high-power direct-diode lasers (HPDDLs) that produce multi-kilowatt output power. Dramatic improvements in laser beam quality now enable users to focus the light to a small point, and this has revealed DDLs to be rapidly evolving tools for metal, plastic and composite processing. Consequently, DDLs and HPDDLs are emerging as major global trends in industrial manufacturing, with Japan's Panasonic acquiring US-based HPDDL maker TeraDiode to enhance their position in the laser material processing market.



Picture: Addressable market for laser diodes. Laser diodes are integrated into direct-diode lasers for material processing applications, and used in academia for science research. Source: IDTechEx.

A particularly important trend is the development of blue diode lasers for applications like welding and 3D printing copper, with key player Laserline in Germany launching a 1kW product in 2019. Blue laser light is faster

and more efficient at processing metals like copper that are poor absorbers of conventional infrared radiation. Key DDL players are now demonstrating novel applications of diode lasers that were dismissed as impossible by critics a decade ago, while partnering with automotive manufacturers like Germany's Volkswagen to optimize laser processing parameters.

Laser diodes for optical sensing markets

The widespread adoption of laser diodes in optical sensing markets is also transforming the automotive and electronics industries. Semiconductor lasers for sensing are manufactured by multi-national giants like Japan's Sony, key laser industry players like II-VI Inc in the USA, and smaller companies like China's CNI (who have expertise in machine vision).



Picture: Examples of industries that benefit from laser diode technologies for 3D sensing and imaging. Source: II-VI Inc.

A key trend in 2019 is the rise of vertical-cavity surface-emitting laser (VCSEL) technology for applications like facial recognition in smartphones. Compared with products like Fabry-Perot laser diodes, VCSELs offer superior beam properties, thermal stability and device scalability. Companies like II-VI are investing in rapidly growing their VCSEL production capacity and enhancing their position in the VCSEL market. In November, II-VI announced plans to acquire US-based VCSEL manufacturing firm Finisar.

Another rapidly evolving laser technology is light detection & ranging (LiDAR). In 2018, BMW venture capital fund BMW i Ventures invested in the US-based LiDAR start-up Blackmore. Blackmore's innovative LiDAR sensors for self-driving cars use a frequency-modulated continuous wave (FMCW) light source and scan laser beams using solid-state methods. This is different to traditional LiDAR systems that use pulsed light and mechanical scanning. FMCW LiDAR combines optical communication hardware and radar signal processing methods to deliver accurate information on both object distance and velocity. The adoption of automotive LiDAR and in-cabin monitoring technologies by the autonomous vehicle (AV) industry are important trends that support growth in the laser diodes market.

OSRAM's quarterly revenue to fall 15% year-on-year; full year to decline 11-14%

SemiconductorToday

OSRAM of Munich, Germany says that its fiscal second-quarter 2019 (to end March) is expected to see a revenue decline of about 15% year-on-year (similar to last quarter's decline, to €828m), combined with an adjusted earnings before interest, taxes, depreciation and amortization (EBITDA) margin in the mid to higher single-digit range (down from last quarter's 11.3%). Similar to fiscal first-quarter 2019, the Opto Semiconductors business unit has been particularly affected, impacted by under-utilization of its production capacities.

The firm has hence lowered its fiscal full-year 2019 forecast for continuing operations. OSRAM's previous guidance was conditional on order intake reviving meaningfully in fiscal second-half 2019, but this has not yet occurred and is it not expected for the rest of the fiscal year.

Among the reasons are the continued market weakness in the automotive industry, in general lighting and in mobile devices that has led to significant inventory build ups, particularly in China. In addition, business development is facing an ongoing impact from the general economic slowdown. Geopolitical uncertainties continue to negatively impact demand, the firm stresses.

For fiscal 2019 OSRAM hence now expects a revenue decline of 11-14% (compared with the prior forecast of 0-3% growth), an adjusted EBITDA margin of 8-10% (cut from 12-14%) and negative free cash flow of €50-150m (compared with the previously forecast positive free cash flow in the mid double-digit million range).

The managing board says that it has already proactively responded to the growing economic challenges in the past few months. As announced in January, Osram is honing its focus on photonics and optical technologies beyond lighting, as reflected by the new organizational structures initiated at the start of fiscal 2019. According to Bayerischer Rundfunk, this involves cutting 300 of the 2800 jobs in Regensburg by the end of September through voluntary redundancy. The firm also wants to cut up to 240 temporary workers. Through such initiatives the annual cost base is expected to be structurally reduced by more than €200m by fiscal year 2021.

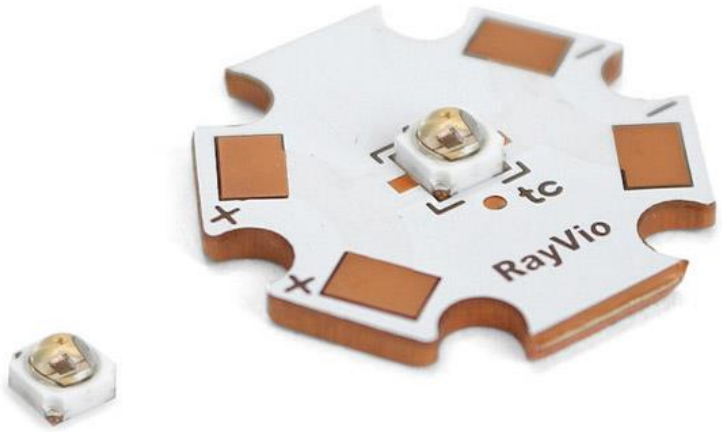
OSRAM says that its strategy - with its focus on optical semiconductors, the automotive sector and digital applications - remains intact, irrespective of the current market weakness, believing that it will provide a sustainable and attractive return profile over the longer term. Transformation of the portfolio is progressing with the initiated sale of the European luminaires business and the sale of the US service business. New business areas such as facial recognition and professional farming are showing positive developments, the firm concludes.

RayVio shipping XR 308nm UVB LEDs for phototherapy treatments of skin diseases

SemiconductorToday

Health and hygiene company RayVio Corp of Haywood, CA, USA, which is commercializing deep-ultraviolet (UV) LEDs and consumer disinfection solutions, is shipping its new 308nm-wavelength XR UVB LEDs and supporting the development of phototherapy treatments for skin diseases.

The new XR UV LEDs are said to enable targeted therapies, smaller and lower-cost treatment devices, and high reliability. Available directly from distributor Digi-Key Corp as an emitter or pre-mounted on a star board for easy development and product integration, the new LEDs deliver output power of 13mW at an injection current of 100mA and are rated for up to 10,000 hours of continuous use.



Picture: RayVio's XR 308nm UVB LEDs.

"UV treatment of psoriasis and vitiligo have been limited because of the size and cost of the equipment as well as the risk to healthy surrounding tissue," says chief innovation officer & co-founder Yitao Liao. "Excimer laser systems address the targeting of treatment to avoid damaging healthy skin, but the systems are bulky and very expensive," he adds. "Our 308nm UV LEDs are being put into compact, handheld devices that are portable."

RayVio says that it has achieved record performance of 300mW output at 308nm from a single UV LED package and is already sampling this option to customers. For phototherapy and Vitamin D production, the firm is preparing a more powerful, 293nm emitter in 2019.

RayVio's work in the UVB range for phototherapy applications complements its UVC LED technology, which can be applied to disinfection and sterilization applications like water purification.

Taiwan's NCTU boosts micro-LED brightness using Picosun ALD passivation technology

SemiconductorToday

Atomic layer deposition (ALD) thin-film coating technology firm Picosun of Espoo, Finland has reported results in boosting micro-LED performance using ALD passivation.

Micro-LEDs present a challenge to existing display technologies such as LCDs (liquid-crystal displays), OLEDs (organic light-emitting diodes) or conventional LEDs. Offering compact size, low power consumption, superior brightness and energy efficiency, greater contrast and color saturation, ultra-high resolution, flexibility and good reliability, micro-LEDs are being studied and developed by leading electronics manufacturers and R&D institutes worldwide, says Picosun. They are typically used for small screens such as those used in tablets, smartphones and smart watches, and the first large-area displays have also been demonstrated.

However, micro-LED technology has drawbacks that have been hindering its full-scale commercial breakthrough. The micro-LED screen consists or minuscule pixels producing green, blue and red light. Some steps in the manufacturing process of these pixels can easily cause damage to their nano-scale structures, leading to loss of light intensity. ALD has now been proven to effectively fix this damage, not only restoring light intensity but actually boosting it to superior levels, says Picosun. At the site of customer National Chiao Tung University (NCTU) in Taiwan, the light-emitting intensity of micro-LEDs has been enhanced by 143.7% by using ALD passivation layers deposited with Picosun ALD equipment, it is claimed (Chen et al, Photonics Research, vol.7 no.4, p416 (2019)).

"Picosun ALD equipment has been an integral part of our facilities for a long time, and we are always impressed by their performance and the superior ALD film quality obtained with them," comments NCTU professor Hao-Chung Kuo. "Picosun's customer support is also impeccable, which is very much appreciated considering we collaborate extensively with industries," he adds.

"Micro-LED technology has immense potential to disrupt the solid-state lighting market, and our Asian customers - both in industries and R&D - will surely lead the forefront of this development," reckons Edwin Wu, CEO of Picosun Asia Pte Ltd.

Samsung achieves record photon efficacy from packaged white LEDs for indoor farms

SemiconductorToday

South Korea's Samsung Electronics Co Ltd has enhanced its LM301H mid-power LED package for horticulture applications, such as greenhouse and vertical farming (growing crops in stacked layers to optimize the use of space, typically in controlled indoor environments). At 3.10 micromoles per joule (µmol/J), the new version of the LM301H now features what is claimed to be the highest photon efficacy among existing mid-power white LED packages.

"This breakthrough in photon efficacy will go a long way in helping indoor farm owners to maximize plant growth and quality, as well as their profits," reckons Un Soo Kim, senior VP of Samsung Electronics' LED Business Team.



Picture: Samsung's enhanced LM301H mid-power LED for indoor farming.

Measuring 3.0mm x 3.0mm, the LM301H has a correlated color temperature of 5000K and a color rendering index (CRI) of 80 for an injection current of 65mA at 25°C. The photosynthetic photon flux (PPF) – indicating the total amount of photons in the photosynthetically active radiation (PAR) range (400–700nm) that can enhance plant photosynthesis – is 0.56µmol/s.

Because of the photon efficacy, lighting manufacturers can use 30% fewer packages in each luminaire to achieve the same efficacy level as the previous version of the LM301H, allowing for smaller and lighter lamp designs as well as lowered manufacturing costs, notes the firm. In addition, by using the same number of packages, the light efficiency of a luminaire can be improved by at least 4%, enabling indoor farms to reduce their energy use.

Samsung achieved the increase in photon efficacy by optimizing the chip's light-emitting layer to convert electrical energy into photons with greater efficiency, while an improvement in chip structure minimizes light loss, delivering more light to plants.

Furthermore, due to Samsung's flip-chip design, the LM301H requires no wire bonding, which helps to extend the packages' performance and reliability. Titanium dioxide around the chip also ensures higher durability when exposed to agricultural chemicals.

To promote even more balanced plant growth, the white LM301H packages encompass a broader spectrum of light from blue and green to red, enhancing immunity from plant disease and providing greater nutritional value.

Samsung expects to begin mass producing the new LM301H packages at the end of April and is showcasing them at LIGHTFAIR International 2019 in Philadelphia, PA, USA (21–23 May).

Nichia launches 280nm UVC LED for water purification and air sterilization

SemiconductorToday

Nichia Corp of Tokushima, Japan has launched the NCSU334A deep ultraviolet (UV) LED.

Following success over the years with UVA LEDs (specifically in conventional resin curing applications), Nichia's new 280nm UVC NCSU334A will be able to address mass-market applications of solid-state lighting in water purification and air sterilization. With its small size (6.8mm x 6.8mm) and strong performance (55mW typical optical power at 350mA), the NCSU334A allows for system miniaturization and longer lifespan compared with previous technologies.

Conventional UVC LEDs (200-280nm) have the problems of more complex crystal growth and a shorter life than UVA LEDs (365-405nm). Nichia says that, through its unique crystal growth technology (cultivated for many years in UVA LEDs), it has developed high-radiant-flux, long-life UVC LED. The NCSU334A achieves a significant lifetime improvement versus conventional UV lamps. Additionally, it uses a newly developed hermetically sealed package, making it highly reliable as it is not as susceptible to external environmental conditions and can therefore be used in various harsh environments.

Nichia expects the LED to contribute to the complete replacement of mercury lamps. The firm aims to continue to improve the characteristics of its UVC LED portfolio.

VerLASE extends IP base to mass-transfer technology for micro-LED displays

SemiconductorToday

VerLASE Technologies LLC of Bridgewater, NJ, USA (which was spun off from technology development firm Versatilis LLC of Shelburne, VT, USA in 2013) says that it is developing unique technologies for massively parallel assembly of micro-LED dies or films (the central challenge in micro-LED display manufacturing currently hindering wide-spread adoption of micro-LED technology).

Many observers point to the inherent advantages of micro-LEDs such as brightness, efficiency, robustness, and a vision of modular panels that could be tiled into displays of any size. Despite being a superior technology in theory which, for example, overcomes the many problems surrounding organic light-emitting diode (OLED) displays, micro-LED displays have been bedeviled by practical manufacturing aspects, notes VerLASE. Among these, perfectly assembling the micro-LED subpixels (which can be 10µm or even smaller) in a commercially viable way on a switching backplane remains a huge, unsolved problem.

Several companies (including a few start-ups) have shown various approaches to solving this problem at trade shows and conferences. However, the proposed methods seem too slow to be cost effective and generally offer no apparent way of repair and replace, since displays must be perfect with no misplaced pixels, notes VerLASE. The micro-LED display prototypes shown to date also tend to have lower resolutions (PPI) than might be needed today, for example, for a typical smartphone display or 8K display.

VerLASE says that it is focused on practical methods that use well-proven semiconductor and MEMS industry methods and existing tools in novel ways to enable deterministic, massively parallel transfers of micro-die, yet with provisions that allow selective repair. The methods employ well-developed techniques used daily in ink-jet printing (although it is not printing per se). Comprehensive patent filings cover multiple variations of the firm's proprietary core Large Area Assembly Process (LAAP). "In levering the ink-jet industry, our solution offers a quick path for micro-LEDs to disrupt the displays industry," believes Ajay Jain, chief technology officer and inventor of the technology.

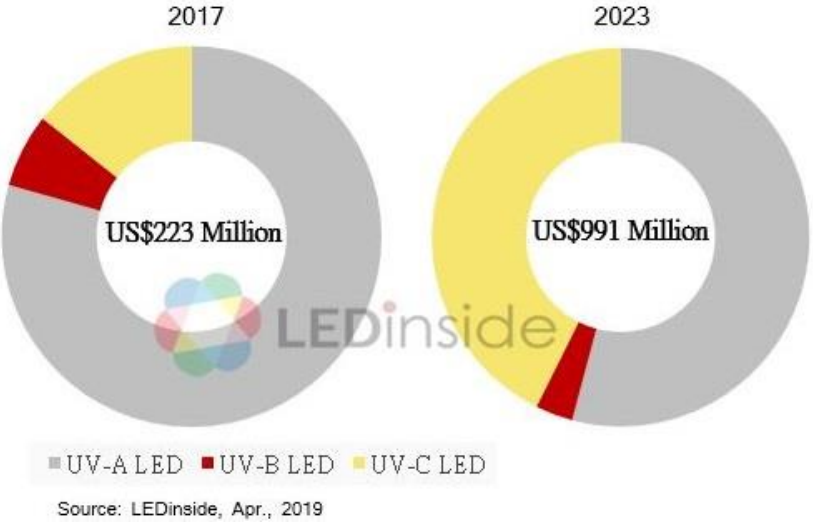
The firm is working on demonstrating the base principles of its solution while being in discussions with potential investors. VerLASE had previously been focused on color conversion technology for micro-LEDs and related applications (which remains a core capability) but decided to broaden the horizon, given its novel solution to the mass-transfer problem. It has seven US patents now issued covering various aspects in color conversion (including some in Japan, Korea and China) with others pending. The firm has now also filed a suite of IP relating to its mass-transfer solution.

The patents that are issued encompass VerLASE's Chromover branded color conversion technology, which can efficiently downconvert colors from inexpensive, widely available blue/violet light sources such as LEDs, micro-LEDs or laser diodes to any color in the visible range for a wide variety of applications, to novel materials used both passively (as phosphors) and actively (as the electroluminescent layer in light engines of the near future).

Anti-bacterial UV-C LED applications driving stable growth in UV-LED market

SemiconductorToday

UV LED makers did not see explosive growth in revenue as expected for 2018 due to the global recession yet they did see a steady increase, according to the report '2019 Deep UV LED Application Market- Sterilization, Purification and Water Treatment Markets' by LEDinside (a division of TrendForce). UV-LED revenues are expected to ride UV-C LED market demand and are rising at a compound annual growth rate (CAGR) of 29% from $223m in 2017 to US$991m in 2023.



Graphic: UV LED revenue in 2017 and 2023 (forecast).

According to analyses by research manager Joanne Wu, as Japanese and Korean manufacturers move eagerly into the UV LED market the global supplier rankings by revenue have been reshuffled in 2018, to Nitride Semiconductors, Seoul Viosys, LG Innotek, Nichia and Epitop (i.e. with Nitride Semiconductors rising from third in 2017, overtaking Seoul Viosys and LG Innotek).

Rank	2017	2018
1	Seoul Viosys	Nitride Semiconductors
2	LG Innotek	Seoul Viosys
3	Nitride Semiconductors	LG Innotek
4	Nichia	Nichia
5	Epitop	Epitop

Source: LEDinside, Apr., 2019

Graphic: UV-LED supplier rankings for 2017 and 2018.

A glance at demand shows that UV-C LED applications continue to be the powerhouse for market growth. LEDinside forecasts that 2019 will see vigorous UV-C LED product development by many LED makers, including Nichia, OSRAM Opto Semiconductors, UV photonics, Violumas and others, injecting new momentum into the market.

Existing UV-C external quantum efficiencies (EQEs) average 1-3%, while industry leader LG Innotek's EQE may reach up to 4.33%. Other suppliers such as Stanley, DOWA, Nitride Semiconductors and Seoul Viosys also continue to raise product efficiencies.

Nichia released its 280nm-wavelength UV-C LED products in April, while OSRAM is poised to release UV-C LED products in second-half 2019. Taiwanese suppliers such as Epistar and Lextar have launched 275-285nm UV-C LED products, whereas Bioraytron has launched a 265nm UV-C LED. Other companies such as Everlight, Lite-On and UVT are also making their way into UV-C LED markets.

Suppliers active in UV-C LED product development; market to split into two

There are three main motivators for UV-C LED application market growth: surface/air sterilization, static water sterilization, and flowing water sterilization.

Static water and surface disinfection (for air purification and appliances etc) have more relaxed exposure time requirements and are used in a wide range of applications. They also gave rise to many emerging markets, including baby products, everyday cell phones, escalators, household products (such as toothbrushes), toiletries, cabinets, sport bottles and thermos flasks.

Flowing water sterilization is more demanding due to its fast-acting nature, and naturally requires a higher power level. The market for household water treatment includes applications such as water dispensers, hot and cold kitchen water, whole house water filters and baby products (baby formula makers) etc.

Commercially and industrially speaking, the global water treatment market is about US$20bn, becoming the UV-C LED target market with the most potential for development. The three main methods used in water

sterilization are gravity-based purification, RO (reverse osmosis) purification and UV purification. RO purification is a widely used technology, yet it should still be used in conjunction with UV purification to rid water of bacteria and viruses and lower overall TOC (total organic carbon) concentration.

To meet the demands of the water treatment market, Japanese and Korean manufacturers are actively developing high-power UV-C LEDs and moving into the market for flowing water modules. LEDinside predicts that the UV-C LED market will diverge into two: a general consumer market and an advanced commercial/industrial market.

Seoul Semiconductor's Q1 revenue falls slightly year-on-year, but improved UV LEDs and VCSEL launches to drive record full-year revenue

SemiconductorToday

For first-quarter 2018, South Korean LED maker Seoul Semiconductor Co Ltd has reported revenue of 282bn Korean won (KRW), down slightly on KRW283bn a year ago.

Operating profit was KRW17bn, down from KRW17.2bn a year ago due to utilization falling from 74% to 60% during the relocation of equipment between factories (in order to further improve product mix and increase cost competitiveness in the long term). When equipment is stabilized and as high seasonality begins in second-half 2019 (fueled in particular by robust revenue from fast-growing automotive lighting and display-related products), the firm expects full-year 2019 revenue and profit to exceed prior annual record sales and profit.

For second-quarter 2019, Seoul forecasts revenue of KRW280-300bn.

Seoul Semiconductor plans to launch many new products in 2019. In Q2/2019, improved UV LED products will begin replacing lower-priced mercury lamps, says the fiirm. UV LEDs are expected to be widely adopted for disinfection systems and healthy lighting (with no mercury). In addition, new vertical-cavity surface-emitting laser (VCSEL) products are scheduled to be launched in second-half 2019.

"Seoul has plans to apply new technologies in the mobile segment this year," says Sam Ryu, executive vice president of IT sales. "These efforts - together with the new Vietnam plant contributing to higher utilization once fully set up - will help deliver superior revenue and profit growth once again exceeding prior annual sales and profits," he adds.

Distributed feed-back gratings for indium gallium nitride laser diodes

SemiconductorToday

Saudi Arabia's King Abdullah University of Science and Technology (KAUST) claims the highest side-mode suppression ratio (SMSR) for indium gallium nitride (InGaN) distributed feed-back (DFB) laser diodes (LDs) so far [Jorge A. Holguín-Lerma et al, Appl. Phys. Express, vol12, p042007, 2019]. The highest SMSR achieved in the KAUST work was 36.9dB. The researchers comment: "This could enable immediate implementation of narrow-line green laser diodes on various applications, such as atom cooling, spectroscopy, and optical communications."

Narrow-line emissions usually require external, complex and bulky filtering techniques to reduce the presence of side-modes relative to the main peak. An attractive alternative is monolithic integration of DFB gratings into the structure of the laser diode. Such an approach is already common in laser diodes constructed in other compound semiconductor systems serving wavelengths in the infrared and red parts of the electromagnetic spectrum. Also, DFBs have been applied to blue and ultraviolet InGaN devices, but with lower SMSR values.

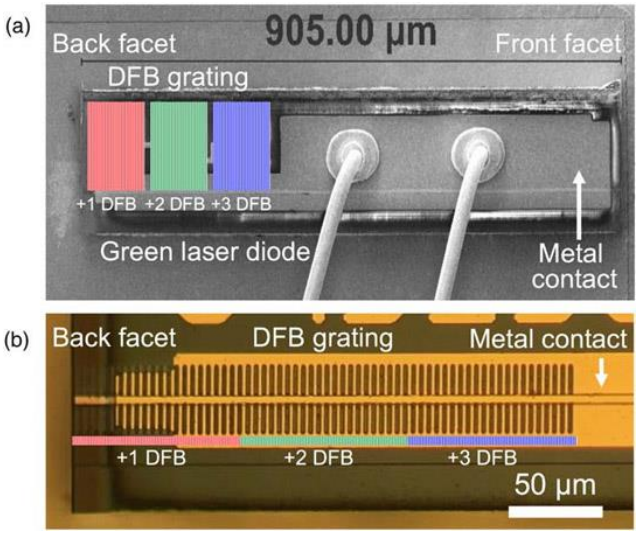


Figure 1: Device A: (a) scanning electron micrograph; (b) optical microscope image of back-facet section of laser diode with DFB grating. Red, green and blue periodic lines overlaid to represent DFB grating sections: +1 DFB, +2 DFB, and +3 DFB.

The KAUST researchers used an Osram PLP520 laser diode. The DFB grating was etched into the device surface using exposure to a focused ion-beam to create grooves. The grating period was 4.12µm, targeting an output wavelength of 515nm, assuming an effective refractive index in the laser diode material of 2.5. The green laser diode had a Fabry-Perot (FP) cavity length of ~905µm and the ridge width was ~4µm.

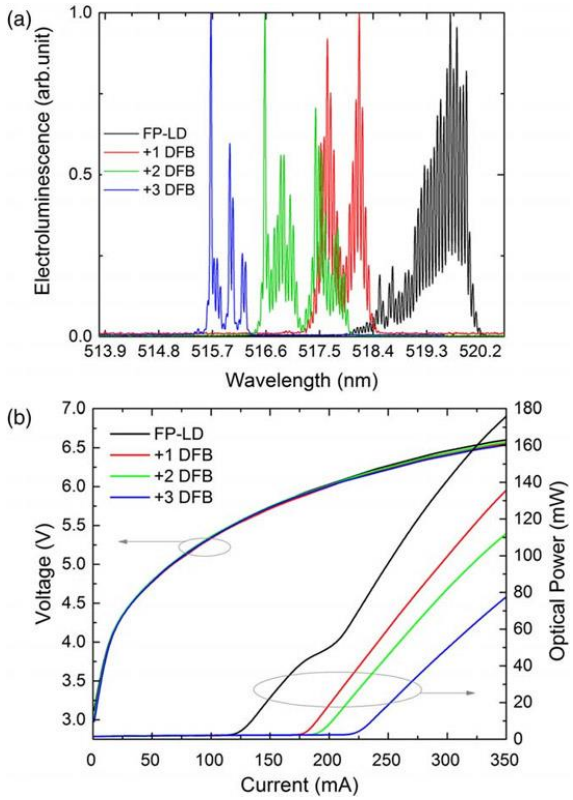


Figure 2: Electro-optical characteristics of device A: (a) spectral evolution after each consecutive DFB grating segment (i.e. +1 DFB, +2 DFB, +3 DFB); (b) light-output–current–voltage characteristics after each DFB grating segment.

Two devices (A and B) were produced. The first, device A, used a DFB that was built up in three stages (DFB+1-+3) with the sections consisting of 22 groove/semiconductor pairs (Figure 1). As the DFB was lengthened, the

SMSR increased. Under 300mA (8.28kA/cm2) continuous-wave current injection and the temperature maintained at 20°C, the SMSR was 0.2dB for the original device without DFB, while as the DFB was built up to the third +3 stage the SMSR increased successively in steps: 0.34dB, 1.45dB and 2.23dB (Figure 2).

The peak shifted to shorter wavelengths due to mismatch between the Bragg resonant wavelength and the main resonance of the Fabry-Perot cavity of the original laser diode. Another effect of the grating was to reduce the output power at 300mA: 141mW for the original laser diode and 49.6mW for the laser diode with +3 DFB. Mode selection and annihilation in the original laser diode did give a kink in the current-power curve, which was not seen in the DFB versions that are expected to have greater mode stability. The electrical voltage-current performance of the various device As was almost identical.

Using parameters derived from device A with +3 DFB sections, the researchers designed an improved 40-order DFB grating for device B. The new gating period was 4.114µm, giving narrow-line emission at 513.85nm. Under 300mA injection, device B achieved an SMSR of 36.9dB (Figure 3). The full-width at half-maximum (FWHM) linewidth of the laser diode without DFB was 544pm; adding the DFB to device B reduced this to 31pm. The corresponding optical powers were 149mW and 14mW. Again, the two set-ups had similar electronic behavior in terms of the current-voltage performance.

Another factor was an increase in threshold current for the laser diode B with DFB: 263mA, compared with 102mA for the raw laser diode. The slope efficiency was also impacted: 0.54W/A without DFB and 0.32W/A with DFB. The external and maximum wall-plug efficiencies for device B with/without DFB were 20.7%/3.5% and 7.7%/1.3%, respectively.

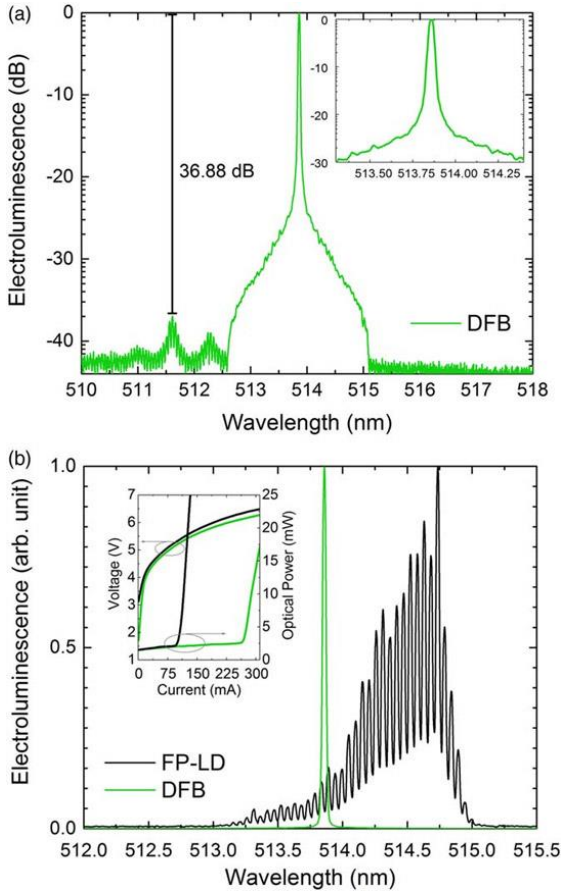


Figure 3: Electro-optical characteristics of DFB-LD (device B). (a) High-resolution optical spectra of green laser narrow-line emission (with detail inset). (b) Comparison of emission spectra before and after fabrication of DFB grating (DFB-LD). Inset: light-output–current–voltage characteristics.

X-Celeprint implements BluGlass' RPCVD p-GaN technology in high-performance micro-LED display prototypes

SemiconductorToday

BluGlass Ltd of Silverwater, Australia (which was spun off from the III-nitride department of Macquarie University in 2005) and its foundry customer X-Celeprint of Cork, Ireland – a subsidiary of XTRION N.V. of Tessenderlo, Belgium that uses facilities at Ireland's Tyndall National Institute and in Research Triangle Park, NC, USA to develop and license patented micro-transfer printing (µTP) and related technology – have implemented BluGlass' unique remote-plasma chemical vapor deposition (RPCVD) p-GaN technology in high-performance micro-LED display prototypes.

BluGlass is commercializing its proprietary RPCVD technology in the LED, micro-LED and power electronics industries, for which patented hardware and processes are claimed to offer manufacturers unique performance advantages due to its low-temperature and low-hydrogen growth conditions.

X-Celeprint is using RPCVD deposition for its unique technology demonstrations. X-Celeprint's active-matrix micro-LED displays that use RPCVD p-GaN have demonstrated luminance with colour uniformity, quantum efficiency and forward voltage that equals existing high-performance commercial applications of 2000cd/m2.



Picture: X-Celeprint's 2000cd/m2 micro-LED display, using RPCVD p-GaN, showing good colour uniformity quantum efficiency and forward voltage.

X-Celeprint (which provides custom design services for micro-transfer printing stamps and printers) says that its µTP is a cost-effective and scalable manufacturing platform for integrating microscale devices such as lasers, LEDs or integrated circuits onto non-native substrates. The firm has been a long-standing customer of BluGlass' foundry services and was the first adopter of RPCVD for micro-LED demonstrations.

"X-Celeprint works with BluGlass to demonstrate our micro-transfer printing capability for micro-LED displays," says X-Celeprint's VP of displays Matt Meitl. "BluGlass' creativity in epiwafer design, unique capabilities in epitaxial growth, and dedication to continued product improvement make them a valuable development partner. We continue to use these advantages in our micro-LED development," he adds.

"It's rewarding, after many years of developing RPCVD p-GaN, to see our technology being trialed in customer devices, particularly for the emerging micro-LED display market," comments BluGlass' chief technology officer Dr Ian Mann. "This micro-LED prototype demonstrates good performance, and X-Celeprint are seeing the advantage of using RPCVD in their innovative products."

X-Celeprint continues to use BluGlass' RPCVD foundry services (early-stage, fee-for-service revenue) to advance the technical demonstrations of its active-matrix micro-LED displays, and is actively marketing its high-performance display technology in the emerging micro-LED market.

Graphene interlayer for deep ultraviolet LEDs on nano-patterned sapphire

SemiconductorToday

Researchers based in Beijing, China, have used graphene (Gr) to improve aluminium nitride growth on nano-patterned sapphire substrates (NPSSs) as a template for aluminium gallium nitride (AlGaN) deep ultraviolet (DUV) light-emitting diodes (LEDs) [Hongliang Chang et al, Appl. Phys. Lett., vol114, p091107, 2019].

The team was variously based at Research and Development Center for Semiconductor Lighting Technology, University of Chinese Academy of Sciences, Peking University, and State Key Laboratory of Superlattices and Microstructures.

The presence of graphene improved aluminium mobility on the growth surface, improving crystal quality through quasi-van der Waals epitaxy (QvdWE). In turn, this improved the performance of an AlGaN LED grown on the AlN template.

DUV LEDs are desired for a range of uses such as sterilization, polymer curing, biochemical detection, non-line-of-sight communication and special lighting. However, the efficiency of LEDs in the 200-300nm wavelength range is low (of the order a few percent). Sapphire is the preferred substrate, but suffers from lattice and thermal expansion mismatches with AlN that introduces strain/stress, generating efficiency-killing defects.

The nano-patterned sapphire substrate consisted of 400nm-deep nano-concave cone patterns with 1µm period produced by nano-imprint lithography (NIL) on the sapphire surface. The unetched regions were 300nm wide. The ~0.7nm-thick graphene layer was grown by 1050°C catalyst-free atmospheric pressure chemical vapor deposition (APCVD). The graphene growth process took three hours. The precursor was methane in hydrogen/argon carrier.

The graphene was subjected to reactive ion etch to introduce defects that would increase chemical reactivity with the subsequent AlN growth. Without defects, AlN does not attach easily to graphene, slowing AlN growth.

The graphene on NPSS was prepared with 30-second exposure to nitrogen plasma before loading into the metal-organic chemical vapor deposition (MOCVD) reactor for AlN growth. Raman spectroscopy suggested that the nitrogen plasma treatment generated increased numbers of dangling bonds.

The 1200°C AlN growth used trimethyl-aluminium and ammonia precursors in hydrogen carrier gas. There was no low-temperature nucleation step. The full growth time was two hours. Some samples were grown for just 10 minutes to allow study of the initiation of AlN deposition.

Without a graphene interlayer, two hours of growth on NPSS resulted in rough, non-uniform AlN layers (Figure 1). By contrast, the graphene interlayer enabled rapid coalescence of the AlN, giving a continuous, flat surface. Cross-sectional scanning electron microscopy (SEM) showed that the coalescence occurred within 1µm of the full ~2.4µm growth.

-ray rocking-curve analysis showed a reduction in the full-width at half maximum (FWHM) of the peak associated with the (0002) plane of the AlN lattice from 455.4arcsec to 267.2arcsec, arising from the graphene interlayer. The (10-12) peak FWHM also decreased from 689.2arcsec to 503.4arcsec. These values resulted in respective estimates for screw and edge dislocations: 4.51x108/cm2 and 4.40x109/cm2 without graphene interlayer, reducing to 1.55x108/cm2 and 2.60x109/cm2 with graphene.

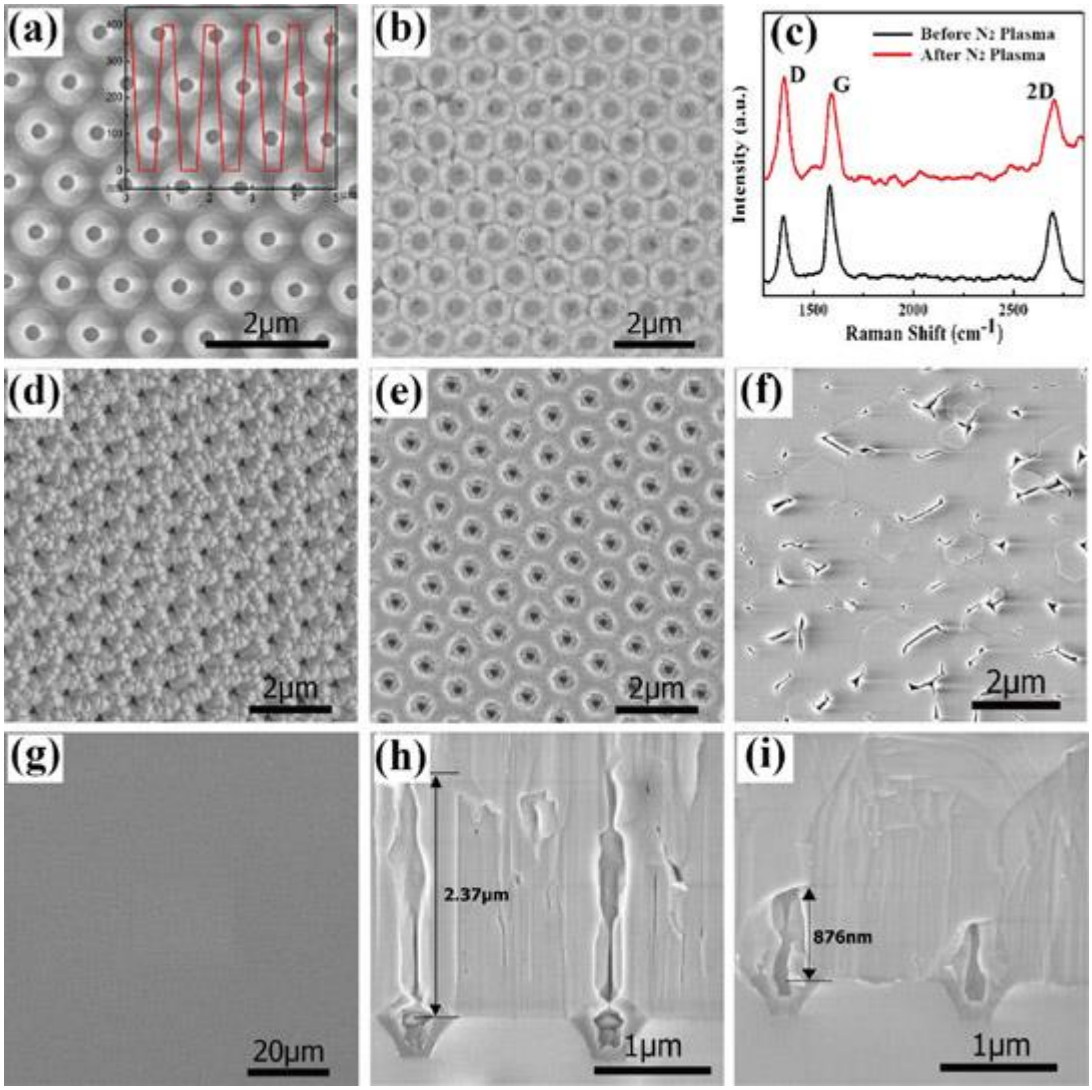


Figure 1: (a) SEM image of bare NPSS. Inset in (a) shows line profile from atomic force microscopy. (b) SEM image of as-grown graphene films on NPSS. (c) Raman spectra of graphene film before (black) and after (red) nitrogen plasma treatment. (d) and (f) SEM images of initial 10 minutes and 2 hours growth of AlN films on NPSS without graphene interlayer. (e) and (g) SEM images of initial 10 minutes and 2 hours growth of AlN films on NPSS with graphene interlayer. (h) and (i) cross-sectional SEM images of AlN films on NPSS without and with graphene interlayer.

According to Raman spectroscopy, the biaxial stress was reduced from 0.87GPa to 0.25GPa by the use of graphene interlayers.

Simulations of the growth process suggested that the effect of the graphene layer was to increase the mobility of aluminium adatoms, compared with the bare NPSS surface. The researchers comment: “The strong binding of Al adatoms to the defect sites and the free diffusion on the non-defective regions ensure the effective nucleation and fast growth for AlN layers, as observed in our experiments.”

The AlN on bare NPSS undergoes “three-dimensional longitudinal island growth” due to the sluggish diffusion of the Al adatoms. The coalescence of the islands is therefore delayed. On graphene, the Al adatoms can diffuse further in shorter time, allowing “lateral two-dimensional growth” with rapid lateral coalescence.

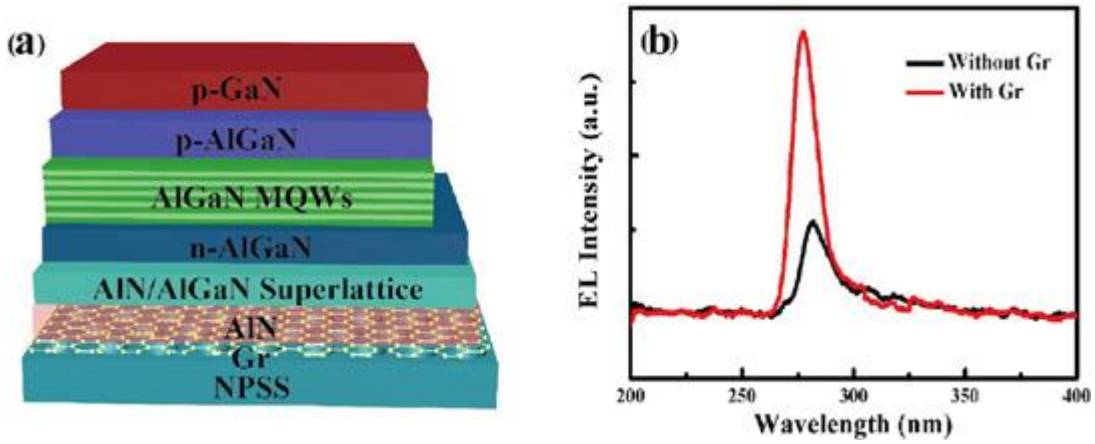


Figure 2: (a) Schematic diagram of AlGaN-based DUV-LED. (b) Electroluminescence spectra with and without graphene interlayer.

The researchers used the AlN/Gr/NPSS template to produce a deep ultraviolet LED (Figure 2). The epitaxial structure consisted of a 1130°C 20-period 2nm/2nm AlN/Al0.6Ga0.4N superlattice, 1.8µm n-Al0.55Ga0.45N contact, 5-period 3nm/12nm Al0.4Ga0.6/Al0.5Ga0.5N multiple quantum well (MQW), 50nm p-Al0.65Ga0.35N electron-blocking layer (EBL), a 30nm p-Al0.5Ga0.5N cladding layer and a 150nm p-GaN contact layer. Post-growth annealing was used to activate the p-type layers (800°C for 20 minutes in nitrogen).

At 40mA, the 280nm-wavelength peak was around 2.6x higher than that for electroluminescence from an LED grown on bare NPSS. The researchers attribute the higher intensity to a reduced defect density in the graphene-based sample.

Cree completes sale of Cree Lighting to Ideal Industries

SemiconductorToday

Cree Inc of Durham, NC, USA has completed the sale (announced on 15 March) of its Lighting Products business unit (Cree Lighting, including the LED lighting fixtures, lamps and corporate lighting solutions business for commercial, industrial and consumer applications) to Inc of Sycamore, IL, USA.

“This represents a pivotal chapter for Cree as we sharpen our focus to become a semiconductor powerhouse in silicon carbide (SiC) and gallium nitride (GaN) technologies,” says CEO Gregg Lowe.”Cree’s technologies are helping to power major transitions in our economy, whether it’s the automotive industry’s transition to electric vehicles or the telecommunications sector’s move to faster 5G networks,” he adds. “Our leadership in SiC and GaN positions us well to help customers improve performance and realize greater efficiencies.”

Cree will use the proceeds from the sale to accelerate the growth of Wolfspeed, its Power & RF business, and expand its semiconductor operations. The firm recently announced plans to invest up to $1bn in the expansion of its silicon carbide capacity to meet the growing demand for SiC and GaN-on-SiC technologies. The expansion includes the development of an automated 200mm silicon carbide fabrication facility and a materials mega factory at its US campus in Durham.

OTHER

UniversityWafer introduces AlN-on-sapphire and AlN-on-silicon wafers

SemiconductorToday

UniversityWafer Inc of South Boston, MA, USA, along with its partners, has introduced a new line of 50.8mm, 100mm and 150mm UV-grade aluminium nitride (AlN) on c-plane single-side-polished (SSP) sapphire and AlN-on-silicon prime-grade for high-electron-mobility transistor (HEMT) templates.

A major use of AlN-on-sapphire are ultraviolet (UV) LEDs. Some of the most powerful applications include irradiating hospital rooms and foundry cleanrooms, since AlN-on-sapphire LEDs disinfect instruments and can purify air and water of germs and bacteria without using chemicals.

The electricity savings of using LEDs instead of traditional cold-cathode fluorescent lamps (CCFLs) can reach 70%. Also, unlike CCFLs, AlN LEDs do not contain mercury, allowing more environmentally friendly disposal. AlN LEDs can also be used for non-line-of-sight communications.

Currently, the newest-generation AlN-on-sapphire LEDs technology is approaching 50,000 hours of life, compared with just 10,000 hours for existing AlN-on-sapphire LEDs. The cost saving will only increase with time, adds the firm.

UniversityWafer says that it carries a large inventory of AlN-on-sapphire substrates, and can also quote unique client specs in small quantities that make it feasible for budget-strapped researchers to obtain the substrates at a reasonable cost. Delivery time is also short, notes the firm. UniversityWafer hence caters to researchers who want both small quantities and short lead-times, with staff trained to handle even the most difficult low-volume requests.

For production, AlN-on-sapphire can be ramped up to meet a client's demands in a timely and affordable manner, UniversityWafer adds.

Riber's Q1 revenue falls 10% year-on-year as weak evaporator sales outweigh MBE system sales growth

SemiconductorToday

For first-quarter 2019, Riber S.A. of Bezons, France – which manufactures molecular beam epitaxy (MBE) systems as well as evaporation sources and effusion cells – has reported revenue of €6.6m (32.3% from Asia, 30.1% from Europe and 37.6% from the USA). This is down 10% on €7.3m a year ago due to a drop in revenue from evaporators, despite strong growth in revenue for MBE systems and services & accessories.

Revenue from evaporators (cells and sources) was just €0.8m, down 85% on €5.2m a year ago, attributed to the freeze on investments in equipment for organic light-emitting diode (OLED) screen production following the major investments made in previous years.

Revenue for MBE systems was €4.1m (reflecting the invoicing of two production systems), up 413% on only €0.8m (just one research system) a year ago.

Revenue for services & accessories was €1.7m, up 31% on €1.3m a year ago, in line with the company's strategy to develop this business (which makes a strong contribution to gross margin).

The order book at the end of March was down 11% from €36.1m a year ago but remained high, at €32.2m, despite no orders being recorded for evaporators (€0.1m versus €8.3m a year ago). This was because MBE systems orders were up 25% from €20.2m to €25.3m (comprising 14 MBE systems, including seven production machines). Services & accessories orders were down 11% from €7.6m a year ago, but still at a 'satisfactory' level of €6.8m.

Riber notes that, considering the good level of orders (with a high percentage of systems to be delivered in 2019), it is forecasting significant growth in full-year revenue in 2019 compared with 2018.

Aixtron's Q1 gross margin and earnings exceed expectations

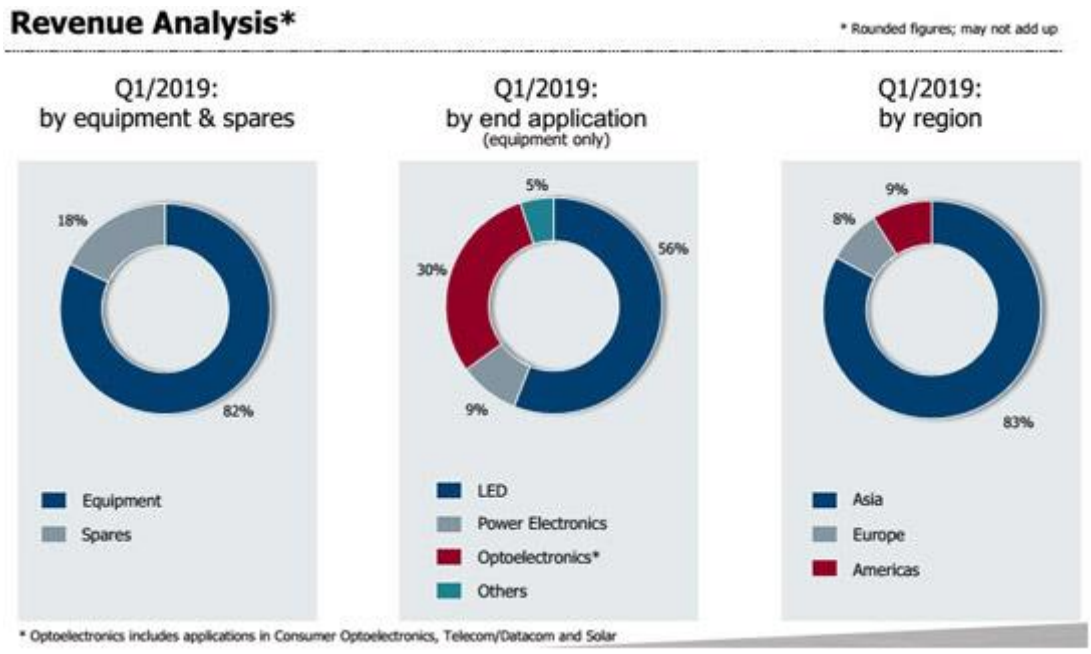
SemiconductorToday

For first-quarter 2019, deposition equipment maker Aixtron SE of Herzogenrath, near Aachen, Germany has reported revenue of €68.7m, down 22% on €87.9m last quarter but up 10% on €62.4m a year ago. "Business development in the first quarter of 2019 was in line with our expectations," says president Dr Bernd Schulte.

Specifically, equipment revenue was €56.1m, up 10% on €50.8m a year ago (rising 81% to 82% of total revenue). Meanwhile, revenue from spare parts & services has grown by 0.9% from €11.6m a year ago to €12.5m.

Of equipment revenue, metal-organic chemical vapor deposition (MOCVD) systems for manufacturing Optoelectronic components (consumer optoelectronics, telecom/datacom and solar) declined from 70% a year ago to 30%, as expected, while systems for manufacturing Power Electronics components fell from 11% to 9%. In contrast, lower-margin MOCVD systems for producing LEDs have risen from a low of just 14% a year ago to 56% of total revenue.

Correspondingly, on a regional basis, Asia has risen from 46% of revenue a year ago to 83% (almost doubling from €29m to €56.7m), while Europe has dropped from 38% to 8% (falling by 77% from €23.5m to €5.4m) and the USA from 16% to 9% (falling by 34% from €9.9m to €6.5m).



Read more

Cree's quarterly revenue grows 22% year-on-year, driven by Wolfspeed's organic growth of 40

SemiconductorToday

For its fiscal third-quarter 2019 (to end-March), Cree Inc of Durham, NC, USA has reported revenue from continuing operations of $274m, down on $356m a year ago. However, this is up 22% on $225.2m excluding (as discontinued operations) the Lighting Products business unit (LED lighting fixtures, lamps and corporate lighting for commercial, industrial and consumer applications), which Cree agreed on 14 March to sell for about $310m to IDEAL Industries Inc of Sycamore, IL, USA. (After receiving early termination of the waiting period under the Hart-Scott-Rodino Act in April, the transaction is expected to close by the end of fiscal Q4.)

Fiscal	Q3/2018	Q4/2018	Q1/2019	Q2/2019	Q3/2019
Revenue	$356m	$409.5m	$408.3m	$413m	$274m

LED Product sales were $132.8m (48.5% of total revenue), down 8.5% (more than the expected 5%) on $145.2m last quarter and down 7% on $143.3m (63.6% of total revenue for continuing operations) a year ago. LED gross margin was 27.8%, down from 30% last quarter but up from 26.4% a year ago (and above the targeted 27%) as a result of strong execution and a strategy to focus on business where the firm thinks its products are differentiated and valued.

Revenue for the Wolfspeed business (Power & RF devices and silicon carbide materials) was $141.3m (51.5% of total revenue), up 4% on last quarter's record of $135.3m and up 72% on $81.9m a year ago (just 36.4% of total revenue for continuing operations) – or up over 40% organically (excluding revenue from the Infineon RF Power business, acquired on 6 March 2018). Wolfspeed gross margin was 48.7% (better than the targeted 48%), up from 47.8% last quarter and 48% a year ago, as it continues to balance rapidly increasing capacity while maintaining yield. "Wolfspeed is now our largest business and represents two-thirds of our gross profit from continuing operations," says CEO Gregg Lowe.

Read more

HexaTech achieves defect-free 2"-diameter aluminium nitride substrate

SemiconductorToday

As part of its R&D program (combined with the direct support of its strategic business partners), HexaTech Inc of Morrisville, NC, USA – which manufactures single-crystal aluminium nitride (AlN) substrates for long-life UV-C LEDs in disinfection applications, deep UV lasers in biological threat detection, and high-voltage power switching devices in efficient power conversion as well as RF components in satellite communications – has announced what it reckons is the first demonstration of a defect-free 2"-diameter AlN substrate.

"This is the largest known single-crystal AlN substrate that is completely free of macroscopic defects, and accomplishes a long-standing goal as part of our 2" product development," says co-founder & chief technology officer Dr Raoul Schlesser. "Full-substrate reflection x-ray topography confirms this achievement, which will support and accelerate commercial production of high-quality 2" material," he adds.

"Less than a year from our first 2" demonstration, reaching this level of perfection is a testament to the efforts of the entire HexaTech team," says CEO John Goehrke. "This capability establishes a new baseline for sustaining our vision of continued diameter expansion and greater market adoption."

HexaTech's 2"-diameter substrates, in addition to 35mm and 25mm substrates, are available now with standard lead times.

Veeco's Q1 revenue levels out at $99m after drop off of commodity LED MOCVD system sales to China

SemiconductorToday

For first-quarter 2019, Epitaxial deposition and process equipment maker Veeco Instruments Inc of Plainview, NY, USA has reported revenue of $99.4m, down 37% on $158.6m a year ago but roughly level with $99m last quarter (and above the midpoint of the $85-105m guidance range, driven by strength in services business). "With the commodity LED business [which includes the sale of metal-organic chemical vapor deposition (MOCVD) systems to the China LED market] largely behind us, our revenues for the quarter have stabilized," notes CEO Bill Miller.

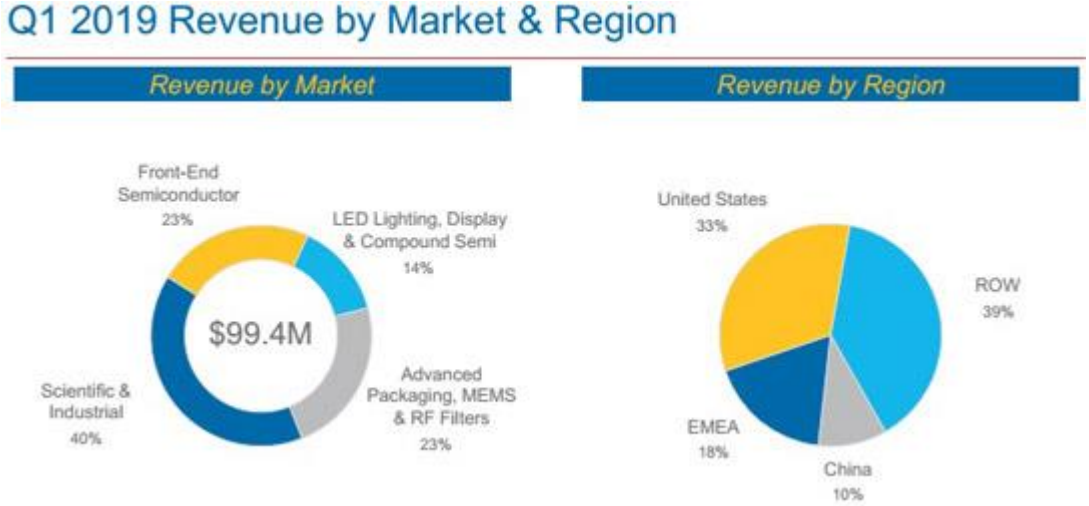
With almost no contribution from commodity LED equipment sales (as expected), the LED Lighting, Display & Compound Semiconductor segment remained just 14% of total revenue (following the plunge from 46% in Q3/2018 to 14% in Q4/2018). Most of the segment's revenue was therefore in Compound Semiconductors, including MOCVD systems for specialty LEDs, automotive, photonics and power electronics applications.

The Advanced Packaging, MEMS & RF Filter segment – including lithography and Precision Surface Processing (PSP) systems sold to integrated device manufacturers (IDMs) and outsourced assembly & test firms (OSATs) for Advanced Packaging in automotive, memory and other areas – has rebounded from a low of just 14% of total revenue last quarter to 23%, driven by multiple Advanced Packaging lithography systems sold for high-bandwidth memory as well as CPUs and other applications.

The Front-End Semiconductor segment (formerly part of the Scientific & Industrial segment, before the May 2017 acquisition of lithography, laser-processing and inspection system maker Ultratech Inc) has risen slightly from 22% of total revenue last quarter to 23%, driven by multiple laser spike anneal (LSA) systems shipped to a leading foundry for process steps at an advanced technology node.

The Scientific & Industrial segment has fallen back from last quarter's high of 50% of total revenue to 40%, driven by shipments to data storage customers as well as several ion beam sputtering systems shipped to optical customers.

Geographically, the quarter saw slight rebounds in China from just 9% to 10% of total revenue and in Europe, Middle East & Africa (EMEA) from just 17% to 18%. Meanwhile, the USA has fallen back from 41% to 33%, while the rest of the world (which includes Japan, Taiwan and South Korea) has risen further from 33% to 39%.



Read more

Soitec expanding engineered substrate portfolio into GaN by acquiring EpiGaN

SemiconductorToday

Soitec of Bernin, near Grenoble, France, which makes engineered substrates including silicon-on-insulator (SOI) wafers, has agreed to acquire EpiGaN nv of Hasselt, near Antwerp, Belgium – which supplies gallium nitride on silicon (GaN-on-Si) and gallium nitride on silicon carbide (GaN-on-SiC) epitaxial wafers – for €30m in cash plus an additional earn-out payment based on completion of certain milestones. EpiGaN will be integrated as one of Soitec's business units.

EpiGaN's GaN products are used primarily in RF 5G, power electronics and sensor applications, with the total addressable market of GaN technologies estimated to be 0.5–1 million wafers per year within five years.

Founded in 2010, EpiGaN was founded by chief executive officer Dr Marianne Germain, chief technology officer Dr Joff Derluyn and chief operating officer Dr Stefan Degroote as a spin-off of nanoelectronics research center Imec of Leuven, Belgium. The founders jointly developed GaN-on-Si technology at Imec, part of which has been licensed to EpiGaN. EpiGaN was joined in 2011 by start-up investment firms Robert Bosch Venture Capital, Capricorn CleanTech Fund and LRM (to enable the installation of its wafer production facility), followed later by ACAPITAL and SPFI-FPIM.

"GaN technology is gaining significant traction in RF and power markets," notes Soitec's CEO Paul Boudre. "GaN epiwafers represent a natural strategic fit with Soitec's current portfolio of engineered substrates," he adds. "The acquisition of EpiGaN further extends and complements Soitec's portfolio beyond silicon to create new value-added process solutions for both RF 5G and power systems."

In the mobility space the co-optimization of performance, low power and cost is key, says Soitec. The arrival of 5G sub 6GHz and millimeter wave (mmW) is driving new generations of base stations compared with 4G, which in turn require more energy-efficient, higher-performing, smaller and more affordable power amplifiers (PAs). Soitec will expand its engineered substrates offering for PAs, with GaN leading the way in today's smaller, lighter, more efficient and cost-effective base-station designs, the firm adds.

"EpiGaN has developed a technology which is ready and optimized for 5G broadband network applications," says Germain. "Our technology creates the unique opportunity for Soitec's customers to quickly develop product solutions targeting new high-growth markets, such as RF devices, efficient power switching devices and sensor devices," she adds.

"The GaN technology developed by EpiGaN opens up many future opportunities and we believe Soitec is an excellent partner to further develop the full potential of EpiGaN," comments Katleen Vandersmissen, director of EpiGaN and representative of cornerstone investor LRM (Investment Company of Limburg).

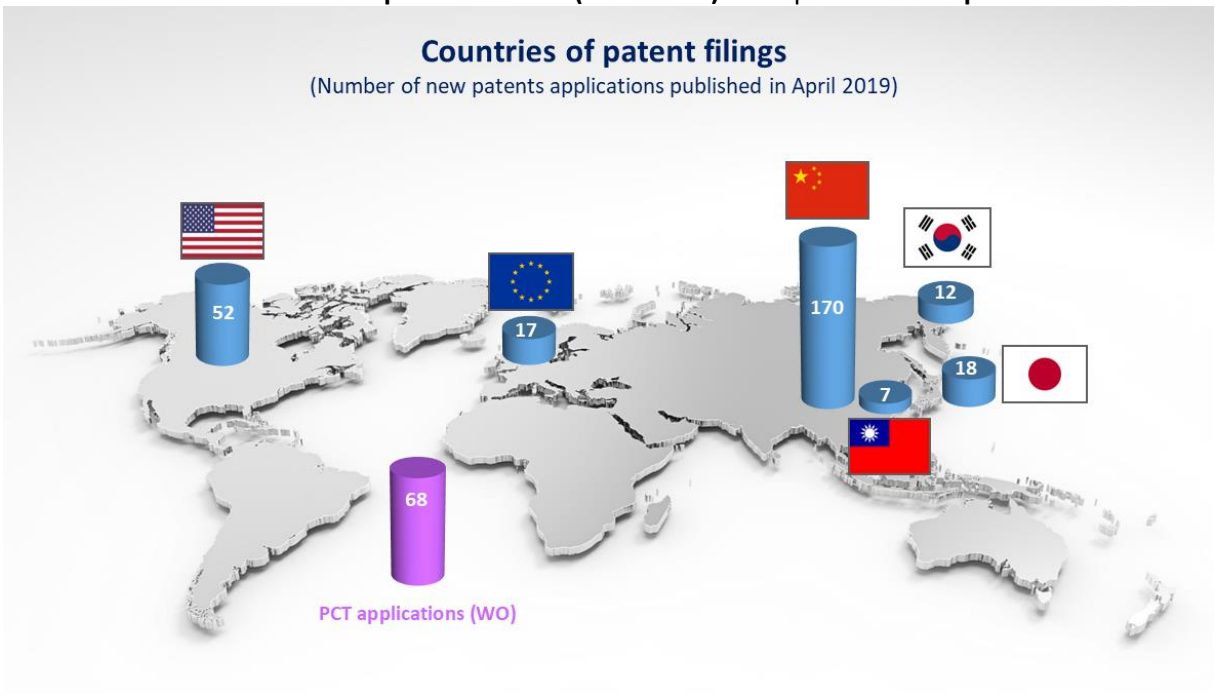
It is reckoned that, given GaN's use in power transistor designs, the EpiGaN acquisition also creates new complementary growth opportunities across Soitec's existing Power-SOI products. Both Power-SOI and GaN address the requirements for integrating high-voltage and analog functions in intelligent, energy-efficient and highly reliable power IC devices, for use in consumer electronics, data-center, automotive and industrial markets.

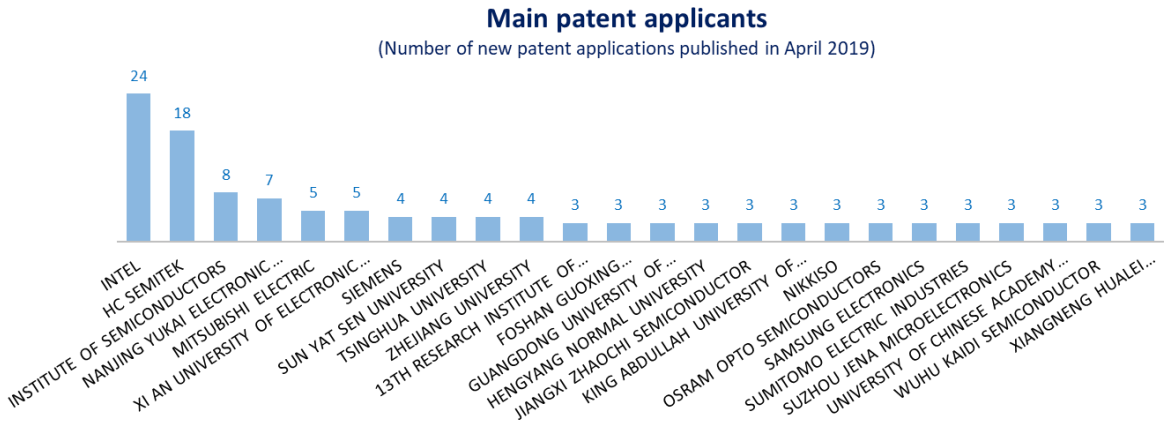
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PATENT APPLICATIONS

More than 270 **new patent families (inventions)** were published in **April 2019**.





Other patent applicants East China Normal University, Fudan University, Guangdong Deli Photoelectric, IBM, KLA, Korea Electronics & Telecommunications Research Institute, NGK Insulators, Nichia, Panasonic, Shanghai Sheng Jia Electronic Technology, South China University of Technology, Toshiba, Toyota Central Research & Development Labs, Toyota Motor, University of Science & Technology Beijing, Vanguard International Semiconductor, Wenzhou University, Xidian University, Advanced Optoelectronic Technology, Aisin Seiki, Akoustis, Basic Power, Beijing CRC Information Technology, Beijing Tianyuan Guangjian Technology R & D, Beijing University of Posts &Telecommunications, BOLB, Cambridge Enterprise, Cea - Commissariat à l'Energie Atomique et aux Energies Alternatives, Central South University, Chengdu RDW Technology, China Railway Tunnel Bureau, China Railway Tunnel Survey & Design Institute, Crystal IS, Dalian University of Technology, Dalian Xinguan Technology, Dialog Semiconductor, Electronics & Telecommunications Research Institute, Elux, Enraytek Optoelectronics, Epistar, Facebook Technology, Furukawa, Fuzhou University, Guangdong Institute of Semiconductor Industrial Technology, Guangdong Midea

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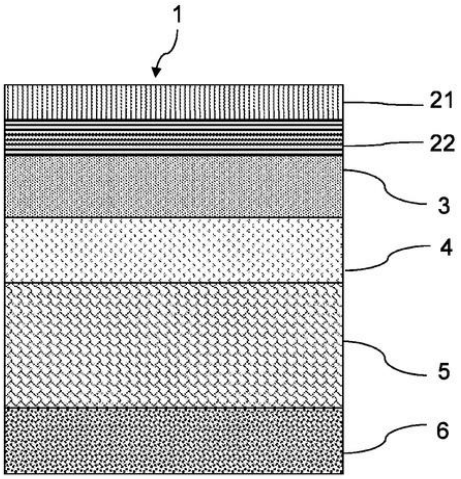
Notable new patent applications

Method for manufacturing an electronic component having a heterojunction equipped with a buried barrier layer

Publication Number: FR3071854, EP3467867, US20190109209

Patent Applicant: Cea

The invention relates to a process for manufacturing a heterojunction electronic component provided with an embedded barrier layer, the process comprising: depositing by epitaxy, in a vapour phase epitaxial growth chamber with an atmosphere exhibiting a first nonzero ammonia concentration, of a GaN precursor layer of the embedded barrier layer, comprising a first layer doped with a Mg or Fe dopant; placing, while maintaining the substrate in the chamber, the atmosphere at a second ammonia concentration at most equal to a third of the first concentration,order to remove an upper part of the precursor layer; and then after the removal of the said upper part, while maintaining the substrate in the chamber, depositing by epitaxy of a layer of semiconductor material of the heterojunction electronic component to be manufactured, the said precursor layer then forming the embedded barrier layer under the said layer of semiconductor material.

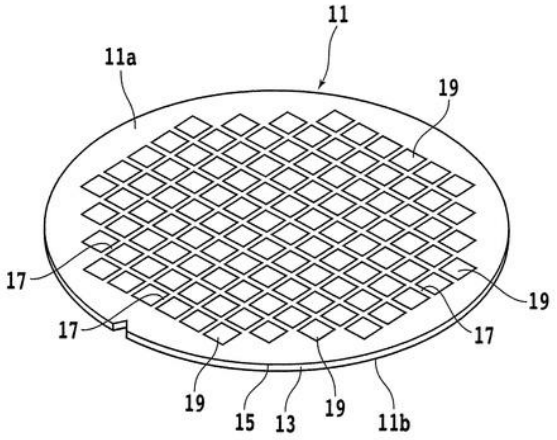


Lift-off method

Publication Number: KR10-2019-0043088, US20190115494, CN109671811, TW201916966

Patent Applicant: Disco

A lift-off method transfers onto a transfer substrate an optical device layer of an optical device wafer in which the optical device layer is formed over a front surface of an epitaxy substrate through a GaN buffer layer.The lift-off method includes: bonding the transfer substrate onto a front surface of the optical device layer through a bonding layer to form a composite substrate; applying a pulsed laser beam of such a wavelength as to be transferred through the epitaxy substrate constituting the composite substrate but to be absorbed in the buffer layer from a back surface side of the epitaxy substrate, to break the buffer layer; and peeling the optical device layer from the epitaxy substrate and transferring the optical device layer onto the transfer substrate, after the buffer layer breaking step is performed.



Semiconductor device having a planar III-N semiconductor layer and fabrication method

Publication Number: WO2019/068919

Patent Applicant: Hexagem

A semiconductor device having a planar III-N semiconductor layer, comprising a substrate comprising a wafer (101) and a buffer layer (102), of a buffer material different from a material of the wafer, the buffer layer having a growth surface (1021); an array of nano structures (1010) epitaxially grown from the growth surface; a continuous planar layer (1020) formed by coalescence of upper parts of the nano structures at an elevated temperature T, wherein the number of lattice cells spanning a center distance between adjacent nano structures are different at the growth surface and at the coalesced planar layer; a growth layer (1030), epitaxially grown on the planar layer (1020).

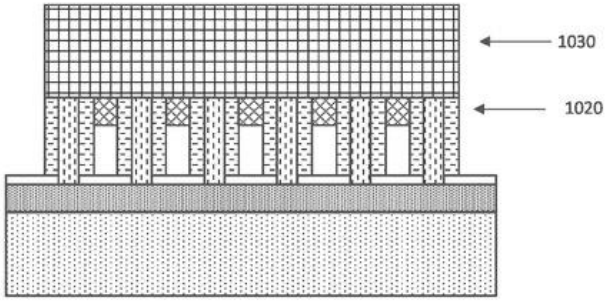


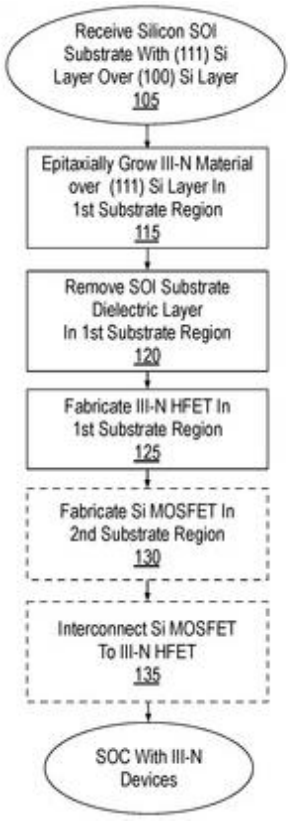
Fig. 12

Group III-nitride devices on soi substrates having a compliant layer

Publication Number: WO2019/066866

Patent Applicant: Intel

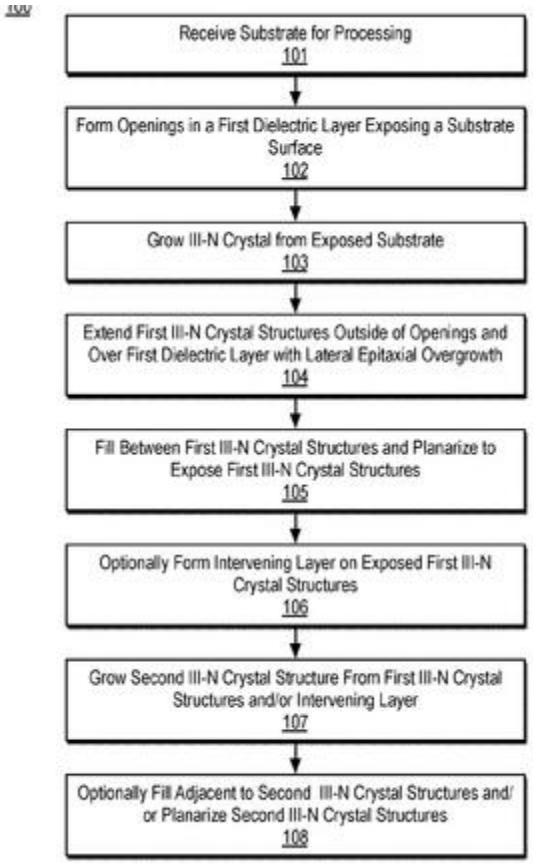
A semiconductor-on-insulator (SOI) substrate with a compliant substrate layer advantageous for seeding an epitaxial III-N semiconductor stack upon which III-N devices (e.g., III-N HFETs) may be formed. The compliant layer may be (111) silicon, for example. The SOI substrate may further include another layer that may have one or more of lower electrical resistivity, greater thickness, or a different crystal orientation relative to the compliant substrate layer. A SOI substrate may include a (100) silicon layer advantageous for integrating Group IV devices (e.g., Si FETs), for example. To reduce parasitic coupling between an HFET and a substrate layer of relatively low electrical resistivity, one or more layers of the substrate may be removed within a region below the HFETs. Once removed, the resulting void may be backfilled with another material, or the void may be sealed, for example during back-end-of-line processing.



Multi-step lateral epitaxial overgrowth for low defect density III-N films

Publication Number: WO2019/066955
Patent Applicant: Intel

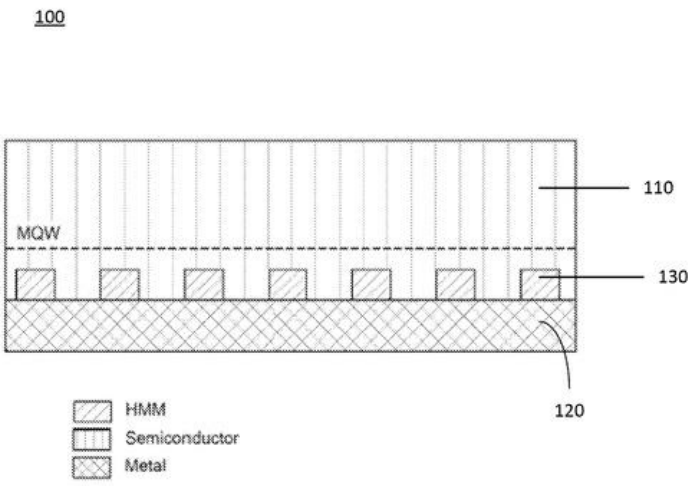
Techniques related to forming low defect density III-N films, device structures, and systems incorporating such films are discussed. Such techniques include epitaxially growing a first crystalline III-N structure within an opening of a first dielectric layer and extending onto the first dielectric layer, forming a second dielectric layer over the first dielectric layer and laterally adjacent to a portion of the first structure, and epitaxially growing a second crystalline III-N structure extending laterally onto a region of the second dielectric layer.



LED emitters with integrated nano-photonic structures to enhance EQE

Publication Number: WO2019/079257, US20190115492
Patent Applicant: Lumileds

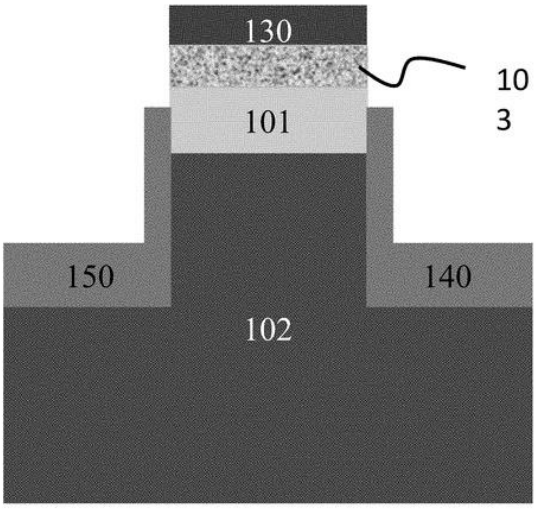
An optoelectronic device a substrate, a first doped contact layer arranged on the substrate, a multiple quantum well layer arranged on the first doped contact layer, a boron nitride alloy electron blocking layer arranged on the multiple quantum well layer, and a second doped contact layer arranged on the boron nitride alloy electron blocking layer.



High electron mobility transistor with tunable threshold voltage

Publication Number: WO2019/077781, US20190115463
Patent Applicant: Mitsubishi Electric

A high electron mobility transistor includes a set of electrodes, such as a source (110), a drain (120), a top gate (130), and a side gate (140, 150), and includes a semiconductor structure having a fin extending between the source and the drain.The top gate is arranged on top of the fin, and the side gate is arranged on a sidewall of the fin at a distance from the top gate.The semiconductor structure includes a cap layer (101) positioned beneath the top gate and a channel layer (102) arranged beneath the cap layer for providing electrical conduction.The cap layer includes nitride-based semiconductor material to enable a heterojunction forming a carrier channel between the source and the drain.



III-nitride surface-emitting laser and method of fabrication

Publication Number: WO2019/070719
Patent Applicant: University of California

A Vertical Cavity Surface Emitting Laser (VCSEL) including a light emitting III-nitride active region including quantum wells (QWs), wherein each of the quantum wells have a thickness of more than 8 nm, a cavity length of at least 7λ or at least 20 λ, where lambda is a peak wavelength of the light emitted from the active region, layers with reduced surface roughness, a tunnel junction intracavity contact. The VCSEL is flip chip bonded using In-Au bonding. This is the first report of a VCSEL capable of continuous wave operation.

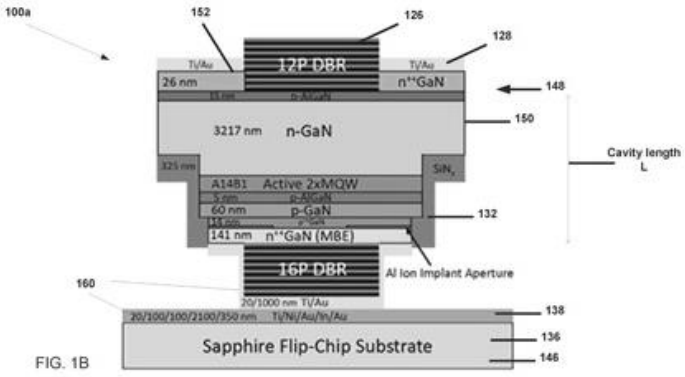


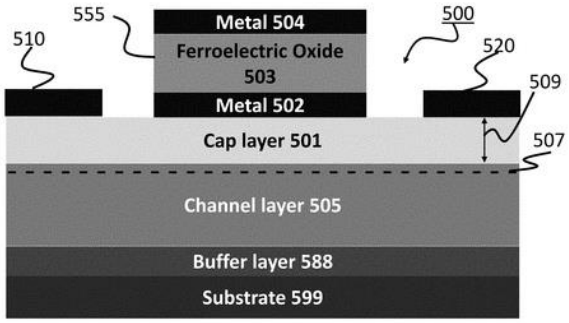
FIG. 1B

High electron mobility transistor with negative capacitor gate

Publication Number: US10276704, WO2019/077782

Patent Applicant: Mitsubishi Electric

A high electron mobility transistor (500) includes a semiconductor structure including a channel layer (505) and a cap layer (501) arranged on the channel layer to form a two dimensional electron gas (2-DEG) channel (507) at an interface of the channel layer and the cap layer, a set of electrodes including a source (510) and a drain (520) arranged on the cap layer with electrical connection to the 2- DEG channel, and a gate (555) arranged on the cap layer between the source and the drain, such that the conductivity of the 2-DEG channel is modulated in response to applying voltage to the gate.The cap layer includes III-N material.The gate has a layered structure including a bottom metal layer (502) arranged on top of the cap layer, a ferroelectric oxide (FEO) layer (503) arranged on top of the bottom metal layer, and a top metal layer (504) arranged on top of the FEO layer.The thickness of the FEO layer is less than tcap/(2□εcap), wherein□ is a parameter of material of the FEO layer, tcap is the thickness of the cap layer, and εcap is the electric permittivity of the cap layer.

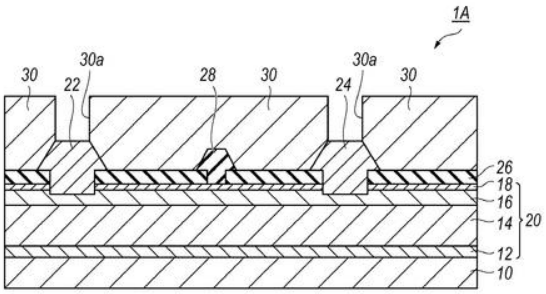


Process of forming silicon nitride film

Publication Number: JP2019067887, CN109585267, US20190103264

Patent Applicant: Sumitomo Electric Industries

A process of depositing a silicon nitride (SiN) film on a nitride semiconductor layer is disclosed.The process includes steps of: (a) loading an epitaxial substrate including the nitride semiconductor layer into a reaction furnace at a first temperature and converting an atmosphere in the furnace into nitrogen (N2); (b) raising a temperature in the furnace to a second temperature keeping a pressure in the furnace higher than 30 kPa; (c) converting the atmosphere in the furnace to ammonia (NH3) at the second temperature; and (d) beginning the deposition by supplying SiH2Cl2 as a source gas for silicon (Si) at a second pressure lower than 100 Pa.A feature of the process is that a time span from the temperature in the furnace reaches the critical temperature to the supply of SiH2Cl2 is shorter than 20 minutes, where the first pressure becomes the equilibrium pressure at the critical temperature.

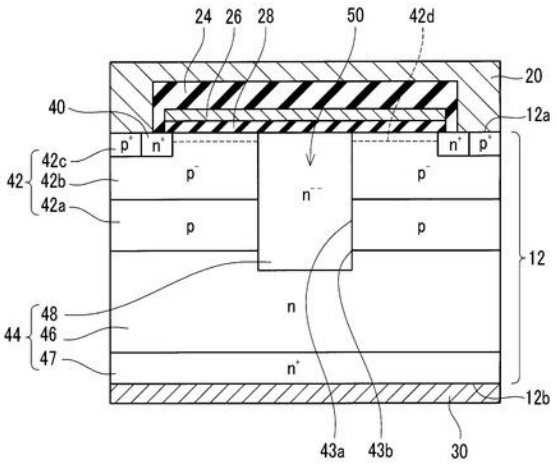


Nitride semiconductor apparatus and method of manufacturing nitride semiconductor apparatus

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Patent Applicant: Toyota Motor

A nitride semiconductor apparatus includes a nitride semiconductor layer (12), a gate insulating film (28), a source electrode (20), a drain electrode (30), and a gate electrode (26).The nitride semiconductor layer (12) includes a first body layer, a second body layer, a drift layer (44), a first source layer, and a second source layer.The drift layer (44) includes a first drift layer (46) that extends from a position in contact with a bottom surface of the first body layer to a position in contact with a bottom surface of the second body layer, and an electric field relaxation layer (48) that is in contact with a lower end portion of a side surface of the first body layer and a lower end portion of a side surface of the second body layer, is in contact with the first drift layer (46), and has a second conduction type impurity concentration lower than that of the first drift layer (46).



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