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Monolithic integration of four-colour InGaN-based nanocolumn LEDs
Kishino, K. ; Yanagihara, A. ; Ikeda, K. ; Yamano, K. Sophia University, Japan ;
Electronics Letters
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The monolithic integration of four-colour indium gallium nitride (InGaN)-based nanocolumn light-emitting diodes (LEDs) is demonstrated. In the integrated nanocolumn LED unit, blue-, sky-blue-, green- and yellow-emitting micro-LEDs (LEDs 1–4) with a 65 µm diameter circular indium tin oxide emission window were arrayed in a 2 × 2 square lattice with a lattice constant of 190 µm. LEDs 1–4 consisted of nanocolumn arrays arranged in a triangular lattice with a lattice constant of 300 nm and their nanocolumn diameters at the position of the InGaN/gallium nitride (GaN) multiple quantum wells (MQWs) were 119, 145, 188 and 231 nm, respectively. The increase in nanocolumn diameter from LED 1 to LED 4 resulted in increasing emission peak wavelengths, which were 465, 489, 510 and 570 nm for LEDs 1–4, respectively. On the same substrate, a red-emitting micro-LED was prepared, in which the nanocolumn diameter was increased to 260 nm by using a 350 nm-lattice-constant nanocolumn array. A combination of different lattice constants in an integrated LED unit is expected to contribute to the achievement of red–green–blue–yellow (RGBY)-colour-integrated nanocolumn LEDs.

Gallium Nitride Nanowires and Heterostructures: Toward Color-Tunable and White-Light Sources
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Advanced Materials
http://dx.doi.org/10.1002/adma.201500522

Gallium-nitride-based light-emitting diodes have enabled the commercialization of efficient solid-state lighting devices. Nonplanar nanomaterial architectures, such as nanowires and nanowire-based heterostructures, have the potential to significantly improve the performance of light-emitting devices through defect reduction, strain relaxation, and increased junction area. In addition, relaxation of internal strain caused by indium incorporation will facilitate pushing the emission wavelength into the red. This could eliminate inefficient phosphor conversion and enable color-tunable emission or white-light emission by combining blue, green, and red sources. Utilizing the waveguiding modes of the individual nanowires will further enhance light emission, and the properties of photonic structures formed by nanowire arrays can be implemented to improve light extraction. Recent advances in synthetic methods leading to better control over GaN and InGaN nanowire synthesis are described along with new concept devices leading to efficient white-light emission.

Cascaded GaN light-emitting diodes with hybrid tunnel junction layers
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Quantum Electronics, IEEE Journal of
http://dx.doi.org/10.1109/JQE.2015.2440757

The authors report the fabrication of cascaded GaN light-emitting diodes (LEDs) with previously reported p++-GaN/i-InGaN/n++-GaN tunnel junction layers (TJL) and with hybrid TJL. Compared with the conventional LED, it was
found that we could enhance the output power by 35% and 80% from the LED with p++-GaN/InGaN/n++-GaN TJL and the LED with hybrid TJL. It was also found that the TJ resistances were $6.05 \times 10^{-3}$ and $1.95 \times 10^{-3}$ Ω·cm² for the LED with p++-GaN/InGaN/n++-GaN TJL and the LED with hybrid TJL, respectively. It was also found that the use of hybrid TJL could result in smaller efficiency droop. These improvements could all be attributed to the larger polarization charges induced at the AlGaN/InGaN interface which could enhance the tunneling current. Furthermore, it was found that the cascaded GaN LEDs with hybrid TJL were also reliable.

**Semipolar (112−2) InGaN light-emitting diodes grown on chemically–mechanically polished GaN templates**

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Physica status solidi (a)

http://dx.doi.org/10.1002/pssa.201532350

InGaN multiple quantum well light-emitting diodes (LEDs) were grown on chemically–mechanically polished (11inlong image2) GaN templates (up to 100 mm diameter wafers) by metalorganic vapour phase epitaxy. Initial GaN overgrowth on the polished templates in nitrogen ambient maintained the polished surface. The peak emission wavelength of the LEDs varied from 445 to 550 nm. In contrast to the simultaneously grown LEDs on as-grown templates, the LEDs on polished templates have very smooth surface morphology, uniform luminescence, and higher output power.

**Suppression of metastable-phase inclusion in N-polar (0001°) InGaN/GaN multiple quantum wells grown by metalorganic vapor phase epitaxy**

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Applied Physics Letters
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The metastable zincblende (ZB) phase in N-polar (0001°) (−c-plane) InGaN/GaN multiple quantum wells (MQWs) grown by metalorganic vapor phase epitaxy is elucidated by the electron backscatter diffraction measurements. From the comparison between the −c-plane and Ga-polar (0001) (+c-plane), the −c-plane MQWs were found to be suffered from the severe ZB-phase inclusion, while ZB-inclusion is negligible in the +c-plane MQWs grown under the same growth conditions. The ZB-phase inclusion is a hurdle for fabricating the −c-plane light-emitting diodes because the islands with a triangular shape appeared on a surface in the ZB-phase domains. To improve the purity of stable wurtzite (WZ)-phase, the optimum conditions were investigated. The ZB-phase is dramatically eliminated with decreasing the V/III ratio and increasing the growth temperature. To obtain much-higher-quality MQWs, the thinner InGaN wells and the hydrogen introduction during GaN barriers growth were tried. Consequently, MQWs with almost pure WZ phase and with atomically smooth surface have been demonstrated.

**Realization of high-luminous-efficiency InGaN light-emitting diodes in the “green gap” range**

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Key Laboratory for Renewable Energy, Beijing Key Laboratory for New Energy Materials and Devices, Beijing National Laboratory for Condensed Matter
Light-emitting diodes (LEDs) in the wavelength region of 535–570 nm are still inefficient, which is known as the “green gap” problem. Light in this range causes maximum luminous sensation in the human eye and is therefore advantageous for many potential uses. Here, we demonstrate a high-brightness InGaN LED with a normal voltage in the “green gap” range based on hybrid multi-quantum wells (MQWs). A yellow-green LED device is successfully fabricated and has a dominant wavelength, light output power, luminous efficiency and forward voltage of 560 nm, 2.14 mW, 19.58 lm/W and 3.39 V, respectively. To investigate the light emitting mechanism, a comparative analysis of the hybrid MQW LED and a conventional LED is conducted. The results show a 2.4-fold enhancement of the 540-nm light output power at a 20-mA injection current by the new structure due to the stronger localization effect, and such enhancement becomes larger at longer wavelengths. Our experimental data suggest that the hybrid MQW structure can effectively push the efficient InGaN LED emission toward longer wavelengths, connecting to the lower limit of the AlGaInP LEDs’ spectral range, thus enabling completion of the LED product line covering the entire visible spectrum with sufficient luminous efficacy.

Red to blue wavelength emission of N-polar $(000\bar{1})$–(−c-plane) InGaN light-emitting diodes grown by metalorganic vapor phase epitaxy

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Applied Physics Express
Vol. 8; 061005
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Progress in research of GaN-based LEDs fabricated on SiC substrate

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Chinese Physics B
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The influence of buffer layer growth conditions on the crystal quality and residual stress of GaN film grown on silicon carbide substrate is investigated. It is found that the AlGaN nucleation layer with high growth temperature can efficiently decrease the dislocation density and stress of the GaN film compared with AlN buffer layer. To increase the light extraction efficiency of GaN-based LEDs on SiC substrate, flip-chip structure and thin film flip-chip structure were designed and optimized. The fabricated blue LED had a maximum wall-plug efficiency of 72% at 80 mA. At 350 mA, the output power, the Vf, the dominant wavelength, and the wall-plug efficiency of the blue LED were 644 mW, 2.95 V, 460 nm, and 63%, respectively.
Increased p-type conductivity through use of an indium surfactant in the growth of Mg-doped GaN
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Applied Physics Letters
Vol. 106, 221103 (2015);
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We have examined the effect of an indium surfactant on the growth of p-type GaN by ammonia-based molecular beam epitaxy. p-type GaN was grown at temperatures ranging from 700 to 780 °C with and without an indium surfactant. The Mg concentration in all films in this study was 4.5–6 × 1019 cm–3 as measured by secondary ion mass spectroscopy. All p-type GaN films grown with an indium surfactant had higher p-type conductivities and higher hole concentrations than similar films grown without an indium surfactant. The lowest p-type GaN room temperature resistivity was 0.59 Ω-cm, and the highest room temperature carrier concentration was 1.6 × 1018 cm–3. Fits of the temperature-dependent carrier concentration data showed a one to two order of magnitude lower unintentional compensating defect concentration in samples grown with the indium surfactant. Samples grown at higher temperature had a lower active acceptor concentration. Improvements in band-edge luminescence were seen by cathodoluminescence for samples grown with the indium surfactant, confirming the trends seen in the Hall data.

High Brightness, Large Scale GaN Based Light-Emitting Diode Grown on 8-Inch Si Substrate
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ECS Journal of Solid State Science & Technology
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A crack-free, uniform InGaN/GaN light-emitting diode (LED) structure with strain-engineered buffer layer was grown on an 8-inch diameter Si(111) substrate. The full width at half maximum (FWHM) of (002) and (102) ω-scan is 280 and 420 arcsec, respectively. For LED on 8-inch Si, multiple quantum well (MQW) photoluminescence (PL) wavelength uniformity of 0.55% (2.4 nm) has been achieved by using proper curvature engineered wafer carrier. We demonstrated high brightness 1×1 mm2 LED devices utilizing vertical chip process then evaluated their device properties. The electro-optical characteristics of the fabricated vertical LED (VLED) shows around 1 W light output power at 1 A injection current with operating voltage of 4.0 V.

Epitaxial growth of group III-nitride films by pulsed laser deposition and their use in the development of LED devices
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Surface Science Reports
Volume 70, Issue 3, November 2015, Pages 380–423
http://dx.doi.org/10.1016/j.surfrep.2015.06.001

Recently, pulsed laser deposition (PLD) technology makes viable the epitaxial growth of group III-nitrides on thermally active substrates at low temperature. The precursors generated from the pulsed laser ablating the target has enough kinetic energy when arriving at substrates, thereby effectively suppressing the interfacial reactions between the epitaxial films and the substrates, and eventually makes the film growth at low temperature possible. So far, high-quality group III-nitride epitaxial films have been successfully grown on a variety of thermally active substrates...
by PLD. By combining PLD with other technologies such as laser rastering technique, molecular beam epitaxy (MBE), and metal-organic chemical vapor deposition (MOCVD), III-nitride-based light-emitting diode (LED) structures have been realized on different thermally active substrates, with high-performance LED devices being demonstrated. This review focuses on the epitaxial growth of group III-nitrides on thermally active substrates by PLD and their use in the development of LED devices. The surface morphology, interfacial property between film and substrate, and crystalline quality of as-grown group III-nitride films by PLD, are systematically reviewed. The corresponding solutions for film homogeneity on large size substrates, defect control, and InGaN films growth by PLD are also discussed in depth, together with introductions to some newly developed technologies for PLD in order to realize LED structures, which provides great opportunities for commercialization of LEDs on thermally active substrates.

Visible Light-Emitting Diodes With Thin-Film-Flip-Chip-Based Wafer-Level Chip-Scale Package Technology Using Anisotropic Conductive Film Bonding

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Electron Device Letters, IEEE
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Demonstrated is advanced device and packaging architecture of visible GaN-based light-emitting diodes (LEDs) combining thin-film flip-chip devices and wafer-level chip-scale package with through-silicon-via (TSV) and wafer-to-wafer alignment bonding. In addition, a new interconnect technique for LEDs is introduced using an anisotropic conductive film with metal balls. Thermal rollover in light output versus current characteristics is not observed up to 700 mA. A forward voltage at 350 mA is 3.06 V. The architecture can facilitate excellent heat removal through a TSV-formed Si wafer in addition to expected benefits of easy integration of Si-based devices in lighting modules. Light-output power at 350 mA increases by 11.1% compared with that of conventional flip-chip LEDs. A Lambertian-like emission pattern is also achieved.

High efficiency, full-color AlInGaN quaternary nanowire light emitting diodes with spontaneous core-shell structures on Si

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Applied Physics Letters
Vol. 106, 261104 (2015);
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We have developed AlInGaN quaternary core-shell nanowire heterostructures on Si substrate, wherein an In-rich core and an Al-rich shell were spontaneously formed during the epitaxial growth process. By varying the growth conditions, the emission wavelengths can be tuned from ∼430 nm to ∼630 nm. Such core-shell structures can largely suppress nonradiative surface recombination, leading to a significant enhancement of carrier lifetime from ∼0.2 ns to ∼2 ns. The resulting nanowire light emitting diodes can exhibit an output power exceeding 30 mW for a ∼1 × 1 mm2 non-packaged device at a current density of 100 A/cm2.
Deep traps in GaN-based structures as affecting the performance of GaN devices
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New developments in theoretical studies of defects and impurities in III-Nitrides as pertinent to compensation and recombination in these materials are discussed. New results on experimental studies on defect states of Si, O, Mg, C, Fe in GaN, InGaN, and AlGaN are surveyed. Deep electron and hole traps data reported for GaN and AlGaN are critically assessed. The role of deep defects in trapping in AlGaN/GaN, InAlN/GaN structures and transistors and in degradation of transistor parameters during electrical stress tests and after irradiation is discussed. The recent data on deep traps influence on luminescent efficiency and degradation of characteristics of III-Nitride light emitting devices and laser diodes are reviewed.

Room-temperature continuous-wave operation of GaN-based vertical-cavity surface-emitting lasers fabricated using epitaxial lateral overgrowth
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We have successfully demonstrated the room-temperature continuous-wave operation of GaN-based vertical-cavity surface-emitting lasers (VCSELs) with all-dielectric reflectors, which were fabricated using epitaxial lateral overgrowth. The VCSELs exhibited a threshold current of 8 mA and a threshold voltage of 4.5 V at a lasing wavelength of 446 nm. The maximum output power was 0.9 mW for an 8-μm-diameter current aperture, which was made possible because of the high thermal conductivity of the GaN substrate.

Strain dependence on polarization properties of AlGaN and AlGaN-based ultraviolet lasers grown on AlN substrates
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Since the band ordering in AlGaN has a profound effect on the performance of UVC light emitting diodes (LEDs) and even determines the feasibility of surface emitting lasers, the polarization properties of emitted light from c-oriented AlGaN and AlGaN-based laser structures were studied over the whole composition range, as well as various strain states, quantum confinements, and carrier densities. A quantitative relationship between the theoretical valence band separation, determined using k•p theory, and the experimentally measured degree of polarization is presented. Next to composition, strain was found to have the largest influence on the degree of polarization while all other factors were practically insignificant. The lowest crossover point from the transverse electric to transverse...
magnetic polarized emission of 245 nm was found for structures pseudomorphically grown on AlN substrates. This finding has significant implications toward the efficiency and feasibility of surface emitting devices below this wavelength.

4 Gbps direct modulation of 450 nm GaN laser for high-speed visible light communication
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Optics Express
http://dx.doi.org/10.1364/OE.23.016232

We demonstrate high-speed data transmission with a commercial high power GaN laser diode at 450 nm. 2.6 GHz bandwidth was achieved at an injection current of 500 mA using a high-speed visible light communication setup. Record high 4 Gbps free-space data transmission rate was achieved at room temperature.

Ultra-low threshold gallium nitride photonic crystal nanobeam laser
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We report exceptionally low thresholds (9.1 μJ/cm2) for room temperature lasing at ~450 nm in optically pumped Gallium Nitride (GaN) nanobeam cavity structures. The nanobeam cavity geometry provides high theoretical Q (>100 000) with small modal volume, leading to a high spontaneous emission factor, β = 0.94. The active layer materials are Indium Gallium Nitride (InGaN) fragmented quantum wells (fQWs), a critical factor in achieving the low thresholds, which are an order-of-magnitude lower than obtainable with continuous QW active layers. We suggest that the extra confinement of photo-generated carriers for fQWs (compared to QWs) is responsible for the excellent performance.

Kinetics of catastrophic optical damage in GaN-based diode lasers
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Semiconductor Science & Technology
Vol. 30; 072001
http://dx.doi.org/10.1088/0268-1242/30/7/072001

Catastrophic optical damage (COD) in 450 nm emitting InGaN/GaN diode lasers is artificially provoked by applying single sub-microsecond current pulses of increasing amplitude. Studying a batch of devices in which COD does not represent the main degradation mode, we find that COD is a 'hot' process. It becomes re-ignited in subsequent pulses. During the process, the spatial filamentation changes abruptly and the outer appearance of the damage pattern is predominantly created within the initial pulse. The process can cause material ejection out of the front facet as shown by thermography.

Lasing characteristics of GaN-based photonic quasicrystal surface emitting lasers operated at higher order Γ mode
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Selected Topics in Quantum Electronics, IEEE Journal of
http://dx.doi.org/10.1109/JSTQE.2015.2443979
In this study, GaN-based photonic quasicrystal surface emitting lasers (PQCSELs) operated at different band-edge modes were fabricated and investigated. The photonic quasicrystal patterns were defined by utilizing electron-beam lithography and inductively coupled plasma etching. Distinctive higher order band-edge lasing modes were identified in the GaN PQCSELs. The threshold energy density and lasing wavelength for the S3 band-edge mode were 4.6 mJ/cm² and 394.2 nm, respectively. The decreasing tendency of threshold energy of PQCSEL was observed while the designed lasing mode moved from the higher band to the lower band. Numerical results showed that the S3 mode had the lower threshold and the threshold gain would be largely varied by tuning the ratio of air hole radius/lattice constant (r/a). Based on calculations and experiments, PQCSELs show the opportunity to realize lower threshold lasers than typical PC laser for specific value of r/a and appropriate higher order band-edge modes.

Ultrafast dynamics of lasing semiconductor nanowires
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Nano Letters
http://dx.doi.org/10.1021/acs.nanolett.5b01271

Semiconductor nanowire lasers operate at ultrafast timescales; here we report their temporal dynamics, including laser onset time and pulse width, using a double-pump approach. Wide bandgap gallium nitride (GaN), zinc oxide (ZnO) and cadmium sulfide (CdS) nanowires reveal laser onset times of a few picoseconds, driven by carrier thermalization within the optically excited semiconductor. Strong carrier-phonon coupling in ZnO leads to the fastest laser onset time of ~ 1 ps in comparison to CdS and GaN exhibiting values of ~ 2.5 ps and ~ 3.5 ps, respectively. These values are constant between nanowires of different sizes implying independence from any optical influences. However, we demonstrate that the lasing onset times vary with excitation wavelength relative to the semiconductor band gap. Meanwhile, the laser pulse widths are dependent on the optical system. While the fastest ultrashort pulses are attained using the thinnest possible nanowires, a sudden change in pulse width from ~ 5 ps to ~ 15 ps occurs at a critical nanowire diameter. We attribute this to the transition from single to multimode waveguiding, as it is accompanied by a change in laser polarization.
Vacuum ultraviolet (VUV) and vapor-combined surface modification for hybrid bonding at low temperature and atmospheric pressure
Shigetou, Akitsu Mizuno, Jun; Shoji, Shuichi
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Electronic Packaging and iMAPS All Asia Conference (ICEP-IACC), 2015 International Conference on http://dx.doi.org/10.1109/ICEP-IAAC.2015.7111030

High feasibility of the vacuum ultraviolet (VUV) and vapor-combined surface modification method was demonstrated at the temperatures lower than 200 °C and atmospheric pressure, for the power/green electronic materials such as SiC (Si-related semiconductors), and GaN. Hybrid bonding of these materials will be of practical use in obtaining high reliability and performance in thin power devices. The water vapor, which was included in VUV irradiation atmosphere (N2) at the tuned amount of exposure (g/(m3)s), helped generate hydrogen and hydroxyl radicals, then resulted in the elimination of surface contaminant, partial deoxidization of native oxide, and the formation of hydrate bridging layers at the same time. According to the change in the generation ratio of bridging layers, the exposure of 3 – 4 × 103 (g/(m3)s) was chosen as a possible process window. Upon heating at 150 – 200 °C, the hydrogen bonds, which were followed by the dehydration inside the bridging layers, formed tight adhesion between the surfaces. Although the bond area was limited due to the partial contact at the touchdown, the interface did not contain readily visible voids.

Low leakage current AlGaN/GaN on Si-based Schottky barrier diode with bonding-pad electrode mesa etching
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Bonding-pad electrode-area-etched AlGaN/GaN on a Si-based Schottky barrier diode (SBD) is fabricated. Electrode mesa etching leads to reverse bias leakage current about one order of magnitude lower than that of SBD without electrode mesa etching, but forward currents do not vary greatly, compared with that in
conventional SBD, which has no electrode mesa etching.

High Reverse Blocking and Low Onset Voltage AlGaN/GaN-on-Si Lateral Power Diode With MIS-Gated Hybrid Anode
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An AlGaN/GaN-on-Si lateral power diode with recessed metal/Al2O3/III-nitride (MIS)-gated ohmic anode for improved forward conduction and reverse blocking has been realized. The low onset voltage of $\sim$0.6 V with good uniformity for the fabricated 189 devices is obtained. In comparison with the conventional Schottky diode the specific ON-resistance ($R_{\text{ON}}$) was reduced by 51% in a device with anode-to-cathode spacing ($L_{\text{SC}}$) of 5 $\mu$m. The incorporation of high-k dielectric in the recessed gate region enabling two-order lower reverse leakage comparing with the conventional device, leading to a high breakdown voltage over 1.1 kV at leakage current as low as 10 $\mu$A/mm in device with $L_{\text{SC}}=20$ $\mu$m. The strong reverse blocking over 600 V was still achieved at 150 $^\circ$C. The proposed diode is compatible with GaN normally activated ($\text{OFF}$) MIS high-electron-mobility transistors, revealing its potential for highly efficient GaN-on-Si power ICs.

Effective interface trap characterization approaches are indispensable in the development of gate stack and dielectric surface passivation technologies in III-nitride (III-N) insulated-gate power switching transistors for enhanced stability and dynamic performance. In III-N metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) that feature a buried channel, the polarized barrier layer separates the critical dielectric/III-N interface from the two-dimensional electron gas (2DEG) channel and consequently complicates interface trap analysis. The barrier layer not only causes underestimation/uncertainty in interface trap extraction using conventional ac-conductance method but also allows the Fermi level dipping deep into the bandgap at the pinch-off of the 2DEG channel. To address these issues, we analyze the frequency/temperature dispersions of the second slope in capacitance-voltage characteristics and develop systematic ac-capacitance techniques to realize interface trap mapping in MIS-HEMTs. The correlation between ac-capacitance and pulse-mode hysteresis measurements show that appropriate gate bias need to be selected in the interface trap characterization of MIS-HEMTs, in order to match the time constant of interface traps at the Fermi level with ac frequency and pulsewidth.

The advancement of gallium nitride (GaN) power switches brings with it a multitude of performance benefits while also providing many challenges. While GaN switches may be very close to the mainstream, our ability to perform the high-fidelity measurements necessary for characterizing, troubleshooting, and optimizing their implementation is considerably lagging.

AC-Capacitance Techniques for Interface Trap Analysis in GaN-Based Buried-Channel MIS-HEMTs
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Electron Devices, IEEE Transactions on
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Faster-Switching GaN : Presenting a number of interesting measurement challenges
Sandler, S.;
Picotest.com

Power Electronics Magazine, IEEE
Volume:2 , Issue: 2 , Page(s):24 - 31 ISSN :2329-9207
http://dx.doi.org/10.1109/MPEL.2015.2420232
Improving the off-state characteristics and dynamic on-resistance of AlInN/AIN/GaN HEMTs with a GaN cap layer
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Applied Physics Express
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The electrical characteristics of a series of AlInN high-electron-mobility transistors (HEMTs) with a GaN cap layer ranging from 0 to 26 nm are investigated for power switching applications. The breakdown voltage (VB), mobility of two-dimensional electron gas, on-state resistance (Ron), and dynamic Ron of the HEMTs are improved by increasing the cap layer thickness. The improved electrical characteristics are attributed to the GaN cap layer, which not only reduces the surface E-field but also raises the conduction band of the barrier layer and effectively prevents electrons from being trapped in the AlInN barrier and above.

Characterization of SiNx/AIN passivation stack with epitaxial AIN grown on AlGaN/GaN heterojunctions by plasma-enhanced atomic layer deposition
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A SiNx/AIN dielectric stack, which has been shown to provide a practical, robust, and effective passivation for GaN-based lateral heterojunction power switching devices, was characterized in this work to provide insights on the mechanisms of its current collapse suppression ability. The interface between the SiNx/AIN passivation stack and the AlGaN/GaN structure was characterized by investigating the interface state distribution and its chemical composition. Such interface was found to have much less trap states and significantly less oxidation than that in the heterostructure passivated by an Al2O3/AIN stack, validating that SiNx/AIN passivation is superior to Al2O3/AIN passivation.

Fabrication of vertical Schottky barrier diodes on n-type freestanding AIN substrates grown by hydride vapor phase epitaxy
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Applied Physics Express
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Thick Si-doped AIN layers were homoepitaxially grown by hydride vapor phase epitaxy on AIN(0001) seed substrates. Following the removal of the seed substrate, an n-type AIN substrate with a carrier concentration of 2.4 x 1014 cm−3 was obtained. Vertical Schottky barrier diodes were fabricated by depositing Ni/Au Schottky contacts on the N-polar surface of the substrate. High rectification with a turn-on voltage of approximately 2.2 V was observed. The ideality factor of the diode at room temperature was estimated to be ~8. The reverse breakdown voltage, defined as the leakage current level of 10−3 A/cm2, ranged from 550 to 770 V.
**GaN-based multi-two-dimensional-electron-gas-channel diodes on sapphire substrates with breakdown voltage of over 3 kV**

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We investigated the achievability of low specific on-resistance and high breakdown voltage by GaN diodes consisting of three, five, and eight two-dimensional-electron-gas (2DEG) channels. The anode Schottky electrode and cathode Ohmic electrode were formed on each side wall of the multi-2DEG-channel and the n-type region was formed by Si-ion implantation in the cathode electrode-formation area of each multi-2DEG-channel. With increasing number of 2DEG channels of the diodes, specific on-resistance (RonA) showed a tendency to decrease; RonA of eight-2DEG-channel diodes was as low as 12.1 mΩ cm2. The breakdown voltage of all the fabricated diodes exceeded 3 kV. Although the electrical characteristics of the multi-2DEG-channel diodes fabricated on sapphire substrates were demonstrated, the number of cracks appearing on the epitaxial layer surface was found to increase with increasing number of 2DEG channels. Such crack formation was concluded to govern the practical limit for the number of 2DEG channels.

**Normally-off AlGaN/GaN high-electron-mobility transistor using digital etching technique**

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*Japanese Journal of Applied Physics Vol. 54; 06FG04* [http://dx.doi.org/10.7567/JJAP.54.06FG04](http://dx.doi.org/10.7567/JJAP.54.06FG04)

A normally-off AlGaN/GaN high-electron-mobility transistor (HEMT) with a recessed-gate structure fabricated by novel digital etching is reported. Digital etching consists of multiple cycles of oxidation and wet etching of the oxide, and has the merits of easy control of the recess depth and reduction of surface damage in comparison with conventional dry etching. However, in conventional digital etching, the oxidation process involves the possibility of undercutting. In the digital etching, a reactive ion etcher was used and recess etching without any undercut was confirmed. Normally-off operation and the improvement of transconductance were confirmed in an AlGaN/GaN HEMT fabricated by this technique.

**Mechanical design and analysis of direct plated copper film on AlN substrates for thermal reliability in high power module applications**


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For the high-power module applications, direct-plated-copper (DPC) aluminum nitride (AlN) substrate with a high thermal conductivity provide a good alternative to conventional aluminum oxide (Al2O3) substrate for better heat dissipation. However, the DPC AlN substrate suffers the delamination failures between Cu film and AlN substrate during thermal cycling, due to the higher thermal expansion coefficient mismatch with copper material. This study is to resolve the delamination problem of DPC AlN substrate during thermal cycling and further to provide important parameters for mechanical design for ensuring good thermal reliability. Prior to the analysis, the out-of-plane deformation measurement of a Cu-AlN bi-material plate subject to the solder reflow heating and cooling is conducted for evaluating the material property of the plated Cu film and residual stresses induced from the manufacturing and solder reflow process. The results show the hysteresis and Bauschinger-like behaviors for the Cu-AlN plate during the solder reflow heating and cooling. It is also found from finite element simulation that the
Cu-film wedge angle and thickness significantly affect the maximum principal stress of AlN during thermal cyclic loading, and the predicted failure mode based on the maximum principal stress is consistent with experimental observation. The other factors, such as single-side and double-side Cu-film (sandwich-structure-alike) substrates and length difference of Cu film, will be presented and discussed as well.

The influence of high-k passivation layer on breakdown voltage of Schottky AlGaN/GaN HEMTs
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Microelectronics Journal
http://dx.doi.org/10.1016/j.mejo.2015.04.006

In this work, analysis and optimization of different high-k material in the passivation layer is carried out to improve the breakdown voltage in a Schottky based AlGaN/GaN High Electron Mobility Transistor (HEMT). The enhancement in Off-state breakdown voltage is observed for different high-k dielectric in the passivation layer. The device with Lgd of 1.5 µm and with high-k passivation layer provides a higher Off-state breakdown voltage. A maximum of 380 V is obtained as the Off-state breakdown for high-k (~HfO2) passivation layer and the obtained result is validated using experimental data. The improved drain current and transconductance for the device obtained is 0.51 A/mm and 143 mS/mm respectively. These results show that the Schottky Source Drain contact (SSD) high-k passivated AlGaN/GaN device is suitable for high power application.

650-V GaN-based MIS-HEMTs using LPCVD-SiNx as passivation and gate dielectric
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In this work, silicon nitride (SiNx) film deposited at 780 °C by low pressure chemical vapor deposition (LPCVD) was employed as the passivation layer and gate dielectric for GaN-based MIS-HEMTs. The LPCVD-SiNx/AlGaN/GaN MIS-HEMTs exhibit suppressed current collapse, small gate leakage current at both reverse and forward gate bias, high forward gate breakdown voltage and high time dependent gate dielectric reliability.

GaN transistors — Giving new life to Moore's Law
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Power Semiconductor Devices & IC’s (ISPSD), 2015 IEEE 27th International Symposium on
http://dx.doi.org/10.1109/ISPSD.2015.7123375

Enhancement-mode gallium nitride transistors have been commercially available for over five years and have infiltrated many applications previously monopolized by the aging silicon power MOSFET. In this paper, we discuss the state-of-the-art and the expected progress of GaN technology over the next few years, showing that Moore's Law is alive and well in the world of power semiconductor technology. We begin by enumerating the advantages of GaN over silicon in terms of performance, cost, and reliability.
Current-collapse-free operations up to 850 V by GaN-GiT utilizing hole injection from drain

Over 1.1 kV breakdown low turn-on voltage GaN-on-Si power diode with MIS-Gated hybrid anode

Quasi-normally-off GaN gate driver for high slew-rate d-mode GaN-on-Si HEMTs

An AlGaN/GaN lateral power diode on Si substrate with recessed Metal/Al2O3/III-Nitride (MIS) Gated hybrid anode (MG-HAD) for improved forward conduction and reverse blocking has been realized. The low turn-on voltage of 0.6 V with good uniformity for the fabricated 189 devices is obtained. In comparison with the conventional device, the forward current at 2 V was increased by 5 times that leading to a 51% reduction in specific ON-resistance (RON, SP). The incorporation of high-k dielectric in the recessed gate region enabling 2-order lower reverse leakage comparing with the conventional device, leading to a high breakdown voltage over 1.1 kV at leakage current as low as 10 μA/mm in the MG-HAD with anode-to-cathode distance (LD) of 20 μm. The strong reverse blocking over 600 V was still achieved at 150 °C. The proposed diode is compatible with GaN normally-off MIS high-electron-mobility transistors (MISHEMTs), revealing its great potential for highly efficient GaN-on-Si power ICs.
GaN-based monolithic power integrated circuit technology with wide operating temperature on polarization-junction platform

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Polarization junction platforms have high-density 2D hole gas (2DHG) and 2D electron gas (2DEG) respectively induced by negative and positive polarization charges in undoped GaN/AlGaN/GaN double heterostructures. Sheet resistance measurements in a wide temperature range (6–460 K) revealed that 2DHG and 2DEG resistances were monotonically enhanced with the temperature reduction. On the platform, monolithic operations of GaN-based devices including high-voltage n-channel (N-ch) transistors, N-ch Schottky diodes, low-voltage N-ch transistors and p-channel transistors has been demonstrated.

A modeling and experimental method for accurate thermal analysis of AlGaN/GaN powerbars

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In this work we present a novel and comprehensive method for thermal characterization of GaN based transistors. By means of two coupled simulations (TCAD and FEM) a detailed insight into the device physics has been provided whereas an experimental method (low-RF drain conductance measurement) is recognized as a simple and accurate method for a full transient analysis of the transistors. The method (modeling and experiments) has been performed on several different GaN based transistors where a good agreement between the simulations and experiments is obtained.

Impact of the backside potential on the current collapse of GaN SBDs and HEMTs

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This paper shows both experimentally and in simulation that the amount of current collapse for GaN SBDs and HEMTs strongly depends on the node to which the backside is connected, i.e., how the device is packaged, and the underlying physics is explained. It is shown that the difference in current collapse is not due to a difference in charge trapping. The reduction in current collapse for a backside-to-anode/source connection is due to a compensating switching charge that is not present when the backside is connected to the cathode/drain, for which stronger current collapse is observed.

Numerical study of GaN-on-Si HEMT breakdown instability accounting for substrate and packaging interactions

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The electron and hole impact-ionization coefficients in AlxGa1-xN have been calibrated through a Chynoweth law by using a Monte Carlo theoretical study and experimental data at different ambient temperatures. The model has been used to investigate the breakdown characteristics in AlGaN/GaN HEMTs. The concurrent effect of charge trapping in the GaN buffer and impact-ionization generation in the device failure mechanism has been studied by simulating the off-state breakdown under a dc stress. The sensitivity of the AlGaN/GaN HEMT to
parasitic charging in molding compound has been investigated by incorporating the passivation and encapsulation layers in the TCAD setup and implementing the conductivity losses in the mold compound at high temperature.

**Normally-off GaN MIS-HEMT with improved thermal stability in DC and dynamic performance**

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http://dx.doi.org/10.1109/ISPSD.2015.7123427

We report normally-off Al2O3/AlGaN/GaN metal-isolator-semiconductor high-electron-mobility transistor (MIS-HEMT) with improved thermal stability in DC and dynamic performance. The MIS-HEMTs featuring a partially recessed (Al)GaN barrier were realized by a fluorine-plasma implantation/etch technique. Both the well-controlled slow dry etching for gate recess and implanting fluorine ions into the AlGaN barrier are carried out with CF4 plasma at a relative high RF driving power. The partially recessed barrier leads to improved thermal stability, while the fluorine implantation can convert the device from depletion-mode to enhancement-mode without completely removing the barrier and sacrificing the high mobility heterojunction channel. From room temperature to 200 °C, the device exhibits improved thermal stability with a small negative shift of VTH (~0.5 V) that is attributed to the high-quality dielectric/F-implanted-(Al)GaN interface and the partially recessed barrier.

**Enhancement-mode GaN-on-Si MOS-FET using Au-free Si process and its operation in PFC system with high-efficiency**

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http://dx.doi.org/10.1109/ISPSD.2015.7123426

We have developed an enhancement-mode GaN-on-Si MOS-FET with a thin GaN channel (40nm) on a thick AlGaN back barrier layer (1um), using Au-free 150-mm Si process. The developed device showed a threshold voltage Vt of 1.1 V, an on-resistance Ron of 5.4 mΩcm2 and a breakdown voltage BV of 730 V. The developed E-mode GaN MOS-FETs demonstrated the potential for compact and efficient power electronics. A Power Factor Correction (PFC) circuit using the packaged GaN device (20A, 650V) operated with high efficiency of > 94 % at Pout=300 W, Vout=390 V and fSW=300 kHz.

**Enhancement-mode GaN-on-Silicon MOS-HEMT using pure wet etch technique**

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http://dx.doi.org/10.1109/ISPSD.2015.7123432

This paper reports for the first time a gate-recessed GaN-on-Silicon MOS-HEMT device with true normally-off operation and high breakdown voltage using a one step simultaneous oxidation/dissolving treatment by hybrid alkaline solution with hydrogen peroxide and potassium hydroxide. After 40-min wet etching at 95 °C solution temperature, the Al2O3/GaN MOS-HEMT device features a truenormally-off operation with a threshold voltage of 3 V, extracted by the linear extrapolation of the transfer curve. Combined with the three-terminal off-state breakdown voltage up to 1492 V for the device with 28 μm gate-to-drain distance, this technique manifests an easy, stable and low cost approach for the commercialization of normally-off GaN power devices.
Integrated reverse-diodes for GaN-HEMT structures
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Power Semiconductor Devices & IC’s (ISPSD), 2015 IEEE 27th International Symposium on http://dx.doi.org/10.1109/ISPSD.2015.7123385

This work introduces an enhanced GaN-HEMT structure that uses separated Schottky contacts as integrated free-wheeling diodes for the reverse operation. The principle is investigated and compared to other integrated reverse-diode concepts. Different diode structures are fabricated and evaluated. The new concept is demonstrated on a large gate width 600 V-device with on-state currents up to 30 A and an on-state resistance of 215 mΩ. Furthermore, the device achieves a very low gate-charge of below 3 nC and a reverse recovery charge of 8 nC.

A GaN HEMT driver IC with programmable slew rate and monolithic negative gate-drive supply and digital current-mode control
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Power Semiconductor Devices & IC’s (ISPSD), 2015 IEEE 27th International Symposium on http://dx.doi.org/10.1109/ISPSD.2015.7123464

This work presents an intelligent driver IC for 400 V GaN-based Power Factor Correction (PFC) applications. The targeted power level of the converter is 100 W, with a switching frequency above 500 kHz. The IC was implemented in a 140 nm automotive BCD SOI process, while the GaN HEMT and Schottky diode were optimized in a Si-fab compatible GaN-on-Si process. A low-Ron DMOS is integrated in the driver IC to achieve high-speed cascode switching operation. The chip also features a novel dual-mode drive scheme with monolithic negative drive voltage capability and programmable slew rate, as well as a digital peak current-mode controller. Advanced digital PFC control schemes can therefore be implemented, while EMC performance and efficiency can be optimized through active slope control.

70 mΩ/600 V normally-off GaN transistors on SiC and Si substrates
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Power Semiconductor Devices & IC’s (ISPSD), 2015 IEEE 27th International Symposium on http://dx.doi.org/10.1109/ISPSD.2015.7123433

The static and dynamic electrical performance of normally-off p-GaN gate AlGaN/GaN HFETs, manufactured on SiC and on Si substrates are compared. By implementing a p-type GaN gate, normally-off operation with 1 V threshold voltage has been realized for 70 mΩ / 600 V transistors on both substrates. The GaN-on-SiC devices outperform Si-based superjunction MOSFETs in terms of gate charge and switching energy and feature a low area-specific on-state resistance, also when considering the full chip area. The higher thermal impedance of the GaN-on-Si devices is reflected in a reduced maximum drain current for pulse lengths > 1 μs. However, no significant thermal effect was found for lower pulse powers as targeted for efficient power switching.

Analysis of off-state leakage mechanisms in GaN-based MIS-HEMTs: Experimental data and numerical simulation
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Solid-State Electronics http://dx.doi.org/10.1016/j.sse.2015.05.012
This paper presents an extensive analysis of the off-state conduction mechanisms in AlGaN/GaN Meta–Insulator–Semiconductor (MIS) transistors. Based on combined bi-dimensional numerical simulation and experimental measurements, we demonstrate the following relevant results: (i) under off-state bias conditions, the drain current can show a significant increase when the drain bias is swept up to 600 V; (ii) several mechanisms can be responsible for off-state current conduction, including band-to-band tunneling and impact ionization; (iii) two-dimensional numerical simulations indicate that band-to-band tunneling plays a major role, while impact ionization does not significantly contribute to the overall leakage. Temperature-dependent I–V measurements were also carried out to identify the origin of the vertical drain-bulk leakage.

**Reduction of leakage current by O2 plasma treatment for device isolation of AlGaN/GaN heterojunction field-effect transistors**

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The influence of O2 plasma treatment on the mesa-isolated region of AlGaN/GaN heterojunction field-effect transistors (HFETs) was studied. The etched surface of the undoped GaN layer was exposed to O2 plasma generated by a plasma-enhanced chemical vapor deposition system. The current-voltage characteristics indicated that the current of the mesa-isolated region was strongly dependent on the treatment temperature. Treatment with O2 plasma at 300 °C and 250 W for 15 min was confirmed to be the optimal condition, under which isolation current was reduced by four orders of magnitude and photovoltaic response was suppressed. The photoluminescence spectrum showed a decrease in the density of defects related to the yellow luminescence band and the occurrence of defects related to the blue luminescence band. X-ray photoelectron spectroscopy results showed the formation of Ga2O3 and a possible defect of substitutional oxygen on the nitrogen site ON. AlGaN/GaN HFETs with an on/off drain current ratio of \(1.73 \times 10^7\) were obtained, and the breakdown voltage of the mesa-isolated region increased from 171.5 V to 467.2 V.

**High temperature performances of normally-off p-GaN gate AlGaN/GaN HEMTs on SiC and Si substrates for power applications**

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Microelectronics Reliability
http://dx.doi.org/10.1016/j.microrel.2015.06.010

We analyse high temperature effects (up to 420 °C) in the performances of p-GaN gate normally-off AlGaN/GaN HEMTs on Si and SiC substrates for power applications. With increasing temperature, IDMAX (RON) decreases (increases) and the threshold voltage slightly decreases independently of the substrate and doping. The room temperature (RT) DC IV characteristics of the devices after 90 min at temperatures above 300 °C are not affected. Step stress experiments at 420 °C show more than twofold decrease of the blocking capabilities compared to RT. Finally, thermal activation of the vertical leakage current has been analysed up to 180 °C.
Dynamic Performance of AlN-Passivated AlGaN/GaN MIS-High Electron Mobility Transistors under Hard Switching Operation

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Electron Device Letters, IEEE
http://dx.doi.org/10.1109/LED.2015.2450695

High-frequency and high-temperature dynamic performance of plasma-enhanced atomic layer deposition (PEALD)-AlN-passivated enhancement-mode GaN metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs) has been investigated under hard switching conditions. Low dynamic ON-resistance (RON) degradation with small frequency dispersion and weak temperature dependence are obtained. The effectiveness of AlN passivation in suppressing current collapse is proved even under hard switching operations, which, according to other reports of SiNx-passivated devices, could worsen the dynamic RON degradation due to trapping of additional hot electrons.

Temperature-Dependent Characteristics of GaN Homojunction Rectifiers

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Electron Devices, IEEE Transactions on
http://dx.doi.org/10.1109/TED.2015.2443135

We report a homojunction gallium nitride (GaN) p-i-n rectifier fabricated on free-standing GaN substrates with the breakdown voltage >800 V and low specific ON-resistance (RONA). At 298 K, RONA is 0.28 mΩ-cm² at the current density (J) of 2.5 kA/cm² and the corresponding Baliga’s figure of merit is >2.5 GW/cm². At a given temperature, RONA values decrease with J due to conductivity modulation in the drift region. The ambipolar lifetime (τa) is also determined by open-circuit voltage decay measurement. The value for τa is 9.6 ns at 298 K and it monotonically increases to 22 ns at 448 K. The reverse I-V measurement reveals the reverse leakage current mechanism is mainly attributed to a field-assisted ionization process from deep-level centers in the space-charge region. The analysis of T-I-V curve yields the Poole-Frenkel coefficient (~3.1 x 10⁻⁴ eV · V⁻¹/² · cm⁻¹/² and a deep-level trap (~0.7 eV) at zero bias.
In this paper, we report on a novel V-Ti/Al/Ni/Au metal stack as an Ohmic contact to AlGaN/GaN heterostructures with a thin GaN cap layer. The thin vanadium layer (10 nm) is employed as the first layer under the conventional Ti/Al/Ni/Au contact. This layer is shown to play a crucial role in achieving low specific contact resistance (pc) and smooth surface morphology. The V-Ti/Al/Ni/Au contact exhibits significantly improved surface roughness when compared with Ti/Al/Ni/Au contacts with a root mean square value of 11 nm. The specific contact resistivity is measured to be $2.3 \times 10^{-6} \, \Omega \cdot \text{cm}^2$. According to cross-sectional transmission electron microscopy (TEM) analysis, very limited reaction is observed between the V-Ti/Al/Ni/Au contact and the AlGaN surface. It is demonstrated that the thin vanadium layer prevents excessive formation of TiN protrusions, which is considered to be the key to improving surface morphology with low contact resistance.

Influence of AlN buffer layer thickness on material and electrical properties of InAlN/GaN high-electron-mobility transistors  
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Japanese Journal of Applied Physics  
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The influence of the thickness of a high-temperature AlN (HT-AlN) buffer layer on the properties of an InAlN/GaN high-electron-mobility transistor (HEMT) grown on a sapphire substrate was investigated. As revealed by atomic force microscope analysis, a rougher surface and larger grain size were observed with a thicker buffer...
layer. The larger grains promoted the two-dimensional (2D) growth mode of the GaN layer at the initial growth stage. This suppressed oxygen incorporation at the GaN/HT-AlN interface and thus improved the resistivity of the GaN layer. Moreover, the lower grain density also resulted in enhanced GaN crystal quality of the GaN layer. As a consequence, the electrical properties of the InAlN/GaN HEMT device, such as output current, transconductance and off-state breakdown voltage, were improved by increasing the HT-AlN buffer layer thickness.

**InAlN/InGaN/GaN double heterostructure with improved carrier confinement and high-temperature transport performance grown by metal-organic chemical vapor deposition**

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A nearly lattice-matched InAlN/InGaN/GaN double heterostructure (DH) and traditional InAlN/GaN single heterostructure (SH) were grown by metal–organic chemical vapor deposition. The InN mole fraction of InGaN channel was deduced by XRD and photoluminescence. The electrical properties were characterized by capacitance-voltage and temperature-dependent Hall measurements. Both results revealed that the InAlN/InGaN/GaN DH possessed superior carrier confinement over traditional InAlN/GaN SH owing to the back barrier formed at the InGaN/GaN interface, which prevents the spilling over of carriers and thus remarkably improves the transport performance at high temperature. Furthermore, a thin InGaN layer was preferable for carrier channel applications to a thick one.

**A conduction model for contacts to Si-doped AlGaN grown on sapphire and single-crystalline AlN**

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Ohmic contacts to AlGaN grown on sapphire substrates have been previously demonstrated for various compositions of AlGaN, but contacts to AlGaN grown on native AlN substrates are more difficult to obtain. In this paper, a model is developed that describes current flow through contacts to Si-doped AlGaN. This model treats the current through reverse-biased Schottky barriers as a consequence of two different tunneling-dependent conduction mechanisms in parallel, i.e., Fowler-Nordheim emission and defect-assisted Frenkel-Poole emission. At low bias, the defect-assisted tunneling dominates, but as the potential across the depletion region increases, tunneling begins to occur without the assistance of defects, and the Fowler-Nordheim emission becomes the dominant conduction mechanism. Transfer length method measurements and temperature-dependent current-voltage (I-V) measurements of Ti/Al-based contacts to Si-doped AlGaN grown on sapphire and AlN substrates support this model. Defect-assisted tunneling plays a much larger role in the contacts to AlGaN on sapphire, resulting in nearly linear I-V characteristics. In contrast, contacts to AlGaN on AlN show limited defect-assisted tunneling appear to be only semi-Ohmic.

**Study on GaN buffer leakage current in AlGaN/GaN high electron mobility transistor structures grown by ammonia-molecular beam epitaxy on 100-mm Si(111)**

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The effect of carbon doping on the structural and electrical properties of GaN buffer layer of AlGaN/GaN high electron mobility transistor (HEMT) structures has been studied. In the undoped HEMT structures, oxygen was identified as the dominant impurity using secondary ion mass spectroscopy and photoluminescence (PL) measurements. In addition, a notable parallel conduction channel was identified in the GaN buffer at the interface. The AlGaN/GaN HEMT structures with carbon doped GaN buffer using a CBr4 beam equivalent pressure of $1.86 \times 10^{-7}$ mTorr showed a reduction in the buffer leakage current by two orders of magnitude. Carbon doped GaN buffers also exhibited a slight increase in the crystalline tilt with some pits on the growth surface. PL and Raman measurements indicated only a partial compensation of donor states with carbon acceptors. However, AlGaN/GaN HEMT structures with carbon doped GaN buffer with 200 nm thick undoped GaN near the channel exhibited good 2DEG characteristics.

Fabrication of AlGaN/GaN Ω-shaped nanowire fin-shaped FETs by a top-down approach
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Applied Physics Express
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An AlGaN/GaN-based Ω-shaped nanowire fin-shaped FET (FinFET) with a fin width of 50 nm was fabricated using tetramethylammonium hydroxide (TMAH)-based lateral wet etching. An atomic layer deposited (ALD) HfO2 side-wall layer served as the etching mask. ALD Al2O3 and TiN layers were used as the gate dielectric and gate metal, respectively. The Ω-shaped gate structure fully depletes the active fin body and almost completely separates the depleted fin from the underlying thick GaN buffer layer, resulting in superior device performance. The top-down processing proposed in this work provides a viable pathway towards gate-all-around devices for III-nitride semiconductors.

Effects of recess process and surface treatment on the threshold voltage of GaN MOSFETs fabricated on a AlGaN/GaN heterostructure
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GaN MOSFETs on a AlGaN/GaN heterostructure with a recess gate were fabricated. The charges near the SiO2/GaN interface of the GaN MOSFETs with different etching conditions were evaluated. It was found that stronger bombardment damage in the dry process will bring more charges near the interface and finally make the threshold voltage of the device negative. Nitrogen plasma treatment and ammonia water (NH4OH) treatment were investigated to recover or remove the damaged layer in order to achieve an enhancement-mode (E-mode) device with positive threshold voltage on the dry-recessed semi-insulating (SI) GaN surface. The influence of these treatments on the interface state density was also characterized using the Terman method by using the GaN MOS capacitor. An E-mode GaN MOSFET with a maximum field-effect mobility of 148.1 cm2
In recent years, investigating and engineering the oxide-semiconductor interface in GaN-based devices has come into focus. This has been driven by a large effort to increase the gate robustness and to obtain enhancement mode transistors. Since it has been shown that deep interface states act as fixed interface charge in the typical transistor operating regime, it appears desirable to intentionally incorporate negative interface charge, and thus, to allow for a positive shift in threshold voltage of transistors to realise enhancement mode behaviour. A rather new approach to obtain such negative charge is the plasma-oxidised layers. In this study, we present transmission electron microscopy and energy dispersive X-ray spectroscopy analysis as well as electrical data for Al-, Ti-, and Zr-based thin oxide films on a GaN-based heterostructure. It is shown that the plasma-oxidised layers have a polycrystalline morphology. An interfacial amorphous oxide layer is only detectable in the case of Zr. In addition, all films exhibit net negative charge with varying densities. The Zr layer is providing a negative interface charge density of more than $1 \times 1013 \text{ cm}^{-2}$ allowing to considerably shift the threshold voltage to more positive values.

**Experimental observation of RF avalanche gain in GaN-based PN junction diodes**

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Electronics Letters
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http://dx.doi.org/10.1049/el.2015.1551

Radio-frequency (RF) reflection gain in GaN homojunction p-n diode structures has been observed experimentally. A vertical p+/n structure grown on a native GaN substrate was used to achieve the high internal electric fields necessary to induce impact ionisation in GaN while minimising the effects of dislocations on the device performance. Amplitude and phase signatures in the measured RF reflection coefficient indicate the onset of impact ionisation within the device, with reflection gain observed at frequencies above 350 MHz. The magnitude of the measured gain is consistent with theoretical estimates of impact ionisation parameters, and the bias dependence of the measured reflection phase response is consistent with avalanche as the gain mechanism.

**High PAE high reliability AlN/GaN double heterostructure**

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Solid-State Electronics
http://dx.doi.org/10.1016/j.sse.2015.05.009

We report on AlN/GaN double heterostructures for high frequency applications. 600 h preliminary reliability assessment has been performed on these emerging RF devices, showing promising millimeter-wave 100 nm gate length GaN-on-Si
device stability for the first time. A 150 nm AlN/GaN double heterostructure has been developed and evaluated on SiC substrate. State-of-the-art CW power-added-efficiencies (PAE) up to 40 GHz have been achieved on ultrathin barrier (6 nm) GaN devices while operating at a drain bias exceeding 30 V.

Impact of proton fluence on DC and trapping characteristics in InAlN/GaN HEMTs
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Solid-State Electronics
http://dx.doi.org/10.1016/j.sse.2015.05.013

Robustness of InAlN/GaN devices under proton radiation is investigated. Several proton fluences ranging from $1 \times 10^{14}$ to $4 \times 10^{14}$ have been considered on two typologies of devices. Displacement damage is found to be the major responsible of device DC degradation leading to threshold voltage positive shift, ON resistance increase and drain current decrease, in all cases well correlated with proton fluence. Negligible difference is noticed in displacement damage effects measured on different device typologies. Furthermore, device geometry does not influence the impact of proton radiation on main DC parameters, either if gate width or length are considered. Radiation significantly affects trapping properties. A good correlation between the so-called current collapse increase and proton fluence is demonstrated when a high gate drain voltage value is imposed as trapping condition. Moreover radiation enhances the contribution of dynamic ON resistance and transconductance peak variation on current collapse increase.

Low-damage sputtered silver ohmic contacts to p-GaN with thermal stability
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Materials Letters
http://dx.doi.org/10.1016/j.matlet.2015.05.169

Low damage sputtered silver (Ag) contacts to p-GaN with low contact resistivity (pc) and improved thermal stability were examined by changing the power ratio and power value in radio frequency (RF)/direct current (DC) magnetron sputtering. A decrease in DC power in RF/DC sputtering resulted in a decrease in pc of the Ag films on p-GaN, and Ag sputtered at a low RF power only showed a significantly lower pc ($2 \times 10^{-3}$ Ω cm²), which can be attributed to the lower deposition rate and reduced sputtering damage. The Ag contacts prepared by RF sputtering showed a good adhesion and higher thermal stability in terms of the reflectivity compared to the Ag films deposited by electron-beam evaporation. The temperature-dependent pc of the RF sputtered Ag contacts suggested that the carrier transport at the sputtered Ag/p-GaN interface could be dominated by a deep level defect band in p-GaN.

Electric Field Reduction in C-doped AlGaN/GaN on Si High Electron Mobility Transistors
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Electron Device Letters, IEEE
http://dx.doi.org/10.1109/LED.2015.2442293

It is shown by simulation supported by experiment that a reduced surface field (RESURF) effect, associated with compensated deep acceptors, can occur in carbon doped GaN-on-Si power switching AlGaN/GaN transistors, provided there is a vertical leakage path from the 2DEG to the carbon doped layer. Simulations show that this effect is not present in devices using iron doped GaN buffers explaining the higher voltage capability of carbon doped devices.
T/R modules front-end integration in GaN technology

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Wireless and Microwave Technology Conference (WAMICON), 2015 IEEE 16th Annual
http://dx.doi.org/10.1109/WAMICON.2015.7120435

The present contribution summarizes the activities performed towards the realization of a Single-Chip Front-End (SCFE) operating in C Band, integrating the High Power, Low Noise amplification and switching functionalities to be provided in modern T/R modules' Front-Ends for space SAR applications. The technologies adopted in this project are provided by United Monolithic Semiconductors (UMS) and Selex Electronic Systems (SLX), the GH25-10 0.25 µm gate length and the GaN technology featured by 0.5 µm gate length for UMS and SLX respectively. At the completion of the design phase two SCFEs have been designed in the two technologies, each in two slightly different versions, featured by state-of-the-art performance. In particular, in Tx-mode, both are featured by approximately 40 W power output, with 36 dB large-signal gain and 38 % / 27 % PAE for UMS and SLX versions respectively, while in Rx-mode 2.5 dB noise figure resulted, with robust operation. The two dies are featured by 6.9 × 5.4 mm2 and 7.28 × 5.40 mm2 for UMS and SLX versions respectively.

High RF Performance Enhancement-Mode Al2O3/AlGaN/GaN MIS-HEMTs Fabricated with High-Temperature Gate-Recess Technique

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Electron Device Letters, IEEE
http://dx.doi.org/10.1109/LED.2015.2445353

In this letter, we report high-performance enhancement-mode (E-mode) Al2O3/AlGaN/GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) fabricated with high-temperature low-damage gate recess technique. The high-temperature gate recess is implemented by increasing the substrate temperature to 180 oC to enhance the desorption of chlorine-based etching residues during the dry etching of AlGaN barrier. High-crystal-quality Al2O3 gate dielectric was grown by ALD (atomic-layer-deposition) using O3 as the oxygen source to suppress hydrogen-induced weak bonds. The fabricated E-mode MIS-HEMTs exhibit a threshold voltage of +1.6 V, a pulsed drive current of 1.13 A/mm, and very low OFF-state standby power of 6.8×10-8 W/mm at VGS = 0 V and VDS = 30 V. At 4 GHz and in pulse-mode operation, the output power density and power-added efficiency were measured to be 5.76 W/mm and 57%, both of which are the highest for GaN-based Emode MIS-HEMTs reported to date.
Reduction of Current Collapse in GaN High Electron Mobility Transistors Using a Repeated Ozone Oxidation and Wet Surface Treatment
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Electron Device Letters, IEEE
http://dx.doi.org/10.1109/LED.2015.2445495

This letter reports a GaN high electron mobility transistor with reduced current collapse using a multi-cycle combined plasma-free ozone oxidation and wet surface treatment before Si3N4 passivation. The surface oxide and decomposed layers could be effectively removed and a perfect AlGaN surface is obtained after the treatment. Pulsed IV and RF power measurement indicate that the current collapse is greatly suppressed due to the removing of imperfect surface layer and damage free nature, providing an effective surface treatment method to improve the effect of passivation in GaN HEMT.

Reduction of leakage current by O2 plasma treatment for device isolation of AlGaN/GaN heterojunction field-effect transistors
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Applied Surface Science
http://dx.doi.org/10.1016/j.apsusc.2015.06.092

The influence of O2 plasma treatment on the mesa-isolated region of AlGaN/GaN heterojunction field-effect transistors (HFETs) was studied. The etched surface of the undoped GaN layer was exposed to O2 plasma generated by a plasma-enhanced chemical vapor deposition system. The current-voltage characteristics indicated that the current of the mesa-isolated region was strongly dependent on the treatment temperature. Treatment with O2 plasma at 300 °C and 250 W for 15 min was confirmed to be the optimal condition, under which isolation current was reduced by four orders of magnitude and photovoltaic response was suppressed. The photoluminescence spectrum showed a decrease in the density of defects related to the yellow luminescence band and the occurrence of defects related to the blue luminescence band. X-ray photoelectron spectroscopy results showed the formation of Ga2O3 and a possible defect of substitutional oxygen on the nitrogen site ON. AlGaN/GaN HFETs with an on/off drain current ratio of 1.73 × 107 were obtained, and the breakdown voltage of the mesa-isolated region increased from 171.5 V to 467.2 V.

Degradation of 0.25 μm GaN HEMTs under high temperature stress test
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Microelectronics Reliability
http://dx.doi.org/10.1016/j.microrel.2015.06.042

The temperature dependence of device degradation of AlGaN/GaN HEMTs on SiC substrate with a gate length of 0.25 μm has been investigated. The critical surface temperature, where device degradation sets in has been determined using drain-current step-stress tests in combination with infrared microscopy. Using this fast reliability test, devices with different passivation technologies have been compared and, by optimizing the passivation technology, the critical temperature at which degradation of the threshold voltage begins has been improved from 310 °C to above 330 °C. Storage tests at 300 °C in nitrogen atmosphere confirm the improvement in high temperature stability. Physical failure analysis using electroluminescence and TEM/EDX cross-section revealed void formation and Au-
diffusion at the gate as the main degradation mechanisms of devices with the conventional passivation technology.

European gallium nitride capability
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Radar Conference (RadarCon), 2015 IEEE
http://dx.doi.org/10.1109/RADAR.2015.7131004

Gallium nitride (GaN) provides clear advantages over other technologies such as gallium arsenide (GaAs) for high power solid state radio frequency (RF) applications. However Europe is currently reliant on other countries, in particular the US, for GaN components and systems. This paper summarises recent research into GaN within Europe and the progress towards establishing an independent European supply chain.

Integrated power switches for X-Band PA
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Radar Conference (RadarCon), 2015 IEEE
http://dx.doi.org/10.1109/RADAR.2015.7131257

This paper reports on the development of high frequency, high efficiency integrated supply modulators for airborne and space based high power amplifier modules. The power switches within the integrated modulators were RF HEMTs optimized for power amplifier applications. The modulators were fabricated in commercial foundry GaN process and delivered 10W of output power with an efficiency of 83.5% while switching at a frequency of 100 MHz. Development of high frequency supply modulators paves the way for integration of the HPA and modulators onto the MMIC die and on-chip drain bias modulation for efficiency enhancement of the HPA.

A high-power Ka-band single-pole single-throw switch MMIC using 0.25 μm GaN on SiC
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Radio and Wireless Symposium (RWS), 2015 IEEE
http://dx.doi.org/10.1109/RWS.2015.7129738

A single-pole single-throw switch monolithic microwave integrated circuit using 0.25 μm GaN HEMT technology is presented for Ka-band downlink frequencies 17 – 22 GHz. On-wafer small-signal measurements demonstrated a low insertion loss of ≤1 dB, a high on-to-off isolation of ≥28 dB and a switch figure-of-merit RonCoff of 330 fs. Large-signal measurements at 20GHz revealed input compression points ‘P−1dB’ of 40dBm and 36dBm in the transmit (Vc = −20 V) and isolation (Vc = 0) states, respectively. The low insertion loss, high isolation, high power handling, and negligible static power consumption in compact dimensions of 1.75mm × 1.75mm form a baseline for an advanced design of a reconfigurable switch matrix based on GaN passive-HEMT.

Microwave and millimeter wave power amplifiers: Technology, applications, benchmarks, and future trends
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Radio and Wireless Symposium (RWS), 2015 IEEE
http://dx.doi.org/10.1109/RWS.2015.7129767

Solid State Transistor Device Technology is ubiquitous in communications, radar, electronic warfare, and instrumentation applications. This abridged presentation will cover Si LDMOS, PHEMT, InP HEMT/MHEMT and GaN HEMT. Content includes principles of operation, structures, characteristics, classes of operation, and device state of the art benchmarks. The art of power amplifier design is approached from a historical perspective. Power amplifiers utilizing these device technologies covering UHF through sub-millimeter wave are described including amplifier state of the art benchmarks. Future trends are highlighted and summarized.
Piezoelectric actuation of aluminum nitride contour mode optomechanical resonators

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Optics Express
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We present a fully-integrated monolithic aluminum nitride optomechanical device in which lateral vibrations generated by a piezoelectric contour mode acoustic ring resonator are used to produce amplitude modulation of an optical signal in a whispering gallery mode photonic ring resonator. Acoustic and optical resonances are independently characterized in this contour mode optomechanical resonator (CMOMR). Electrically driven mechanical modes are optically detected at 35MHz, 654MHz and 884MHz.

GaN metal–semiconductor–metal UV sensor with multi-layer graphene as Schottky electrodes

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We fabricated a GaN-based metal–semiconductor–metal (MSM)-type UV sensor using a multilayer graphene as transparent Schottky electrodes. The fabricated GaN MSM UV sensor showed a high photo-to-dark current contrast ratio of 3.9 × 105 and a UV-to-visible rejection ratio of 1.8 × 103 at 7 V. The as-fabricated GaN MSM UV sensor with graphene electrodes has a low bias dependence of maximum photoresponsivity and a noise-like response at a visible wavelength in the 500 nm region. These problems were successfully solved by treatment with a buffered oxide etcher (BOE), and the photoresponse characteristics of the fabricated GaN MSM UV sensor after the treatment were better than those before the treatment.

Sensing operations based on hexagonal GaN microdisks acting as whispering-gallery mode optical microcavities

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Using room temperature photoluminescence measurements, we have demonstrated a sensing operation based on hexagonal GaN microdisks with a side length of approximately 1.5 μm that acted as optical microcavities. In the experiment, the optical microresonant systems based on the whispering-gallery mode (WGM) in the microdisks were affected by their ambient conditions, resulting in shifts of the lasing wavelength by varying the mixing ratios of isopropanol and o-xylene. We also obtained such shifts for aqueous solutions with varying sucrose concentrations. In addition, we demonstrated that tiny waterborne particles can be detected using a microdisk. These results indicate that the WGM in the hexagonal GaN microdisks potentially can be used to develop optical microbiosensors that can evaluate a limited area with a radius of 1–2 μm.
Highly piezoelectric co-doped AlN thin films for wideband FBAR applications
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Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on
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We report piezoelectric materials composed of charge-compensated co-doped (Mg, β)\(\varepsilon\)Al\(1-\beta\)N (β = Zr or Hf) thin films. The effect of the dopant element into AlN on the crystal structure, and piezoelectric properties of co-doped AlN was determined on the basis of a first-principles calculation, and the theoretical piezoelectric properties were confirmed by experimentally depositing thin films of magnesium (Mg) and zirconium (Zr) co-doped AlN (Mg-Zr-doped AlN). The Mg-Zrdoped AlN thin films were prepared on Si (100) substrates by using a triple-radio-frequency magnetron reactive co-sputtering system. The crystal structures and piezoelectric coefficients (d33) were investigated as a function of the concentrations, which were measured by X-ray diffraction and a piezometer. The results show that the d33 of Mg-Zr-doped AlN at total Mg and Zr concentrations (both expressed as β) of 0.35 was 280% larger than that of pure AlN. The experimentally measured parameter of the crystal structure and d33 of Mg-Zr-doped AlN (plotted as functions of total Mg and Zr concentrations) were in very close agreement with the corresponding values obtained by the first-principle calculations. Thin film bulk acoustic wave resonators (FBAR) employing (Mg,Zr)0.13Al0.87N and (Mg, Hf)0.13 Al0.87N as a piezoelectric thin film were fabricated, and their resonant characteristics were evaluated. The measured electromechanical coupling coefficient increased from 7.1% for pure AlN to 8.5% for Mg-Zr-doped AlN and 10.0% for Mg- Hf-doped AlN. These results indicate that co-doped (Mg, β)\(\varepsilon\)Al\(1-\beta\)N (β = Zr or Hf) films have potential as piezoelectric thin films for wideband RF applications.

Highly sensitive detection of NO2 gas using BGaN/GaN superlattice-based double Schottky junction sensors
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Applied Physics Letters
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We report a double Schottky junction gas sensor based on a BGaN/GaN superlattice and Pt contacts. NO2 is detected at concentrations from 4.5 to 450 ppm with current responsivity of 6.7 mA/(cm² x ppm) at 250°C with a response time of 5 s. The sensor is also selective against NH3 at least for concentrations less than 15 ppm. The BGaN layer at the surface increases surface trap density and trap depth, which improves responsivity and high temperature stability while the GaN layer improves the magnitude of the diode current. The BGaN layer’s columnar growth structure also causes a Pt morphology that improves O2– diffusion.

Terahertz acoustic wave on piezoelectric semiconductor film via large-scale molecular dynamics simulation
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By atomistic simulation, we investigate an acoustic wave at THz frequencies in nanoscale thin films of aluminum–nitride piezoelectric material. A mode analysis reveals that the
thickness longitudinal mode along the [0001] direction exists stably at the atomic level. To control the acoustic wave, we introduce a phononic crystal (PC) structure in the films. We determine the band-gap frequency in the phonon dispersion of the PC structure and confirm via molecular dynamics simulation that the acoustic wave within the band-gap frequency can be confined by a waveguide structure with a PC. The possibility of designing and controlling a THz acoustic wave in a nanoscale thin film with a PC is thereby demonstrated.

Acoustic properties of co-doped AlN thin films at low temperatures studied by picosecond ultrasonics
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(Mg0.5Zr0.5)xAl1–xN and (Mg0.5Hf0.5)xAl1–xN thin films are AlN-base piezoelectric materials, and their piezoelectric coefficients are higher than those of pure AlN, being promising materials for acoustic devices. However, their acoustic properties remain unknown because of measurement difficulty for deposited thin films. In this study, we measure their longitudinal-wave elastic constants C33 and their temperature coefficients using picosecond ultrasound spectroscopy for 0 < x < 0.13; we obtain C33 = 398.2 ± 0.7 GPa for pure AlN, and it largely decreases by doping Mg, Zr, and Hf, leading to a minimum values of 316.8 ± 1.6 GPa for (Mg0.5Zr0.5)0.126Al0.874N.

Methods for improving electromechanical coupling coefficient in two dimensional electric field excited AlN Lamb wave resonators
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An AlN piezoelectric Lamb-wave resonator, which is excited by two dimensional electric field, is reported in this paper. Rhombus-shape electrodes are arranged on AlN thin film in a checkered formation. When out-of-phase alternating currents are applied to adjacent checkers, two dimensional acoustic Lamb waves are excited in the piezoelectric layer along orthogonal directions, achieving high electromechanical coupling coefficient, which is comparable to film bulk acoustic resonators. The electromechanical coupling coefficient of the 285.3 MHz resonator presented in this paper is 5.33%, which is the highest among AlN based Lamb-wave resonators reported in literature. Moreover, the spurious signal within a wide frequency range is significantly suppressed to be 90% lower than that of the resonance mode. By varying the electrode dimension and inter-electrode distance, resonators having different resonant frequencies can be fabricated on a single wafer, making single-chip broadband filters, duplexers, and multiplexers possible.

Demonstration of an AlGaN-based solar-blind high-voltage photoconductive switch
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A solar-blind photoconductive semiconductor switch (PCSS) is first fabricated on high-resistivity Al0.4Ga0.6N layer grown on sapphire substrate. The PCSS exhibits a cutoff wavelength of ~280 nm and a dark resistivity of ~1012 Ω cm. A maximum blocking voltage of more than 950 V is obtained, corresponding to a breakdown electric-field of >1.35 MV/cm for the active AlGaN layer. When excited by a 266 nm ultraviolet pulsed laser, the PCSS under 500 V bias could produce a peak photocurrent density of 11.5 kA/cm2 within a rise time of ~15 ns. The fall time of the photocurrent pulse is mainly RC time limited.

On a Schottky diode-type hydrogen sensor with pyramid-like Pd nanostructures
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A new Pd/AlGaN/GaN Schottky diode-type hydrogen sensor with pyramid-like Pd nanostructures is fabricated and studied comprehensively. The employed pyramid-like Pd nanostructures cause the substantial increase of surface roughness and surface-to-volume aspect ratio which give the remarkable increase of adsorption sites on the surface for hydrogen molecules. Experimentally, the studied device with pyramid-like Pd nanostructures demonstrates enhanced hydrogen sensing performance, including a large forward-bias current variation of 1.95 × 10−6 A and a high sensing response of 1454 under an introduced 1% H2/air gas at 300 K. These properties are remarkably superior to those of the conventional planar-surface device. In addition, an improved hydrogen detection limit of 10 ppb H2/air at 300 K is found for the studied device with pyramid-like Pd nanostructures. The related hydrogen sensing characteristics including transient responses and steady-state analysis are also studied in this work. Therefore, based on the improved sensing properties and advantages of low-cost, easy fabrication, and solid stability of operation, the studied device shows the promise for high-performance hydrogen sensing applications.

Frequency response modeling and optimization of a PIN photodiode based on GaN/InGaN adapted to photodetection at a wavelength of 633 nm
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Materials Chemistry and Physics
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In this paper, the frequency response calculation and optimization of PIN photodiodes based on GaN/InGaN, suitable for photodetection at the wavelength of 633 nm, are presented. The calculations of the impulse as well as the frequency response are performed using the impulse method. The frequency response optimization is a result of optimizing the transport of photo-generated carriers in the absorbent layer of the photodiode, using a mixed depletion region rather than a single absorbing depletion region. Cut-off frequencies of about 82 GHz and 48 GHz have been obtained in the case of transparent layer thickness of 500 nm and 1000 nm, respectively. The aforementioned results represent a very good improvement.

Dual mode UV/Visible-IR Gallium-Nitride light detector
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Gallium-Nitride (GaN) light detectors are sensitive to ultraviolet (UV) radiation below 365 nm wavelength due to their wide bandgap – 3.4 eV. However, the presence of impurities, especially surface traps, leads to slow relaxation rates and sub-bandgap response due to new energy levels. In the present work we offer utilizing these impurities to broaden the spectral range up to the near-infrared (NIR) and modifying the surface of the photoresistors to enhance the response, the recovery time, and the repeatability by using several surface treatments such as plasma asher and the adsorption of organic molecules. The wide band response up to the NIR range was achieved by exciting the detector with a constant UV light intensity, resulting in a responsivity of $10^{-100} \text{ A/W}$. We ascribe the high sensitivity to visible and NIR wavelengths to a gating amplification effect caused by trapped charges. Owing to the band bending of energy levels, a large depletion layer is created on the surface of the GaN layer, effectively separating the surface conductivity from the bulk. These properties make the detector sensitive to changes on the surface, thus making it ideal for biological and chemical uses as well as for broadband light detectors.

A Fully Integrated Oven Controlled Microelectromechanical Oscillator--Part I: Design and Fabrication

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Microelectromechanical Systems, Journal of http://dx.doi.org/10.1109/JMEMS.2015.2441037

This paper, the first of two parts, reports the design and fabrication of a fully integrated oven controlled microelectromechanical oscillator (OCMO). This paper begins by describing the limits on oscillator frequency stability imposed by the thermal drift and electronic properties (Q, resistance) of both the resonant tank circuit and feedback electronics required to form an electronic oscillator. An OCMO is presented that takes advantage of high thermal isolation and monolithic integration of both micromechanical resonators and electronic circuitry to thermally stabilize or ovenize all the components that comprise an oscillator. This was achieved by developing a processing technique where both silicon-on-insulator complementary metal-oxide-semiconductor (CMOS) circuitry and piezoelectric aluminum nitride, AlN, micromechanical resonators are placed on a suspended platform within a standard CMOS integrated circuit. Operation at microscale sizes achieves high thermal resistances (~$10 \text{ °C/mW}$), and hence thermal stabilization of the oscillators at very low-power levels when compared with the state-of-the-art ovenized crystal oscillators, OCXO. A constant resistance feedback circuit is presented that incorporates on platform resistive heaters and temperature sensors to both measure and stabilize the platform temperature. The limits on temperature stability of the OCMO platform and oscillator frequency imposed by the gain of the constant resistance feedback loop, placement of the heater and temperature sensing resistors, as well as platform radiative and convective heat losses are investigated. [2015-0035]
milliwatts of supply power and with a volume of 2.3 mm$^3$ (not including the printed circuit board-based thermal control loop). In addition, due to its small thermal time constant, the thermal compensation loop can maintain stability during fast thermal transients (>10 °C/min). This new technology has resulted in a new paradigm in terms of power, size, and warm up time for high thermal stability oscillators. [2015-0036]
Enhancing the photocatalytic activity of GaN by electrochemical etching
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Nanoporous (NP) GaN thin films prepared with electrochemical etching method were investigated as photocatalysts in dye photodegradation systematically. The comparison of NP GaN thin films with GaN thin films showed that NP GaN thin films with high surface-to-volume ratio exhibited much better photocatalytic activity. In comparison with porous Si wafers, NP GaN thin films with lower surface area exhibited much better photocatalytic activity, because GaN is efficient not only for dye reduction like Si, but also for dye oxidation. Due to its ceramic-like chemical inertness, moreover, NP GaN showed more excellent stability to photodegrade organic dye than porous Si under basic conditions. The band gap of GaN can be modulated in visible-light region, which will be beneficial to a photodegradation system with concentrated solar light.

Valorization of GaN based metal-organic chemical vapor deposition dust a semiconductor power device industry waste through mechanochemical oxidation and leaching: A sustainable green process
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Dust generated during metal organic vapor deposition (MOCVD) process of GaN based semiconductor power device industry contains significant amounts of gallium and indium. These semiconductor power device industry wastes contain gallium as GaN and Ga0.97N0.9O0.09 is a concern for the environment which can add value through recycling. In the present study, this waste is recycled through mechanochemical oxidation and leaching. For quantitative recovery of gallium, two different mechanochemical oxidation leaching process flow sheets are proposed. In one process, first the Ga0.97N0.900.09 of the MOCVD dust is leached at the optimum condition. Subsequently, the leach residue is mechanochemically treated, followed by oxidative annealing and finally re-leached. In the second process, the MOCVD waste dust is mechanochemically treated, followed by oxidative annealing and finally leached. Both of these treatment processes are competitive with each other, appropriate for gallium leaching and treatment of the waste MOCVD dust. Without mechanochemical oxidation, 40.11 and 1.86w/w% of gallium and Indium are leached using 4M HCl, 100 °C and pulp density of 100kg/m3, respectively. After mechanochemical oxidation, both these processes achieved 90w/w% of gallium and 1.86w/w% of Indium leaching at their optimum condition.

Novel Recycle Technology for Recovering Rare Metals (Ga, In) from Waste Light-emitting Diodes
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http://dx.doi.org/10.1016/j.jhazmat.2015.06.029
This work develops a novel process of recycling rare metals (Ga, In) from waste light-emitting diodes using the combination of pyrolysis, physical disaggregation methods and vacuum metallurgy separation. Firstly, the pure chips containing InGaN/GaN are adopted to study the vacuum separation behavior of rare metals, which aims to provide the theoretical foundation for recycling gallium and indium from waste light-emitting diodes. In order to extract the rare-metal-rich particles from waste light-emitting diodes, pyrolysis and physical disaggregation methods (crushing, screening, grinding and secondly screening) are studied respectively, and the operating parameters are optimized. With low boiling points and high saturation vapor pressures under vacuum, gallium and indium are separated from rare-metal-rich particles by the process of evaporation and condensation. By reference to the separating parameters of pure chips, gallium and indium in waste light-emitting diodes are recycled with the recovery efficiencies of 93.48 % and 95.67 % under the conditions as follows: heating temperature of 1373 K, vacuum pressure of 0.01-0.1 Pa, and holding time of 60 min. There are no secondary hazardous materials generated in the whole processes. This work provides an efficient and environmentally friendly process for recycling rare metals from waste light-emitting diodes.
**Monolithic integration of four-colour InGaN-based nanocolumn LEDs**

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The monolithic integration of four-colour indium gallium nitride (InGaN)-based nanocolumn light-emitting diodes (LEDs) is demonstrated. In the integrated nanocolumn LED unit, blue-, sky-blue-, green- and yellow-emitting micro-LEDs (LEDs 1–4) with a 65 μm diameter circular indium tin oxide emission window were arrayed in a 2 × 2 square lattice with a lattice constant of 190 μm. LEDs 1–4 consisted of nanocolumn arrays arranged in a triangular lattice with a lattice constant of 300 nm and their nanocolumn diameters at the position of the InGaN/gallium nitride (GaN) multiple quantum wells (MQWs) were 119, 145, 188 and 231 nm, respectively. The increase in nanocolumn diameter from LED 1 to LED 4 resulted in increasing emission peak wavelengths, which were 465, 489, 510 and 570 nm for LEDs 1–4, respectively. On the same substrate, a red-emitting micro-LED was prepared, in which the nanocolumn diameter was increased to 260 nm by using a 350 nm-lattice-constant nanocolumn array. A combination of different lattice constants in an integrated LED unit is expected to contribute to the achievement of red–green–blue–yellow (RGBY)-colour-integrated nanocolumn LEDs.

**Long-lived excitons in GaN/AlN nanowire heterostructures**

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GaN/AlN nanowire heterostructures can display photoluminescence (PL) decay times on the order of microseconds that persist up to room temperature. Doping the GaN nanodisk insertions with Ge can reduce these PL decay times by two orders of magnitude. These phenomena are explained by the three-dimensional electric field distribution within the GaN nanodisks, which has an axial component in the range of a few MV/cm associated to the spontaneous and piezoelectric polarization, and a radial piezoelectric contribution associated to the shear components of the lattice strain. At low dopant concentrations, a large electron-hole separation in both the axial and radial directions is present. The relatively weak radial electric fields, which are about one order of magnitude smaller than the axial fields, are rapidly screened by doping. This bidirectional screening leads to a radial and axial centralization of the hole underneath the electron, and consequently, to large decreases in PL decay times, in addition to luminescence blue shifts.

**Ultraviolet photoconductive devices with an n-GaN nanorod-graphene hybrid structure synthesized by metal-organic chemical vapor deposition**

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The superior photoconductive behavior of a simple, cost-effective n-GaN nanorod (NR)-graphene hybrid device structure is demonstrated for the first time. The proposed hybrid structure was synthesized on a Si (111) substrate using the high-quality graphene transfer method and the relatively low-temperature metal-organic chemical vapor deposition (MOCVD) process with a high V/III ratio to protect the graphene layer from thermal damage during the growth of n-GaN nanorods. Defect-free n-GaN NRs were grown on a highly ordered graphene monolayer on Si without forming any metal-catalyst or droplet seeds. The prominent existence of the undamaged monolayer graphene even after the growth of highly dense n-GaN NRs, as determined using Raman spectroscopy and high-resolution transmission electron microscopy (HR-TEM), facilitated the excellent transport of the generated charge carriers through the photoconductive channel. The highly matched n-GaN NR-graphene hybrid structure exhibited enhancement in the photocurrent along with increased sensitivity and photoresponsivity, which were attributed to the extremely low carrier trap density in the photoconductive channel.

Fabrication of AlGaN/GaN Ω-shaped nanowire fin-shaped FETs by a top-down approach
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An AlGaN/GaN-based Ω-shaped nanowire fin-shaped FET (FinFET) with a fin width of 50 nm was fabricated using tetramethylammonium hydroxide (TMAH)-based lateral wet etching. An atomic layer deposited (ALD) HfO2 side-wall layer served as the etching mask. ALD Al2O3 and TiN layers were used as the gate dielectric and gate metal, respectively. The Ω-shaped gate structure fully depletes the active fin body and almost completely separates the depleted fin from the underlying thick GaN buffer layer, resulting in superior device performance. The top-down processing proposed in this work provides a viable pathway towards gate-all-around devices for III-nitride semiconductors.

Selective-area growth of GaN nanocolumns on Si(111) substrates for application to nanocolumn emitters with systematic analysis of dislocation filtering effect of nanocolumns
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The growth of highly uniform arrays of GaN nanocolumns with diameters from 122 to 430 nm on Si (111) substrates was demonstrated. The employment of GaN film templates with flat surfaces (root mean square surface roughness of 0.84 nm), which were obtained using an AlN/GaN superlattice (SL) buffer on Si, contributed to the high-quality selective-area growth of nanocolumns using a thin Ti mask of 5 nm thickness by rf-plasma-assisted molecular beam epitaxy. Although the GaN template included a large number of dislocations (dislocation density ~1011 cm−2), the dislocation filtering effect of nanocolumns was enhanced with decreasing nanocolumn diameters (D). Systematic
transmission electron microscopy (TEM) observation enabled us to explain the dependence of the dislocation propagation behavior in nanocolumns on the nanocolumn diameter for the first time. Plan-view TEM analysis was performed for nanocolumns with D = 120–324 nm by slicing the nanocolumns horizontally at a height of ~300 nm above their bottoms and dislocation propagation through the nanocolumns was analyzed by the cross-sectional TEM observation of nanocolumns with D ~ 200 nm. It was clarified that dislocations were effectively filtered in the bottom 300 nm region of the nanocolumns, the dislocation density of the nanocolumns decreased with decreasing D, and for narrow nanocolumns with D < 200 nm, dislocation-free crystals were obtained in the upper part of the nanocolumns. The dramatic improvement in the emission properties of GaN nanocolumns observed with decreasing diameter is discussed in relation to the decreased dislocation density. The laser action of InGaN/GaN-based nanocolumn arrays with a nanocolumn diameter of 170 nm and a period of 200 nm on Si under optical excitation was obtained with an emission wavelength of 407 nm. We also fabricated red-emitting InGaN-based nanocolumn light-emitting diodes on Si that operated at a wavelength of 652 nm, demonstrating vertical conduction through the AlN/GaN SL buffer to the Si substrate.

**Growth of vertically oriented InN nanorods from In-rich conditions on unintentionally patterned sapphire substrates**

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Vertically oriented InN nanorods were grown on selective areas of unintentionally patterned c-oriented sapphire substrates exhibiting sharp needles that preferentially accommodate In-metal liquid droplets, using Migration Enhanced Afterglow (MEAglow) growth technique. We point out that the formation of AlN needles on selected areas can be reproduced intentionally by over-nitridation of unmasked areas of sapphire substrates. The liquid indium droplets serve as a self-catalyst and the nanorods grow from the supersaturated indium melt in the droplet in a vertical direction. X-ray diffraction measurements indicate the presence of hexagonal InN only, with preferred orientation along (0 0 0 1) crystal axis, and very good crystalline quality. The room temperature Raman spectrum shows the presence of the A1(TO), E2(high) and A1(LO) phonon modes of the hexagonal InN.

**Quantum coherence of electrons in random networks of c-axis oriented wedge-shaped GaN nanowalls grown by molecular beam epitaxy**

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The depth distribution of the transport properties as well as the temperature dependence of the low field magneto-conductance for \( c \)-axis oriented GaN nanowall network samples grown with different average wall-widths \( \langle t \rangle \) are investigated. Magneto-conductance recorded at low temperatures shows clear signature of weak localization effect in all samples studied here. The scattering mean free path \( \langle l \rangle \) and the phase coherence time \( \langle \tau \rangle \), are extracted from the magneto-conductance profile. Electron mobility estimated from \( \langle l \rangle \) is found to be comparable with those estimated previously from room temperature conductivity data for these samples, confirming independently the substantial mobility.
enhancement in these nanowalls as compared to bulk. Our study furthermore reveals that the high electron mobility region extends down to several hundreds of nanometer below the tip of the walls. Like mobility, phase coherence length ($\langle l_{\phi}\rangle$) is found to increase with the reduction of the average wall width. Interestingly, for samples with lower values of the average wall width, $\langle l_{\phi}\rangle$ is estimated to be as high as 60 μm, which is much larger than those reported for GaN/AlGaN heterostructure based two-dimensional electron gas (2DEG) systems.

**The influence of AlN buffer over the polarity and the nucleation of self-organized GaN nanowires**

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We experimentally investigate the influence of AlN buffer growth on the nucleation and the polarity of a self-organized assembly of GaN nanowires (NWs) grown on Si. Two complementary growth mechanisms for AlN buffer deposited on Si are demonstrated. Both emphasize the aggregation of Si on the AlN surface and the growth of large cubic crystallites, namely, AlN pedestals. Further growths of GaN NWs assembly reveal that the GaN 2D layer found at the bottom of the NW assembly is the result of the coalescence of Ga-polar pyramids, whereas AlN pedestals are observed as preferential but not exclusive NW nucleation sites. NWs are N-polar or exhibit inversion domains with a Ga-polar core/N-polar shell structure. This suggests that N-polarity is a necessary condition to trigger NW self-organized nucleation due to a different facets energy hierarchy between the Ga- and the N-polar sides.

**Space-and-time-resolved spectroscopy of single GaN nanowires**

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Applied Physics Letters
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Gallium nitride nanowires have garnered much attention in recent years due to their attractive optical and electrical properties. An understanding of carrier transport, relaxation, and recombination in these quasi-one-dimensional nanosystems is therefore important in optimizing them for various applications. Here, we present ultrafast optical microscopic measurements on single GaN nanowires. Our experiments, performed while varying the light polarization, excitation fluence, and position, give insight into the mechanisms governing carrier dynamics in these nanosystems.

**High efficiency, full-color AlInGaN quaternary nanowire light emitting diodes with spontaneous core-shell structures on Si**

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We have developed AlInGaN quaternary core-shell nanowire heterostructures on Si substrate, wherein an In-rich core and an Al-rich shell were spontaneously formed during the epitaxial growth process. By varying the growth conditions, the emission wavelengths can be tuned from ∼430 nm to ∼630 nm. Such core-shell structures can largely suppress nonradiative surface recombination, leading to a significant enhancement of carrier lifetime from ∼0.2 ns to ∼2 ns. The resulting nanowire light emitting diodes can exhibit an output power exceeding 30 mW for a ∼1×1 mm2 non-packaged device at a current density of 100 A/cm2.

Impact of random dopant fluctuations on the electronic properties of InxGa1-xN/GaN axial nanowire heterostructure
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Nano Letters
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We study the electronic properties of axial InxGa1-xN/GaN nanowire heterostructures with randomly placed ionized donors. Our simulations are based on an eight-band k•p model and indicate large variations of both the ground state transition energy and the spatial distribution of the electron and hole charge density. We show that these variations are intrinsic to nanostructures containing ionized donors, and that the presence of donors has important consequences for all nanowire-based light-emitting devices including single-photon emitters required for quantum computing and quantum cryptography.

Surface-Effect-Induced Optical Bandgap Shrinkage in GaN Nanotubes
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Nano Letters
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We investigate nontrivial surface effects on the optical properties of self-assembled crystalline GaN nanotubes grown on Si substrates. The excitonic emission is observed to redshift by ∼100 meV with respect to that of bulk GaN. We find that the conduction band edge is mainly dominated by surface atoms, and that a larger number of surface atoms for the tube is likely to increase the bandwidth, thus reducing the optical bandgap. The experimental findings can have important impacts in the understanding of the role of surfaces in nanostructured semiconductors with an enhanced surface/volume ratio.

Giant Rabi Splitting of Whispering Gallery Polaritons in GaN/InGaN Core–Shell Wire
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Nano Letters
http://dx.doi.org/10.1021/acs.nanolett.5b01023

The hybrid nature of exciton polaritons opens up possibilities for developing a new concept nonlinear photonic device (e.g., polariton condensation, switching, and transistor) with great potential for controllability. Here, we proposed a novel type of polariton system resulting from strong coupling between a two-dimensional exciton and whispering gallery mode photon using a core–shell GaN/InGaN hexagonal wire. High quality, nonpolar InGaN multiple-quantum wells (MQWs) were conformally formed on a GaN core nanowire, which was spatially well matched with whispering gallery modes inside the wire. Both high longitudinal-transverse splitting of nonpolar MQWs and high spatial overlap with
whispering gallery modes lead to unprecedented large Rabi splitting energy of \( \sim 180 \text{ meV} \). This structure provides a robust polariton effect with a small footprint; thus, it could be utilized for a wide range of interesting applications.

**Ultrafast dynamics of lasing semiconductor nanowires**

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Semiconductor nanowire lasers operate at ultrafast timescales; here we report their temporal dynamics, including laser onset time and pulse width, using a double-pump approach. Wide bandgap gallium nitride (GaN), zinc oxide (ZnO) and cadmium sulfide (CdS) nanowires reveal laser onset times of a few picoseconds, driven by carrier thermalization within the optically excited semiconductor. Strong carrier-phonon coupling in ZnO leads to the fastest laser onset time of \( \sim 1 \text{ ps} \) in comparison to CdS and GaN exhibiting values of \( \sim 2.5 \text{ ps} \) and \( \sim 3.5 \text{ ps} \), respectively. These values are constant between nanowires of different sizes implying independence from any optical influences. However, we demonstrate that the lasing onset times vary with excitation wavelength relative to the semiconductor band gap. Meanwhile, the laser pulse widths are dependent on the optical system. While the fastest ultrashort pulses are attained using the thinnest possible nanowires, a sudden change in pulse width from \( \sim 5 \text{ ps} \) to \( \sim 15 \text{ ps} \) occurs at a critical nanowire diameter. We attribute this to the transition from single to multimode waveguiding, as it is accompanied by a change in laser polarization.

**GaN nanowire fabricated by selective wet-etching of GaN micro truncated-pyramid**

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Journal of Crystal Growth
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We demonstrated the fabrication of GaN nanowire (NW) by selective etching of the GaN micro truncated-pyramid (μ-TP) in KOH solution. The GaN μ-TP, which consists of a (0001) Ga-polar top surface and six \{1\overline{0}1\} N-polar sidewalls, were grown on the patterned AlN/Si template in metal organic chemical vapor deposition (MOCVD) system. KOH solution can selectively etch the N-polar sidewalls while leave the Ga-polar top surface intact. Hexagonal-prism-structured GaN NW with (0001) top surface and \{1\overline{0}0\} N-polar sidewalls were obtained after adequate chemical etching. It was found that the three-dimensional geometry of the GaN NW is determined by the diameter of the (0001) top surface and the height of the GaN μ-TP. And the chemical etching mechanism of GaN μ-TP towards GaN NW in hydroxide solution was explained.

**Enhanced field emission properties from AlN nanowires synthesized on conductive graphite substrate**

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Large-scale AlN nanowires have been grown on flexible and conductive graphite substrate
through the catalyst-free chemical vapor deposition (CVD). All the as-grown samples are hexagonal wurtzite structure and grow preferentially along the c-axis. The comparative study on the field emission (FE) properties of AlN nanowires grown on graphite sheet and Si substrates indicates that AlN nanowires grown directly on conductive substrates exhibit good FE properties with low turn on field of 4.9 V/µm at a current density of 10 µA/cm² and low threshold filed of 6.7 V/µm at 1 mA/cm². The enhanced FE property is due to the tapered structures of nanowires with sharp tips and high aspect ratio, and the better electrical contact between conductive graphite substrate and field emitters. These results demonstrate the potential applications of the AlN nanowires grown on graphite sheet in optoelectronic and field-emission nanodevices.

**Selective and controllable lateral photoelectrochemical etching of nonpolar and semipolar InGaN/GaN multiple quantum well active regions**

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We demonstrate the selective and controllable undercut etching of the InGaN/GaN multiple quantum well active regions of nonpolar and semipolar laser diode (LD) structures by photoelectrochemical (PEC) etching without external bias. The lateral etch rate ranged from ~20 nm/min to ~1.2 µm/min. Metal masks were used to define the undercut and to improve the PEC etch resolution by reducing the scattered light in the system, which contributes to degradation of the lateral etch resolution, as suggested by ray tracing simulations. This resulted in a light-exposed-area: masked-area etch selectivity of $\sim 13:1$.

**Growth and characterization of semi-polar (11-22) GaN on patterned (113) Si substrates**

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Patterned (113) Si substrates have been fabricated for the growth of (11-22) semi-polar GaN, which completely eliminates one of the great issues in the growth of semi-polar GaN on silicon substrates, ‘Ga melting-back’. Furthermore, unlike any other mask patterning approaches which normally lead to parallel grooves along a particular orientation, our approach is to form periodic square window patterns. As a result, crack-free semi-polar (11-22) GaN with a significant improvement in crystal quality has been achieved, in particular, basal stacking faults (BSFs) have been significantly reduced. The mechanism for the defect suppression has been investigated based on detailed transmission electron microscopy measurements. It has been found that the BSFs can be impeded effectively at an early growth stage due to the priority growth along the (0001) direction. The additional (1-100) lateral growth above the masks results in a further reduction in dislocation density. The significant reduction in BSFs has been confirmed by low temperature photoluminescence measurements.

Successive selective growth of semipolar (11-22) GaN on patterned sapphire substrate
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Thanks to the use of two successive selective growths by metal organic chemical vapor deposition reactor, high quality semipolar (11-22) GaN with a homogenous defect repartition over the surface was achieved. The procedure starts with a first selective growth on a patterned sapphire substrate, leading to continuous stripes of three dimensional (3D) GaN crystals of low defect density. Then, a second selective growth step is achieved by depositing a SiNx nano-mask and a low temperature GaN nano-layer on the top of the GaN stripes. Hereby, we demonstrate an original way to obtain a homoepitaxial selective growth on 3D GaN crystals by taking advantage of the different crystallographic planes available.

Basal stacking faults (BSFs) are generated during this second selective growth but could be eliminated by using a three-step growth method in which elongated voids are created above the defective area. For a fully coalesced sample grown using the 2 step method, dislocation density of 1.2 × 108 cm−2 and BSFs density of 154 cm−1 with a homogenous distribution have been measured by cathodoluminescence at 80 K. Consequently the material quality of this coalesced semipolar layer is comparable to the one of polar GaN on c-plane sapphire.

K doping effect on structural and optical properties of ZnO nanorods grown on semipolar (112 − 2) GaN films using a hydrothermal growth method
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In this work, we investigated the potassium (K) doping effect on structural and optical properties of ZnO nanorods grown on semipolar (112 − 2) GaN films using a hydrothermal growth method. The X-ray diffraction θ-2θ scan of the ZnO nanorods without any seeding step showed that most of the single-crystalline ZnO nanorods were highly inclined to the c-axis [0001] direction. In the case of hydrothermally-grown K-doped ZnO nanorods, growth occurred not only in the normal [112 − 2] direction, but also along the c-axis [0001] and m-axis [101 − 0] directions. As the growth proceeded even further, micron-sized ZnO pyramids having nonpolar and semipolar planes were formed on the ZnO nanorods. The optical properties of K-doped ZnO nanorods and pyramids were studied using cathodoluminescence measurements. While the near band edge peak was centered at 382 nm for pure c-plane ZnO nanorods, a significant peak
shift to 418 nm for the K-doped ZnO nanorods was observed with relatively broad emissions. It is believed that the violet emissions centered at 418 nm are mainly associated with both K interstitial and Zn interstitial defects. Thus, the electron transitions from K interstitial levels to the valence band can lead to relatively strong violet emissions at 418 nm for K-doped ZnO nanorods and pyramids.

Optical nonlinearities and ultrafast all-optical switching of m-plane GaN in the near-infrared
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We reported a systematic investigation on the three-photon absorption (3PA) spectra and wavelength dispersion of Kerr refraction of bulk m-plane GaN crystal with both polarization E⊥c and E//c by femtosecond Z-scan technique in the near-infrared region from 760 to 1030 nm. Both 3PA spectra and Kerr refraction dispersion were in good agreement with two-band models. The calculated nonlinear figure of merit and measured ultrafast nonlinear refraction dynamics via femtosecond pump-probe with phase object method revealed that m-plane GaN would be a promising candidate for ultrafast all-optical switching and autocorrelation applications at telecommunication wavelengths.

Demonstration of low resistance ohmic contacts to p-type (20bar 2bar 1) GaN
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We demonstrate low resistance Ohmic contacts to (20\bar{2}\bar{2}\bar{1}) semipolar p-type GaN using a thin p++-GaN contact layer. This layer was optimized by varying the V/III ratio, Cp2Mg flow,
thickness, and growth rate which produced low forward voltage devices with specific contact resistivities estimated to be $4 \times 10^{-4}$ $\Omega$ cm$^2$ and $5 \times 10^{-4}$ $\Omega$ cm$^2$ for palladium contacts and indium tin oxide (ITO) contacts respectively. Forward voltages of 2.89 V and 3.47 V were obtained at 20 A cm$^{-2}$ and 800 A cm$^{-2}$ respectively for light emitting diodes (LEDs) emitting at 435 nm with palladium contacts. LEDs with ITO contacts had forward voltages of 2.94 V and 3.55 V at 20 A cm$^{-2}$ and 800 A cm$^{-2}$ respectively.

Semipolar (112－2) InGaN light-emitting diodes grown on chemically–mechanically polished GaN templates

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InGaN multiple quantum well light-emitting diodes (LEDs) were grown on chemically–mechanically polished (112) GaN templates (up to 100 mm diameter wafers) by metalorganic vapour phase epitaxy. Initial GaN overgrowth on the polished templates in nitrogen ambient maintained the polished surface. The peak emission wavelength of the LEDs varied from 445 to 550 nm. In contrast to the simultaneously grown LEDs on as-grown templates, the LEDs on polished templates have very smooth surface morphology, uniform luminescence, and higher output power.

Direct growth of freestanding GaN on C-face SiC by HVPE

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In this work, high quality GaN crystal was successfully grown on C-face 6H-SiC by HVPE using a two steps growth process. Due to the small interaction stress between the GaN and the SiC substrate, the GaN was self-separated from the SiC substrate even with a small thickness of about 100 μm. Moreover, the SiC substrate was excellent without damage after the whole process so that it can be repeatedly used in the GaN growth. Hot phosphoric acid etching (at 240 °C for 30 min) was employed to identify the polarity of the GaN layer. According to the etching results, the obtained layer was Ga-polar GaN. High-resolution X-ray diffraction (HRXRD) and electron backscatter diffraction (EBSD) were done to characterize the quality of the freestanding GaN. The Raman measurements showed that the freestanding GaN film grown on the C-face 6H-SiC was stress-free. The optical properties of the freestanding GaN layer were determined by photoluminescence (PL) spectra.

Progress in bulk GaN growth

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Three main technologies for bulk GaN growth, i.e., hydride vapor phase epitaxy (HVPE), Na-flux method, and ammonothermal method, are
discussed. We report our recent work in HVPE growth of GaN substrate, including dislocation reduction, strain control, separation, and doping of GaN film. The growth mechanisms of GaN by Na-flux and ammonothermal methods are compared with those of HVPE. The mechanical behaviors of dislocation in bulk GaN are investigated through nano-indentation and high-space resolution surface photo-voltage spectroscopy. In the last part, the progress in growing some devices on GaN substrate by homo-epitaxy is introduced.

**Effect of III/V ratio on the polarity of AlN and GaN layers grown in the metal rich growth regime on Si(111) by plasma assisted molecular beam epitaxy**

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Wet chemical etching, reflection high energy electron diffraction, scanning electron microscope and convergent beam electron diffraction have been employed to study the polarities of AlN and the subsequently grown GaN as a function of metal flux in the metal rich growth regime. Both AlN and GaN exhibited metal polarity in the intermediate growth conditions. However, in the droplet growth regime, the polarity of AlN and GaN were N polar and Ga polar, respectively. It was observed that Ga polar GaN could be obtained on both Al and N polar AlN. AlGaN/GaN high electron mobility transistor (HEMT) heterostructure exhibiting hall mobility of 900 cm2 V−1 s−1 and sheet carrier density of 1.2 × 1013 cm−2 was demonstrated using N polar AlN which confirmed Ga polarity of GaN. Al metal flux was likely to play an important role in controlling the polarity of AlN and determining the polarity of the subsequent GaN grown on Si(111) by plasma assisted molecular beam epitaxy (PA-MBE).

**Correlation between switching to n-type conductivity and structural defects in highly Mg-doped InN**

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The effect of Mg doping on the microstructure of InN epitaxial films in relation to their free-charge carrier properties has been investigated by transmission electron microscopy (TEM) and aberration corrected scanning TEM. We observe a direct correlation between Mg concentration and the formation of stacking faults. The threading dislocation density is found to be independent of Mg concentration. The critical Mg concentration for the onset of stacking faults formation is determined and found to correlate with the switch from p- to n-type conductivity in InN. Potential mechanisms involving stacking faults and point defect complexes are invoked in order to explain the observed conductivity reversal. Finally, the stacking faults are structurally determined and their role in the reduction of the free electron mobility in highly doped InN:Mg is discussed.

**Exciton luminescence in AlN triggered by hydrogen and thermal annealing**

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Exciton recombination bands in homoepitaxial AlN layers are strongly dependent on the presence of hydrogen. By thermal treatment under hydrogen-free and hydrogen-rich ambient, respectively, several sharp bound exciton lines are modulated in intensity reversibly. In contrast, the exciton bound at the neutral donor silicon remains unaffected. The mechanism causing these effects is most probably hydrogen in- and out-diffusion into the AlN sample. The main factor determining hydrogenation of AlN layers is found to be molecular H₂ in contrast to NH₃. We find hints that carbon incorporation into AlN may be closely related with that of hydrogen. Besides photoluminescence spectra of exciton bands, our model is supported by theoretical reports and comparison to the case of hydrogen in GaN.

Neutral anodic etching of GaN for vertical or crystallographic alignment
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Etching of gallium nitride for various device applications has attracted much attention; however, previous reports have all been performed in acidic or basic etchant solutions. Herein, we demonstrate how neutral electrolytes such as NaNO₃ or NaCl can be used to rapidly etch n-GaN electrochemically and achieve a porous structure that is either vertically aligned or faceted according to the GaN crystallography, in NaNO₃ and NaCl, respectively. It is demonstrated that the etching properties of NaNO₃ and HNO₃ are very similar, showing that the etching process in this system is surprisingly insensitive to pH. This neutral-pH process enables safer and greener GaN etching, as well as opening up the possibility of crystallographic etching of GaN using an anodic process.

Interfacial reaction control and its mechanism of AlN epitaxial films grown on Si(111) substrates by pulsed laser deposition
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High-quality AlN epitaxial films have been grown on Si substrates by pulsed laser deposition (PLD) by effective control of the interfacial reactions between AlN films and Si substrates. The surface morphology, crystalline quality and interfacial property of as-grown AlN/Si hetero-interfaces obtained by PLD have been systemically studied. It is found that the amorphous SiAlN interfacial layer is formed during high temperature growth, which is ascribed to the serious interfacial reactions between Si atoms diffused from the substrates and the AlN plasmas produced by the pulsed laser when ablating the AlN target during the high temperature growth. On the contrary, abrupt and sharp AlN/Si hetero-interfaces can be achieved by effectively controlling the interfacial reactions at suitable growth temperature. The mechanisms for the evolution of interfacial layer from the amorphous SiAlN layer to the abrupt and sharp AlN/Si hetero-interfaces by PLD are hence proposed. This work of obtaining the abrupt interfaces and the flat surfaces for AlN films grown by PLD is of paramount importance for the application of high-quality AlN-based devices on Si substrates.
Indirect excitation of Eu3+ in GaN codoped with Mg and Eu
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Temperature-dependent Eu3+ luminescence spectra in GaN(Mg):Eu can be assigned to, at least, two distinct Eu3+ centres, denoted by Eu0 and Eu1. The splitting energy levels of the 7FJ (J=1,2) multiplets for the Eu0 and Eu1 centres have been calculated using the equivalent operator Hamiltonian for C3v crystal field with the addition of an odd parity distortion.

Stress engineering in GaN structures grown on Si(111) substrates by SiN masking layer application
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GaN layers without and with an in-situ SiN mask were grown by using metal organic vapor phase epitaxy for three different approaches used in GaN on silicon(111) growth, and the physical and optical properties of the GaN layers were studied. For each approach applied, GaN layers of 1.4 μm total thickness were grown, using silan SiH4 as Si source in order to grow SixNx masking layer. The optical micrographs, scanning electron microscope images, and atomic force microscope images of the grown samples revealed cracks for samples without SiN mask, and micropits, which were characteristic for the samples grown with SiN mask. In situ reflectance signal traces were studied showing a decrease of layer coalescence time and higher degree of 3D growth mode for samples with SiN masking layer. Stress measurements were conducted by two methods—by recording micro-Raman spectra and ex-situ curvature radius measurement—additionally PLs spectra were obtained revealing blueshift of PL peak positions with increasing stress. The authors have shown that a SiN mask significantly improves physical and optical properties of GaN multilayer systems reducing stress in comparison to samples grown applying the same approaches but without SiN masking layer.

Growth of GaN Layers on Sapphire by Low-Temperature-Deposited Buffer Layers and Realization of p-type GaN by Magesium Doping and Electron Beam Irradiation
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This Review is a personal reflection on the research that led to the development of a method for growing gallium nitride (GaN) on a sapphire substrate. The results paved the way for the development of smart display systems using blue LEDs. The most important work was done in the mid to late 80s. The background to the author’s work and the process by which the technology that enables the growth of GaN and the realization of p-type GaN was established are reviewed.

Photo-etching of GaN: Revealing nano-scale non-homogeneities
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Nano-scale non-homogeneities in MOCVD- and HVPE-grown gallium nitride were revealed by means of photo-etching in K2S2O8-KOH solution and by chemical etching in hot KOH solution. These non-homogeneities result in formation of protruding etch features and in-depth elongated nano-pits, respectively. High spatial resolution cathodoluminescence evidenced a non-homogeneous distribution of non-radiative recombination centers, which correlates well with photo-etched pattern of protruding etch features. The density of these features is two orders of magnitude higher than this of threading dislocations. A possible association between the non-uniform in nano-scale distribution of native point-type defects, such as VGa, ON and related VGa-ON complexes, and the observed etch features is presented. Existence of such fluctuations may have a large influence on the reliability of nitride-based electronic and optoelectronic devices.

**Ohmic Contacts on p-GaN**

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Advanced Electronic Materials  
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With the development of GaN-based optoelectronic devices, the need for p-GaN contacts with low resistivity, good thermal stability, and high transparency or reflectivity has become more pressing. Various contact schemes to satisfy these requirements have been investigated in the past two decades. In this progress report, the main developments of contacts on p-GaN throughout these years are summarized. The primary focus is on the materials aspects of the contacts and the functional mechanisms related to their relevant properties. The important process of surface treatment is also discussed briefly at the end of the article.

Critical impact of Ehrlich-Schwöbel barrier on GaN surface morphology during homoepitaxial growth

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We discuss the impact of kinetics, and in particular the effect of the Ehrlich-Schwöbel barrier (ESB), on the growth and surface morphology of homoepitaxial GaN layers. The presence of an ESB can lead to various self-assembled surface features, which strongly affect the surface roughness. We present an in-depth study of this phenomenon on GaN homoepitaxial layers grown by metal organic vapor phase epitaxy and molecular beam epitaxy. We show how a proper tuning of the growth parameters allows for the control of the surface morphology, independent of the growth technique.

Ammonothermal growth of GaN crystals on HVPE-GaN seeds prepared with the use of ammonothermal substrates

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Journal of Crystal Growth  
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Results of gallium nitride crystallization by ammonothermal method are presented. GaN crystals grown earlier by HVPE method on an ammonothermal GaN substrate and an MOCVD-GaN/sapphire template were used as seeds. Structural and optical properties of the obtained materials are studied and compared. Large radius of curvature (>100 m) and low dislocation density (7x10^4 cm^-2) can be reproduced in the ammonothermal method using an HVPE-GaN seed grown before on ammonothermal GaN. This proves that the use of HVPE-GaN grown on ammonothermal seeds allows to reproduce high crystallinity in a subsequent ammonothermal growth. It also demonstrates that a much more effective multiplication process of high quality GaN can be launched using a combination of the ammonothermal and HVPE methods.
PRESS RELEASE

Technical and economic information selected by Knowmade

OPTOELECTRONICS

Nanowire LED firm Aledia completes $31m Series B financing

Semiconductor Today

Aledia S.A. of Grenoble, France, which is developing light-emitting diodes based on 'WireLED' three-dimensional (3D) nanowire GaN-on-silicon technology that is claimed to cut manufacturing costs compared to conventional planar (2D) LEDs, has closed its Series B financing round and executed development and supply contracts with major LED buyers.

The round, totalling up to €28.4m ($31m), includes new investments from Valeo (one of the world’s largest automobile-equipment makers and the world’s second-largest supplier of car lighting systems); IKEA GreenTech AB (the venture capital arm of IKEA); and the Ecotechnologies fund of Bpifrance (the French national industrial bank).

Existing investors Sofinnova Partners, Braemar Energy Ventures, Demeter Partners and CEAi/ATi also participated in the round.

"This financing round, abundantly oversubscribed, and particularly the presence of two very large potential corporate customers, testifies to the interest that our cost-disruptive nanowire LED technology is generating in the customer base, as well as in the financial community," comments CEO, chairman & co-founder Giorgio Anania.

Based on technology originally developed by the CEA-Leti nanotech research institute in Grenoble, Aledia is developing a new generation of LEDs that are fabricated on large-diameter 200mm (8-inch) silicon wafers (allowing manufacturing in existing CMOS foundries), that promise to be significantly less expensive than traditional '2D' LEDs, it is reckoned, and that allow straightforward integration with electronics. Aledia is also working on next-generation displays.

"We are progressing with the development of the technology and this financing round will allow us to accelerate significantly the speed of development and the customer traction," Anania says. "In Valeo we have a major potential customer in the automotive LED market, generally viewed as the most profitable market segment." Simultaneously with the investment, Aledia has signed a supply agreement with Valeo.

"Aledia's 3D LED technology, together with Valeo's expertise in automobile lighting systems, has the potential to put on the market a technological breakthrough in innovative lighting systems, perfectly in line with Valeo Lighting System's mission to provide performance and style, and contribute to the safety of road users," says Maurizio Martinelli, Valeo Visibility business group president.

"This technology will be one important part in the IKEA Group strategy to supply high-quality, energy-saving lighting products to consumers worldwide," says IKEA GreenTech's managing director Christian Ehrenborg. "The low-price opportunity for residential use has the potential of faster implementation of the LED technology," he adds. "The connectivity functions of Aledia's technology also open up new interesting possibilities to make life at home more convenient and smarter."

"Aledia also benefits from its head start to create a French and European sector in LED, among which partnerships with prestigious industrialists such as IKEA and Valeo constitute the first stage," comments Bpifrance Investissement's investments director Anne-Sophie Carrese.

Read more

Leti demos new process for fabricating high-brightness micro-LED arrays for next-gen head-mounted and head-up displays

Semiconductor Today

At SID’s Display Week 2015 event in San Jose, CA, USA (31 May-5 June), Grenoble-based micro/nanotechnology R&D center CEA-Leti of France announced that it has demonstrated a path to fabricating high-density micro-LED arrays...
for the next generation of wearable and nomadic systems in a process that is scalable to the IC manufacturing process.

High-brightness, enhanced-vision systems such as head-up and head-mounted displays can improve safety and performance in fields such as aeronautics and automotive, where the displays allow pilots and drivers to receive key navigation data and information in their line of sight. For consumers, smart glasses or nomadic projection devices with augmented reality provide directions, safety updates, advertisements and other information across the viewing field. LED microdisplays are suited to such wearable systems because of their low footprint, low power consumption, high contrast ratio and ultra-high brightness, says Leti.

Leti researchers have developed gallium nitride (GaN) and indium gallium nitride (InGaN) LED technology for producing high-brightness, emissive microdisplays for these applications, which are expected to grow dramatically in the next 3-5 years. For example, the firm MarketsandMarkets forecasts that the market for head-up displays alone will grow from $1.37bn in 2012 to $8.36bn in 2020. "Currently available microdisplays for both head-mounted and compact head-up applications suffer from fundamental technology limitations that prevent the design of very low-weight, compact and low-energy-use products," notes Ludovic Poupinet, head of Leti's Optics and Photonics Department. "Leti's technology breakthrough is the first demonstration of a high-brightness, high-density micro-LED array that overcomes these limitations and is scalable to a standard microelectronic large-scale process," he adds. "This technology provides a low-cost, leading-edge solution to companies that want to target the fast-growth markets for wearable vision systems."

Leti says that its technology innovation is based on micro-LED arrays that are hybridized on a silicon backplane. Key developments include epitaxial growth of LED layers on sapphire or other substrates, micro-structuring of LED arrays (10μm pitch or smaller), and 3D heterogeneous integration of such LED arrays on CMOS active matrices.

These innovations make it possible to produce a brightness of 1 million cd/m2 for monochrome devices and 100kcd/m2 for full-color devices with a device size below 1-inch and 2.5 million pixels. This is a 100- to 1000-times improvement compared with existing self-emissive microdisplays, with very good power efficiency, it is reckoned. The technology should also allow the fabrication of very compact products that significantly reduce system integration constraints.

The high-density micro-LED array process was developed in collaboration with III-V Lab (a joint venture between Paris-based Alcatel-Lucent Bell Labs France, Thales Research and Technology, and CEA-Leti).

Read more

**Chinese LED maker Changelight buys Veeco EPIK 700 MOCVD systems**

*Semiconductor Today*

Epitaxial deposition and process equipment maker Veeco Instruments Inc of Plainview, NY, USA says that Xiamen Changelight Co Ltd of Xiamen, China has purchased multiple TurboDisc EPIK 700 gallium nitride (GaN) metal-organic chemical vapor deposition (MOCVD) systems for faster production and greater yield of light-emitting diodes for general lighting applications.

Changelight says that the decision to purchase EPIK 700 systems was based on their reliable performance and on Changelight's existing experience with other Veeco TurboDisc MOCVD reactors (including a large installed base of MaxBright and K475 MOCVD systems for high-volume LED production).

"Veeco's TurboDisc platform has provided Changelight with increased LED wafer production and easy process transfer between systems, saving us both time and money," comments Haifang Cai, general manager & board member of Changelight. "By adding multiple EPIK 700 MOCVD systems to our fleet of reactors, we can ramp even more quickly, expand high-volume production with best-in-class wafer uniformity and reduce operating expenses."

Introduced in 2014 and available in one- and two-reactor configurations, the EPIK 700 MOCVD system is reckoned to be the LED industry's highest-productivity system, reducing cost per wafer by up to 20% compared with previous-generation systems. The system features
technologies including the IsoFlange center injection flow and TruHeat wafer coil technologies, which provide homogeneous laminar flow and uniform temperature profile across the entire wafer carrier. These innovations produce wavelength uniformity to drive higher yields in a tighter bin. Veeco says that the EPIK700 system offers a 2.5x throughput advantage over other systems due to its large reactor size. Designed for mass production, it accommodates 31x4", 12x6" and 6x8" wafer carrier sizes. Users can transfer processes from existing TurboDisc platforms to the EPIK 700 MOCVD system, enabling quick-start production of LEDs.

"As the preferred MOCVD system for Changelight, the increased capacity and technology advantages of the EPIK 700 system will support their growth and position as a leading LED manufacturer for general lighting and display markets," says Jim Jenson, senior VP & general manager of Veeco MOCVD Operations.

Epileds qualifies Aixtron’s AIX R6 MOCVD system for LED mass production

Deposition equipment maker Aixtron SE of Herzogenrath, near Aachen, Germany says that its AIX R6 metal-organic chemical vapor deposition (MOCVD) system (launched last November) has been qualified by LED chip maker Epileds Co Ltd of Tainan Science Park, Taiwan for LED epitaxy mass production as part of its capacity expansion. "The AIX R6 has demonstrated its capabilities during our qualification process, especially with regards to LED brightness, uniformity and throughput," says Epileds' president Ming Sen Hsu. "It features a large capacity and ability to perform multiple continuous runs without any maintenance. As a consequence, we have moved the AIX R6 into production. We are looking forward to benefit from its lowest cost of ownership in the market...we intend to make the AIX R6 the backbone of our high-brightness LED production," he adds.

"We have a long-standing and trustful commercial relationship with Epileds," says Aixtron's executive VP & chief operating officer Dr Bernd Schulte. "Due to an already large install base, Epileds has extensive experience with our Close Coupled Showerhead technology which has facilitated the implementation of the AIX R6," he adds. Epileds manufactures blue, green, red, and white light LED wafers and chips with a full range of wavelengths (ranging from 365 to 940nm) suitable for applications such as indicators of consumer electronics, light sources for fax machines and scanners, indoor or outdoor display boards, automotive lighting, traffic signals and illuminators.

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Semi-polar GaN LED firm Seren wins best business and investment award at European Photonics Venture Forum

Seren Photonics Ltd of Pencoed Technology Park, UK, which was spun off from the University of Sheffield in 2009 with funding from venture capital firm FusionIP plc (now part of IPGroup plc), was one of six firms to win an award for best business and investment opportunity at the 1st European Photonics Venture Forum (EPVF) held in Rome, Italy on 16 April.

Organized by the European Photonics Industry Consortium (EPIC) of Paris, France, the event was conceived to enable European technology companies with high potential to gain access to more than 30 venture finance companies and to present to a panel of investment experts.

Seren has commercialized technology developed by professor Tao Wang of the University of Sheffield's Electronic and Electrical Engineering Department and uses nano-engineered structures to enhance the properties of III-nitride materials.

Seren's business plan, presented by CEO Dr Carl Griffiths, highlighted the potential of semi-polar gallium nitride (GaN) material in LEDs and other photonic applications, as well as the significant growth potential for the firm as interconnected light-emitting devices become ever more embedded in everyday products.

"Receiving this award is an acknowledgment of the growth potential and compelling value proposition offered by Seren's semi-polar GaN products," says Griffiths. "As we now begin the process of ramping up to larger volumes and larger wafer sizes, it's always pleasing to receive positive validation of our business plan."
RayVio claims record deep-UV LED cw power density of 30W/cm²

RayVio Corp of Haywood, CA, USA, which is developing and commercializing deep-ultraviolet (UV) LEDs and consumer disinfection solutions, says that it has demonstrated record-performance deep UV LEDs, resulting in a single-chip device capable of delivering 45mW of continuous power at deep-UV wavelengths from a 0.15mm² emitting area, i.e. record continuous-wave (cw) power density of 30W/cm² at the emission surface.

RayVio’s core technology was invented by co-founder Dr Yitao Liao (chief technology officer) and professor Theodore Moustakas, and is exclusively licensed from Boston University. The technology is based on a proprietary and fundamentally different approach compared to techniques that have been attempted by the industry unsuccessfully for the past 15 years, it is claimed, enabling the firm to provide the highest optical power at the lowest cost than is otherwise commercially available. "This enables us to unleash Haitz' Law for deep UV LEDs, the same Haitz' Law that enabled blue and white LEDs to revolutionize the lighting and display industries," says Liao.

RayVio says it is working with OEM customers to develop integrated products enabled by its UV LED devices. Applications range from digital curing to dermatology and biomedical instrumentation, as well as surface, air and water disinfection for consumers.

"Leading OEM and consumer electronics manufacturing partners have been evaluating our current products for the past several months, while we continue to install more capacity at our facility in Silicon Valley and ramp global supply chain partners to satisfy customer demand," says co-founder & CEO Dr Robert C. Walker.

Together with manufacturing and integration support located around the globe, RayVio reckons that its capital-efficient and scalable manufacturing process allows for rapid capacity expansion and lower manufacturing cost. The firm adds that such high-performance and cost effective UV LEDs make it possible to decrease system price, complexity and time to market.

Read more

Lumileds releases lifetime data for LUXEON 3535L mid-power LEDs

Philips Lumileds of San Jose, CA, USA has released LM-80 test results for its LUXEON 3535L mid-power LED line, enabling L90 fixture life of more than a decade.

Completing 10,000 hours of LM-80 testing at 55°C, 85°C and 105°C, Lumileds has exceeded lumen-maintenance requirements of the US Environmental Protection Agency's ENERGY STAR program, qualification by the DesignLights Consortium (DLC), as well as other emerging specifications. Projections based on TM-21-11 show that the devices will maintain 90% of their initial lumen output (L90) for a minimum of 60,000 hours at a 200mA drive current and Ts temperature of 85°C. Exceptional lifetimes were extrapolated at all test conditions, says Lumileds. This performance means that LUXEON 3535L LEDs can operate in an LED fixture for 13 years (based on 12 hours of usage per day, 365 days a year) while maintaining at least 90% of their initial brightness.

Historically, customers have expressed concerns regarding the long-term performance of mid-power LEDs says Lumileds. The firm says that, by leveraging its expertise in high-power LEDs, it has developed the LUXEON 3535L line of mid-power emitters that demonstrate what is claimed to be unparalleled lumen maintenance and reliability. Offered in a range of correlated color temperature (CCT) and color rendering index (CRI) options, the standard-format LEDs are suitable for applications such as troffers, downlights, low-bay and TLEDs. In addition, the LUXEON 3535L packages are offered at three performance and price levels — the 3535LS, 3535L, and 3535L HE — giving fixture designers flexibility.

Read more
Transphorm receives $70m investment led by KKR

**Semiconductor Today**

Transphorm Inc of Goleta, near Santa Barbara, CA, USA (which designs and provides gallium nitride-based power conversion devices and modules) has announced a $70m investment round led by global investment firm KKR. This follows initial funding rounds led by funds affiliated with Kleiner Perkins Caufield and Byers, Foundation Capital, Google Ventures, Soros Quantum Strategic Partners, INCJ and Fujitsu. Transphorm will use the latest funding to support its growth, product innovation and expansion.

"Transphorm was launched to address the urgent and important problem of losses in power conversion," says chairman Dr Umesh Mishra. "By merging the technological leadership of Transphorm with the semiconductor business expertise of KKR, we are taking a major step forward in solving the global problem of energy wasted in power conversion," he claims.

Transphorm believes that there is a large market for its products as its ultra-efficient power devices and modules can eliminate more than 40% of all electric conversion losses by using gallium nitride. Transphorm's products have a power efficiency of up to 98% in data centers and telecom applications, resulting in energy savings of over 10GWh annually in a typical data center (equivalent to the annual electricity usage of 1000 typical US homes), it is reckoned. In addition to solar photovoltaic (PV) inverters and data centers, other applications include power supplies, motor drives and automotive systems.

Manufacturers are now producing what are reckoned to be the world's smallest PV inverters by leveraging Transphorm’s technology. Transphorm has established strategic partnerships with customers and suppliers including motion control, robotics and systems engineering firm Yaskawa Electric Corp, which earlier this year used Transphorm's GaN technology to power what is said to be the first GaN-based commercially produced PV inverter launched on the Japan market. Transphorm’s products enable approximately 50% smaller PV inverters in residential and small commercial installations up to 5kW, resulting in lower system, installation and service costs while delivering more energy per solar panel to the grid, it is claimed. Tata Power Solar (India's leading power conversion player) has also teamed with Transphorm to develop PV inverters. To provide customers with volume production, Transphorm partnered with Fujitsu Semiconductor to produce its products in Fujitsu’s automotive-class wafer fabrication facility in Aizu-Wakamatsu, Japan.

"Right now, Transphorm is the only place where customers can acquire reliable, production-volume GaN products that meet or exceed required performance specs for commercial products," says KKR's senior advisor David Kerko.

"Long term, we believe this has the potential to replace all of the existing silicon-based technology used in high-voltage products, and wide adoption of this technology will dramatically reduce the amount of energy that is wasted by electric devices."

For KKR, the investment is part of the firm's growth equity strategy, which is focused on market-leading, high-growth companies for which it can be a unique partner in helping to reach scale and the next level of growth. The firm is funding the investment from the balance sheet of KKR & Co LP.

As part of the transaction, KKR's David Kerko, Brittany Bagley and Eiji Yatagawa will join Transphorm’s board of directors, and KKR has also nominated semiconductor industry veterans Mario Rivas (former president & CEO of Anadigics Inc) and Michael White to the board.

Read more

**GaN Systems claims smallest 650V, 15A GaN transistor**

**Semiconductor Today**

GaN Systems Inc in Ottawa, Ontario, Canada – a fabless developer of gallium nitride (GaN)-based power switching semiconductors for power conversion and control applications – is claiming that its GS66504B – one of a family of 650V devices spanning currents of 7A to 200A – is the world's smallest 650V, 15A GaN transistor, with a footprint of just 5.0mm x 6.5mm (50% smaller than competing devices).
"We were somewhat surprised to see announcements at last week's PCIM power electronics exhibition and conference that trumpeted gallium nitride 600V, 15A devices in 8mm x 8mm dual-flat no-lead (DFN) packaging as the 'industry’s smallest' enhancement-mode devices – our part is clearly much smaller,” states CEO Jim Witham. "But I suppose this is just an indication of how quickly the GaN market is moving, and a positive indication that silicon has reached its limits," he adds.

"Our message to designers in applications as diverse as flat-screen TVs, games consoles, washing machines, inverters, electric vehicles, motors and wider is the same: if you are not on-board with GaN, you will be left behind by your competitors," continues Witham.

GaN Systems claims to be the first company to have developed and brought to the global market a comprehensive product range of devices with current ratings from 7A to 250A – its Island Technology die design, combined with its extremely low inductance and thermally efficient GaNPX packaging and Drive Assist technology means the company's GaN transistors offer a 40-fold improvement in switching and conduction performance over traditional silicon MOSFETs and IGBTs. Devices are available now through its worldwide distribution network.

GaN Systems showcasing new high-power transistor for first time in China at PCIM Asia

In booth 4D18 at PCIM (Power Conversion Intelligent Motion) Asia 2015 in Shanghai (24–26 June), GaN Systems Inc in Ottawa, Ontario, Canada – a fabless developer of gallium nitride (GaN)-based power switching semiconductors for power conversion and control applications – is showcasing a new addition to its range of GaN high-power transistors for the first time in China. The firm is also demonstrating production models of real customer applications using its devices. PCIM Asia is GaN Systems' first major exhibition in China, which it expects to become an important market as GaN power transistors increasingly replace silicon semiconductors in power electronics.

The new 60A GaN high-power enhancement-mode device (the GS66516T) expands GaN Systems' range of power switching semiconductors, which it claims is already the broadest product offering on the market (with current ratings ranging from 8A to 250A). Based on the firm's Island Technology die design and packaged in low-inductance and thermally efficient GaNPX packaging, the GS66516T also features new proprietary top-side cooling technology (announced in March), enabling it to be cooled using familiar and conventional heatsink or fan cooling techniques. The firm says that, as gallium nitride technology moves into mainstream production in markets ranging from consumer to industrial and clean
tech, early adopters have already released products onto the market that take advantage of GaN Systems’ technology, which harnesses the superior fast switching performance of GaN and reduces power losses by up to 90%, resulting in smaller and far more efficient power electronics.

Also at PCIM Asia, GaN Systems is demonstrating a 650V 30A 3-phase inverter power module from Korea-based LS Industrial Systems, which focuses on delivering safe clean energy. Also being shown is a new 3kW, 800/380V DC/DC bi-directional converter developed by the NextHome consortium in the USA, a group of consumer electronics manufacturers who are developing new energy-efficient power systems for use in the home.

Read more

GaN Converters Charge Simultaneously
EETimes
Mobile devices have gotten slimmer over the years but chargers have remained in the same clunky form factors. Zolt, a subsidiary of gallium nitride (GaN) fab Avogy, has developed a lipstick tube sized charger capable of powering three devices at once at up to 70 Watts.

Zolt’s power converters allow users to charge batteries of different sizes simultaneously without overheating or experiencing large switching losses. The Zolt Laptop Charger Plus can maintain a skin temperature of 63 degrees and is efficient enough dissipate power and save 5-8 degrees in the adapter.

Zolt’s designers hope to replace bulky batteries with a much smaller multi-device charger.
Source: Avogy

The device can power any laptop and two USB-based devices with range of 110V to 240V. An onboard microcontroller runs firmware to identify devices and route a specified amount of current through each of the devices ports, said Poonacha Kongetira, Avogy vice president of systems engineering.

To negate switching losses that typically occur in switch board power supplies, the Zolt Laptop Charger Plus switches the FET when voltage across the device is zero. A wide bandgap semiconductor such as GaN is an excellent fit for heavily modulated power cycling, Kongetira said, noting that you could feed 1,200 V into the semiconductor without degrading reliability.

GaN can also operate at very high frequencies, which allows Zolt to use a resonant tank circuit that oscillates at its own frequency.

“If you operate a device at a higher frequency than the resonant frequency of this tank, you get zero voltage switching. This circuit voltage tech allows us to be very efficient,” Kongetira said.

While the primary consumer need is in charging devices, Avogy officials expect high voltage frequency GaN to fit any market where AC power needs to be converted down – from servers to windmills and data centers where high voltage devices could be made smaller and cooler.

Read more

Viewpoint: GaN power amps start with the transistor
Electronics Weekly
The first step in designing a microwave frequency power amplifier monolithic microwave integrated circuit on a given GaN foundry process is to select the transistor size and bias, writes Liam Devlin.

The high breakdown voltage and operating temperature capability of high electron mobility transistors (HEMTs) fabricated on a gallium nitride (GaN) semiconductor process makes the technology well suited to building power amplifiers (PAs).
A number of commercial GaN foundry processes are now available and the creation of custom microwave GaN PA monolithic microwave integrated circuits (MMICs) is a practical option for many applications.

**Bandgap size matters**
At 3.4eV GaN is a wide bandgap material. This compares to 1.4eV for gallium arsenide (GaAs) which is the other main high-frequency semiconductor process technology. Materials with a wider bandgap can withstand a higher electric field, so transistors made with them can have a higher breakdown voltage, which leads to a higher RF output power capability.

Most of the commercially available GaN foundry processes used for microwave frequency amplifiers are built on semi-insulating silicon carbide (SiC) substrates. The devices are fabricated in a thin layer of GaN on top of the much thicker SiC substrate (Figure 1). GaN transistors often include a source-coupled field-plate (‘Source FP’ in Figure 1). Its main purpose is to reduce the fields at the surface at high drain-gate voltages. The presence of the field plate increases the breakdown voltage of the transistor. The downside of having a field plate is that it also increases the gate-source capacitance, which degrades the maximum operating frequency compared to a device of the same gate length without one.

Another effect of source field plates is that they shield the gate from the drain. This reduces the feedback between the drain and the gate, increasing the RF gain. GaN HEMTs tend to have a higher maximum gain than their GaAs counterparts.

The transistors on GaN IC processes can be operated at significantly higher bias voltages than corresponding GaAs devices – typically 20V to 40V compared to 4V to 12V – so have a higher power density. This is the available output power per millimetre of gate width.

Another effect of the higher bias voltage is that for a given output power a GaN transistor will have a significantly higher output and input impedance than a GaAs PHEMT transistor, so it can be matched more easily, and matching bandwidths can be wider, while matching network losses are normally lower.

**Better thermal conductivity**
The thermal conductivity of the SiC substrate is good – around 10 times that of GaAs at room temperature. The higher power density of GaN transistors necessitates better thermal conductivity than GaAs, and even with an SiC substrate GaN PA transistors normally run at a higher channel temperature than their GaAs counterparts. However, GaN transistors are able to operate at higher junction temperatures than GaAs for a given reliability.

The RF output power that a transistor can produce increases with the physical size (total gate periphery). However, as the number of transistor fingers increases and/or the unit width of each finger increases, the available gain at microwave frequencies decreases as a result of distributed effects and increased parasitics. Microwave frequency PA MMICs therefore tend to make use of multiple power combined transistors to simultaneously achieve high output power and acceptable gain.

**Start with transistor size and bias**
The basic approach to designing a microwave frequency GaN PA MMIC on a given foundry process is to start by selecting the preferred transistor size and bias. Devices are normally operated in Class AB, and a quiescent current of 50mA to 100mA per millimeter of gate width is typical. The size of the device needs to be chosen to provide the required output power while achieving adequate gain. The power-added efficiency and linearity performance should also be assessed.

For power-combined reactively matched designs, a single stage design is normally implemented in the first instance. The transistor is first rendered unconditionally stable across the operating band by the addition of appropriate input losses. A load-pull bench is then used to optimise the matching structures. Multiple parallel copies of the single stage can then be combined to generate higher output power levels.

Two-, four- and eight-transistor designs are most common, as they lend themselves to a more practical layout. It is also common to absorb part of the matching network as an integral part of the combiner. Biasing components and networks to ensure broadband stability can now be added. It is
normal to start with the output stage and then add the driver stages. GaN transistors have a soft compression characteristic, and therefore the driver stages must be of sufficient size to avoid a requirement to drive the overall amplifier far into compression to achieve the expected output power. Liam Devlin is CEO of Plextek RFI

VisIC claims lowest-resistance 650V GaN power conversion switches

*Semiconductor Today*

VisIC Technologies Ltd of Rehovot, Israel, a fabless developer of power conversion devices based on gallium nitride (GaN) metal-insulator-semiconductor high-electron-mobility transistors (MISHEMTs) founded in 2010, has unveiled what it claims is the lowest-resistance 650V blocking voltage transistor, specifying a specific on-resistance (Rds(on)) as low as 12mΩ.

Reducing unnecessary losses in electrical energy conversion has been, and continues to be, a long-term goal for many companies producing energy conversion subsystems such as power supplies, photovoltaic inverters and electrical motor drives. These subsystems are used extensively in industrial, commercial and residential applications (robotics, elevators, washers, air conditioners, etc). Now a step-function reduction in conduction and switching losses for high-speed switching is possible due to VisIC’s developments, says the firm.

Used in power conversion switches (the fundamental building block for most energy conversion subsystems), VisIC’s 650V, 50A GaN transistors are targeted at the $12bn power transistor market. Based on a new design for GaN high-electron-mobility transistors (HEMTs), VisIC reckons that its products can accelerate the push to extend GaN-based technology from communications subsystems into power conversion subsystems.

Exagan raises €5.7m to produce GaN-on-Si power-switching devices on 200mm wafers

*Semiconductor Today*

Exagan of Grenoble, France, a gallium nitride (GaN) technology start-up that enables smaller and more efficient electrical converters, has raised €5.7m in first-round financing that will be used to produce high-speed power switching devices on 200mm wafers. The investors include French venture funds with a record of identifying and fostering promising, fast-growth, early-stage technology companies: Technocom2 (managed by French venture capital firm Innovacom); CM-CIC Innovation (the investment arm of European bank group Crédit Mutuel-CIC Group); IRDInov (a regional seed investor in emerging, fast-growth companies); CEA investissement (a manager of funds invested in technology companies, and which invested via the CEA strategic fund); and Soitec (which provides semiconductor materials).

Based in Grenoble (with a branch office in Toulouse), Exagan was spun off from CEA-Leti and Soitec in 2014 (with financial support from each), and licenses materials and technology from both organizations. Exagan aims to accelerate the power-electronics industry's transition from silicon-based technology to smaller and more efficient electrical converters based on GaN-on-silicon technology. Its GaN power switches are designed to be compatible with manufacturing in standard 200mm-wafer silicon foundries in order to provide high-performance, high-reliability products through a robust supply chain.

Following Exagan’s announcement in May of an agreement with X-FAB Silicon Foundries AG of Erfurt, Germany to produce devices on 200mm wafers, the financing will help to support Exagan's
aim of becoming Europe's primary supplier of GaN-based power switches for the solar, automotive and IT electronics markets. That aim includes its strategic partnership with CEA-Leti, which is developing applications with some of its industrial partners based on Exagan's G-FET 650V platform and its very high power-switching performance and extremely low conduction losses (enabling what is claimed to be unprecedented power integration and efficiency levels).

Power integration is key to meeting the growing demand for less expensive and more efficient electrical converters that silicon power devices cannot meet, says Exagan. In contrast, the material properties of GaN devices offer promising power-integration and efficiency gains that deliver higher power density and switching speed at the device level.

"This significant first round of financing validates our efforts over the past five years with Leti and Soitec to commercialize GaN-on-silicon technology and supports our commitment to provide customers with qualified GaN devices in large volumes," says Exagan's CEO & co-founder Frédéric Dupont. "We are focused on offering our customers reliable, high-performance devices that are developed with industrial partners already sourcing technologies or products for the targeted markets," he adds.

"Their GaN-on-silicon technology, which leverages our own materials expertise, opens very interesting opportunities in promising markets such as electronics, automotive and energy," notes Soitec's CEO Paul Boudre. "Exagan is well positioned to drive innovation in power switching technology, due to its location in Grenoble among the strong mix of innovative companies and technology-integration clusters," he adds.

"Based on our experience with the automotive and aerospace industries, we are convinced of the potential markets for GaN power electronic devices," notes IRDInov's managing director Jean-Michel Petit. "This is all the more reason to further develop its presence in Toulouse, which has a concentration of competencies in power-electronics applications and many potential future clients."

Leti has invested many years in developing GaN technologies because it believes they will drive innovation in the power-electronics industry and accelerate development of sustainable-energy technologies, says Leti’s CEO Marie Semeria, who regards Exagan as a European source of new GaN power switches for key industrial partners in transportation and energy as well as broader markets. "Through our partnership with Exagan, Leti will accelerate its investment in this area to further develop our leading expertise in GaN technology and related systems and applications," says Semeria.

Read more

Luftstrom project targets more efficient and quieter battery charging in electric vehicles

Semiconductor Today

With funding of about €3.9m from the German Federal Ministry of Education and Research (BMBF), 12 partners in the German automotive sector, its supply industry and the sciences (led by Infineon Technologies AG of Munich, Germany) are collaborating on the three-year research project Luftstrom (or Airstream, in English) to investigate how batteries in electric vehicles can be charged more efficiently. The use of gallium nitride (GaN) and silicon carbide (SiC) power semiconductors is expected to reduce losses during charging and, ultimately, make charging almost noiseless.

Electric vehicles are mainly charged overnight. However, charging in the charging device and voltage regulators creates heat that fans of water-cooled aggregates, for example, must dissipate. This can be quite noisy. The Luftstrom research aims to develop electronic power components that lower losses during charging by 30%. A reduction in waste heat and hence cooling effort means that cooling units will become more compact and operate more quietly. Components that already cause very few losses, such as auxiliary power supplies, could even do without the previously required water cooling, so loud fans would be eliminated.

The key to low-loss power electronics lies in power semiconductors based on GaN or SiC. The project will therefore also determine how such power semiconductors can be used reliably in charging devices, voltage regulators and inverters for auxiliary power units. The research results are expected to accelerate the transition to air-cooled
and fan-less systems for future generations of electric vehicles.
The entire automotive value-added chain for the production and use of these new systems is represented in the project. The 12 partners include AVL Software and Functions GmbH, BMW AG, Daimler AG, Fraunhofer Institute for Integrated Systems and Component Technology IISB, the University of Applied Sciences Ostwestfalen-Lippe, Infineon Technologies AG, Lenze Drives GmbH, Robert Bosch GmbH, RWTH Aachen University, Siemens AG, Leibniz University Hannover, and Volkswagen AG.

**Read more**

**Innovations to sustain silicon's 87% share of power electronics market versus wide-bandgap materials**

*Semiconductor Today*

Driven by technology innovations, silicon-based power electronics will continue their domination of the fastest-growing and largest markets, allowing silicon to maintain an 87% market share, worth $20bn by 2024, and constraining wide-bandgap semiconductor (WBG) materials to a smaller market share, according to Lux Research. Innovations in circuit design, control methods and module packaging will help silicon to hold off the adoption of WBG materials in many applications, particularly in the near-term, on account of silicon's high availability and volumes, reckons the market analyst firm.

"Circuit design innovation will have its biggest impact on space and efficiency improvements in IT and consumer electronics, while control method innovation impacts size reduction across all applications," says Lux Research associate Tiffany Huang, the lead author of the report 'Sorting Through the Maze of Silicon Innovations in Power Electronics'. "Innovations in module packing can not only reduce size, but increase the efficiency to be on par with current WBG innovations in transportation markets," she adds.

Lux Research analysts reviewed the ongoing innovations in silicon technology and ranked the leading companies on the Lux Innovation Grid on the basis of their technical and business execution scores. Their findings include the following:

- **TI, Maxim, Qualcomm dominate circuit design.**

  On the strength of their partnerships and customers in multiple market segments, Texas Instruments, Maxim, Power Integrations and Qualcomm are the 'Dominant' circuit design companies on the Lux Innovation Grid. Among start-ups, Ineda, Arctic Sand, Ambiq Micro, Brusa and Alpitronic are ranked 'High-potential'.

- **ABB, Dialog, Omron top in control methods.**

  With efficient products and partnerships, ABB, Dialog and Omron are the 'Dominant' companies pursuing control methods innovation. Start-ups have attained varied degree of success, with Varentec, FiNsix, Gridco and Cirasys all rated 'High-potential'.

- **Bosch, Schneider rule module packaging.**

  In module packaging, the 'Dominant' companies are Bosch and Schneider Electric, on account of their strengths in automotive and industrial markets, respectively. AT&S pursues novel energy-efficient packaging methods but has found little adoption in the market, while AgileSwitch’s success with its digital gate driver has been limited to the USA.

The report 'Sorting Through the Maze of Silicon Innovations in Power Electronics' is part of the Lux Research Energy Electronics Intelligence service.

**Read more**

**Plextek RFI presenting on GaN PA MMICs at microwave circuit design seminar**

*Semiconductor Today*

Plextek RF Integration of Great Chesterford, near Cambridge, UK, which designs and develops RFICs, MMICs and microwave/millimeter-wave modules, says that its CEO Liam Devlin is presenting the paper 'Designing GaN PA MMICs' in the Microwave, RF and Millimetre Wave Modelling & Circuit Design Seminar at the UK's University of Manchester on 17 June (sponsored by Keysight Technologies).

At the seminar, delegates can hear the experiences of industry experts engaged in the key stages of RF, microwave and millimetre-wave design flow, from semiconductor device measurement and model extraction, through to circuit design and packaging.

Devlin’s presentation will explain how the high breakdown voltage and operating temperature capability of gallium nitride (GaN) high-electron-mobility transistors (HEMTs) make the technology
well suited to the realization of power amplifiers (PAs). Many commercial GaN foundry processes are now available, and the realization of custom GaN PA monolithic microwave integrated circuits (MMICs) is now a practical option for many applications, says Plextek RFI.

Devlin's presentation starts with an overview of the structure and operation of a GaN HEMT and then explains how to design a GaN PA MMIC. Design examples will then be presented for a range of applications using several different commercially available GaN processes.

Other speakers at the seminar include Rob Sloan of University of Manchester, Cedric Pujol and Dave Morris of Keysight, Philippe Michel of UMS, Peter King of IDEAL Networks, and Christopher Buck of Filtronic.

EPC adds 5mΩ 150V and 7mΩ 260V eGaN FET power transistors
*Semiconductor Today*

Efficient Power Conversion (EPC) has introduced two GaN fets that handle 31A continuously—the 200V EPC2034 and the 150V EPC2033. Applications include DC-DC converters, synchronous rectification, motor drives, LED lighting, and industrial automation.

The firm is keen to promote pulse capability, which is 140A for the 200V part and 260A for the 150V part. Both are 2.6x4.6mm, and can operate with junctions up to 150°C.

Typical on-resistance is 7mΩ (200V, 10mΩ max) and 5mΩ (150V, 7mΩ max).

Solder balls are placed with a 1mm pitch on one axis. The wider pitch allows for placement of additional and larger vias under the device to enable high current-carrying capability despite the extremely small 2.6mm x 4.6mm footprint.

To simplify the evaluation process of the eGaN FETs, the EPC9047 development board is available to support easy 'in circuit' performance evaluation of the EPC2033. In a half-bridge topology measuring 2" x 1.5", the EPC9047 contains two EPC2033 eGaN FETs using the Texas Instruments UCC27611 gate driver, as well as supply and bypass capacitors. The board contains all critical components that can be easily connected into any existing converter, plus layout for optimal switching performance. There are also various probe points to facilitate simple waveform measurement and efficiency calculation.

The EPC2033 and EPC2034 are priced at $4.25 and $4.37, respectively (in 1000-unit quantities). The EPC9047 development board is $137.75. All are available now for delivery from Digi-Key.
capacitors for supply and bypass — all on 50x37mm.
Both FETs and the development board are available from Digi-Key.

Read more

TRAK launches Ku-band block upconverter with integrated GaN SSPA
Semiconductor Today
TRAK Microwave (a Smiths Microwave brand that designs and manufactures RF and microwave assemblies, subsystems, components and time & frequency systems for defense, space and commercial applications) has launched the Model MFC147 block upconverter (BUC), which provides 13.75-14.50GHz coverage for civilian and military aviation Ku-band SatCom applications, including in-flight entertainment (IFE) systems and unmanned airborne vehicle (UAV) communications.
The unit features a ruggedized design and innovative thermal management technique to withstand challenging airborne environments by using SMT construction with no open die. Input frequency to the block upconverter is 950-1700MHz, with Ku-band output of +12-17dBm.
An integrated, low-noise gallium nitride (GaN) solid-state power amplifier (SSPA) provides 25W minimum output power, providing better than -120dBc/Hz noise power (-140dBc/Hz typical) and less than -22dBc spectral regrowth (OQPSK).
The MFC147 includes built-in test (BIT), temperature monitoring and forward/reverse (FWD/REV) power detectors, all monitored via standard serial commands. Drain voltage control reduces thermal dissipation at lower power output levels. The BUC includes 0 to +7dB gain expansion and 30dB digital gain control for optimum SSPA performance. The device is offered as EAR99 and is not subject to export restrictions.

Read more

Wireless backhaul RF component revenue to fall 2% over 2014-2019, despite unit growth
Semiconductor Today
Although wireless backhaul radio quantities will grow slowly to about 1.7 million units in 2019, price erosion will cause the corresponding RF component revenue in the segment to decline at a compound average growth rate (CAGR) of minus 2% over the forecast period, according to the Strategy Analytics Advanced Semiconductor Applications (ASA) Forecast and Outlook report ‘Wireless Backhaul RF Component Demand: 2014–2019’. The slow growth reflects wireless infrastructure growth in areas that have high wireline network penetration, coupled with a lackluster deployment of the small-cell architecture.

Wireless backhaul RF component revenue by frequency range.

However, the need to accommodate rapidly increasing amounts of data consumption will push equipment manufacturers and operators to higher-frequency bands, says Strategy Analytics. The frequency bands at 60GHz and above will see an annual growth rate of 33%, as enormous available bandwidth outweighs the design challenges of these higher frequencies. While this market is served primarily by gallium arsenide (GaAs) devices, gallium nitride (GaN) technology is beginning to see use in this segment, with GaN revenue for power amplifiers forecast to grow to $6m (about 8% of wireless backhaul RF component revenue) in 2019.
"As radio requirements continue to get tougher, we are seeing manufacturers turn to GaN to solve the linearity, bandwidth, frequency and efficiency challenges," notes Asif Anwar, director in the Strategic Technologies Practice. "The low-power functions are still predominately GaAs, but there are significant development activities aimed at integrating transmit and receive functions in silicon."
"There is no question that backhaul has become a critical part of wireless network deployment and the rapid increase in wireless data consumption is forcing system designers to develop networks that provide options for future growth," says Eric Higham, service director, Advanced Semiconductor Applications. "This ‘future-proofing’ is leading to fast growth in the higher-frequency bands, but it is also creating much more interest in fiber-based front-haul and the added capabilities which that architecture provides," he adds.

So, even though the quantity of wireless backhaul radios will grow and wireless will remain the backhaul method for more than 50% of the market, fiber-based backhaul networks will capture market share, the report concludes.

Read more

Explosive growth in China drives RF power semiconductor device sales for wireless infrastructure to over $1bn in 2014

Semiconductor Today

After a successful 2013, the market for RF power semiconductors for wireless infrastructure blew off the chart in 2014, according to a new report from market analyst firm ABI Research. The Asia-Pacific region, and China specifically, continues to be the main driver for RF power semiconductor devices that are sold into the mobile wireless infrastructure segment.

"LTE and TD-LTE air interfaces will be the technology engines of growth for the next five years," comments research director Lance Wilson. "Although, gallium nitride (GaN) devices had meaningful share, the 2014 story was all about silicon LDMOS, which continues to dominate this segment by a large margin," he adds. The increasing and critical need for wireless data remains an important driver for the overall market for RF power semiconductor devices, the report concludes.

The report (part of ABI Research’s High-Power RF Active Devices Market Research) examines evolving design parameters and materials, price versus performance, and the interdependent relationship of RF power semiconductors to RF power amplifiers.

Read more

Qorvo announces second edition of GaN For Dummies

Semiconductor Today

Qorvo Inc of Greensboro, NC and Hillsboro, OR, USA, a provider of RF solutions for mobile, infrastructure and aerospace/defense applications, has announced a second edition of its 'GaN For Dummies' books, including updates to the original books (published in 2014). Written in conjunction with publisher John Wiley and Sons Inc, the books consist of two volumes:

Volume 1, GaN RF Technology For Dummies, covers:
- The key properties of GaN
- What makes GaN FETs unique
- How GaN compares to other semiconductor technologies
- The thermal challenges of GaN
- Ten important facts about GaN technology.

Volume 2, RF Applications of GaN For Dummies, includes:
- How GaN benefits your system applications
- Why and when to use GaN
- Important design factors for GaN
- GaN’s utility in multiple applications
- Ten keys to success using GaN.

GaN transistors were first demonstrated in the 1990s and now are widely available for commercial and defense applications, based on the high power density and high efficiency that can be achieved. The GaN For Dummies books aim to help both technical and non-technical professionals to learn more about the basics of gallium nitride (GaN) in radio frequency (RF) technology and how they can use GaN in RF product designs.

"GaN technology is rapidly gaining traction for base transceiver stations (BTS), cable TV (CATV) and defense systems because it can meet the exacting performance requirements those applications demand," says Dr Douglas Reep, Qorvo’s senior director of research, Infrastructure and Defense Products. "GaN For Dummies provides company leadership, system engineers and designers with a short course introducing the benefits of GaN, illustrating its exceptional reliability and unique performance capabilities."

Market research firm Strategy Analytics forecasts that revenue for GaN RF devices in both military
and commercial applications will increase at a compound average annual growth rate (CAAGR) of more than 20% to nearly $560m in 2019. Both e-book volumes are free and available for download from the GaN For Dummies landing page on the Qorvo website.

Read more

IHS reports developments in power semiconductors highlighted at PCIM

Richard Eden, senior analyst (Power Semiconductors) at market research firm IHS Technology, attended the recent PCIM (Power Conversion Intelligent Motion) Europe 2015 tradeshow in Nuremberg, Germany (19-21 May), and in a Research Note has reported the following key highlights, including the significance of new product releases, the status of the semiconductor materials battle, and the industries driving current and future market growth.

SiC and GaN developers continue to make headlines

For the past few years, the headlines have been filled with technology announcements by silicon carbide (SiC) and gallium nitride (GaN) startups, and this year’s show was no exception, says Eden. The wider market has caught on to these stories, as well-established manufacturers are now explaining their development strategies and introducing their own products. When it comes to new players coming to market, the attitude of existing SiC and GaN companies as a whole is "the more, the merrier", he adds. For such companies, the main competitors are silicon suppliers, not each other.

In recent years, SiC and GaN semiconductor companies had to explain the benefits of their devices in practical applications, in order to evangelize about the technology. The message appears to have registered with customers, as design engineers are now proactively asking them for products to help provide power conversion efficiency gains. According to IHS, the SiC and GaN power semiconductor market is conservatively forecasted to surpass $270m in 2015.

The silicon empire strikes back

With SiC and GaN power semiconductor developers intent on gaining market share, the dominant silicon suppliers are reacting, says IHS.

Several new devices were on show at PCIM for the first time.

Fairchild Semiconductor introduced its fourth generation of discrete insulated-gate bipolar transistors (IGBTs), which it claims can slash energy loss by 30%. Fairchild’s new approach should enable new ways to efficiently control large amounts of power, it is reckoned.

Germany’s Infineon Technologies launched the MIPAQ Pro, a new intelligent power module (IPM) integrating IGBTs, gate drivers, heat-sink, sensors, digital control electronics and digital bus communication into one robust, reliable package. The new module is aimed at providing an integrated solution for new scalable and compact inverter designs for wind, solar, and industrial motor drive applications.

Eden says that these examples illustrate two trends that were increasingly apparent at the show. First, the devices are aimed squarely at improving power efficiency. Second, power transistors are increasingly being integrated with sensing, control and communication functions in common module packaging.

Merger & acquisition activity increases

The number of semiconductor business mergers and acquisitions has increased recently, and the appetite for mergers and takeovers within the semiconductor industry is expected to continue, notes Eden. For power semiconductors, the biggest story of 2014 was Infineon’s purchase of International Rectifier (IR). The deal completed in January, so the PCIM show was the first time in Europe that the combined power portfolio of Infineon and International Rectifier was presented as one company.

At the event, there was a lot of discussion surrounding the recent $40bn merger of Netherlands-based NXP Semiconductors and US-based Freescale Semiconductor. NXP already supplies discrete power semiconductors to the automotive sector, so combining this strength with Freescale’s significant presence in automotive microcontrollers should increase the merged company’s penetration in that market, reckons IHS.

Conclusions from PCIM

Until 2008 the power semiconductor market grew at about 8% each year, but that is no longer the case following the global financial crisis. The
overall long-term market growth projection for the next five years has slowed to about 5% per year, according to IHS. The key factors causing this reduced optimism are the general global macroeconomic conditions, the weaker Chinese economy, concerns about the Euro-zone countries' prospects, and the Euro-to-dollar exchange rate, notes the firm.

In summary, power semiconductor companies can look forward to an environment of continued merger & acquisition activity, customers demanding improved energy efficiency, and exciting new technologies and products, reckons IHS. However, as long as the need exists to convert electric power into useful work with increasing efficiency, the power semiconductor market will continue to grow, it concludes.

Read more

Anadigics launches GaN-based DOCSIS 3.1 CATV infrastructure line amplifiers with highest RF power per Watt consumed

Semiconductor Today

At ANGA COM 2015 Exhibition & Congress for Broadband, Cable and Satellite in Cologne, Germany (9-11 June), Anadigics Inc of Warren, NJ, USA has introduced two high-power gallium nitride (GaN) infrastructure line amplifiers for CATV systems.

The ACA2455 and ACA4733 power doublers are optimized for fiber deep, Node+0 networks, and node segmentation/split upgrades. With only 12.7W of DC power consumption, the new line amplifiers are claimed to offer the lowest cost per bit for all-digital content delivery (efficiency that helps MSOs to better manage operating costs over the life of the network).

"MSOs aim to enhance services while minimizing expenses," says James Martin, senior business development director of Infrastructure Products. "Our new DOCSIS 3.1 GaN line amplifiers are optimized to support both of these objectives. These power doublers not only deliver the output power and linearity required for DOCSIS 3.1 applications, but also provide exceptional efficiency for energy-saving 'green' networks," he adds.

The ACA2455 and ACA4733 line amplifiers combine the firm's gallium arsenide (GaAs) MESFET technology (for a driver stage with exceptional linearity and reliability) with a GaN output stage (to increase output power, ruggedness and efficiency). The highly linear power doublers provide 28dB gain, +63dBmV per channel output power, and +73.2dBmV total composite power. The ACA2455 and ACA4733 GaN line amplifiers also offer what is claimed to be exceptional composite triple beat (CTB), composite second order (CSO), cross modulation, carrier-to-intermodulation noise (CIN), and modulation-error and bit-error ratio (MER and BER) characteristics for optimal performance in a fully loaded spectrum.

The firm's line amplifier family is claimed to provide the highest single-device output power to support both analog/digital and completely digital CATV systems, as well as the industry's highest performance to enable Node+0 system architectures without active components downstream from the fiber node.

Read more

Raytheon completes milestones on path to production-ready GaN-based AESA Patriot radar

Semiconductor Today

Raytheon Company of Waltham, MA, USA recently completed a series of milestones, bringing the combat-proven Patriot Air and Missile Defense System with 360° of coverage one step closer to production readiness.

The milestones involve upgrading the Patriot's radar main array with gallium nitride (GaN)-based active electronically scanned array (AESA) technology. Completion of those milestones keeps Raytheon engineers, who are currently building a GaN-based AESA full-size main panel radar array, on track to having the system up and running in early 2016.

"A GaN-based AESA radar benefits netted sensors, and gives Patriot greater capability and reliability while significantly reducing operations and sustainment cost," says Ralph Acaba, VP of Integrated Air and Missile Defense at Raytheon’s Integrated Defense Systems business in Tewksbury, MA. "Raytheon recognizes how important this capability is for the warfighter and is investing its own resources to bring Patriot's GaN-based AESA radar to the point where it can enter engineering and manufacturing development with low risk," he adds.
The main AESA array is a bolt-on replacement antenna that measures about 9' wide x 13' tall, which is oriented toward the primary threat. Patriot's new rear-panel arrays (which are a quarter the size of the main array) let the system look behind and to the sides of the main array, enabling Patriot to engage threats in all directions. Earlier this year, Raytheon built a GaN-based AESA Patriot rear-panel array, integrated it with the current Patriot radar using the existing, recently modernized, back-end processing hardware and software, and tracked targets of opportunity to seamlessly create a 360° view.

The milestones accomplished to date include fabricating the main radar array's superstructure, and completing development work on the power and cooling sub-systems. In the months ahead, additional upgrades will focus on integrating the sub-systems and populating the array superstructure with GaN-based transmit-receive units (TRLRU). The GaN TRLRUs are the heart of the radar and are identical to those used for the rear-panel arrays, and are made in the same Massachusetts-based GaN foundry currently producing GaN chips for Navy and Air Force defensive systems.

The GaN-based AESA Patriot radar will work with an open-architecture common command and control (CC2) node and retains backwards compatibility with the current Patriot Engagement Control Station. The CC2 node will be fully interoperable with NATO and the Integrated Air and Missile Defense Battle Command System.

Advantech launches second-gen GaN-based 300W C-band BUC SSPA/SSPB for maritime application

Advantech Wireless Inc of Montreal, Canada (which manufactures satellite, RF equipment and microwave systems) has launched a second-generation SapphireBlu gallium nitride (GaN)-based 400W C-band SSPA/SSPB (solid-state power amplifier/solid-state power block) designed for broadcasting applications.

Offering very high linearity (yet no additional increase in size, weight and energy consumption) in a compact single package, the systems are designed for Ultra HD transmission broadcasting and are DVB-S2X ready.

"We have over 20 years of experience working with broadcasters and providing cutting-edge technologies to deliver audio and visual content clearly and reliably," says VP business development Cristi Damian. "We understand the challenges that broadcasters and service providers face while adopting the new bandwidth-demanding Ultra HD standard," he adds. "The second generation of GaN SSPAs empowers broadcasters to deliver their messages while maximizing efficiency and reducing operational cost." The units are designed for very high linearity, as imposed by the heavy Ultra HD traffic, and at the same time be ready to operate under...
the high-density modulation schemes that are now part of the DVB-S2X standard.

GREAT2 GaN transmitter completes second year aboard ESA's Proba-V satellite as industrial prototypes complete testing

Semiconductor Today

What is described as the first European-made device based on gallium nitride (GaN) to be sent into space has completed its second year of operations. Hosted by the European Space Agency (ESA) on its Earth-observing Proba-V mini-satellite in 2013 as a test prototype, the transmitter is currently used routinely to return mission imagery to the ground.

"The X-band transmitter in question incorporates an experimental gallium nitride (GaN) amplifier," says Andrew Barnes, overseeing ESA's work in GaN. "It is still working seamlessly today after two years in orbit, showing no drift in performance," he adds.

The GaN-based transmitter is used to downlink data to Proba-V's Kiruna ground station – in the Swedish Arctic – once per orbit for a week at a time, alternating with a second transmitter using a conventional gallium arsenide (GaAs) amplifier. With its data coming down at a standard rate of 42.22Mb/s during each approximately 12 minute pass, the cubic-metre-sized Proba-V builds up a complete picture of all the Earth's vegetation every two days.

Access to the GaN-based transmitter also increases the operational flexibility of the satellite – in principle its data rate can be boosted to 100Mb/s, while its programmable radio-frequency output power can also be increased as needed, while operating at a lower voltage than its conventional equivalent.

Gallium nitride has been described as the most promising semiconductor since silicon, capable of operating at much higher voltages and temperatures than comparable materials. GaN also possesses inherent resistance against the radiation encountered in space.

"In terms of communications for space, GaN offers a five- to ten-fold increase in communications power, while requiring no additional cooling systems," says Barnes. "Its promise is such that back in 2008 ESA launched the 'GaN Reliability Enhancement and Technology Transfer Initiative' (GREAT2), bringing together leading universities, research institutes and industry to develop space-compatible production processes for making GaN microwave power transistors and integrated circuits," he adds.

"With GREAT2, ESA has come in at an early stage of industrialization to ensure that the resulting products meet the demanding requirements of space use, such as resistance to shock and temperature extremes, as well as continuous operations for years at a time," continues Barnes.

The GREAT2 partners include United Monolithic Semiconductors (UMS) based in Germany and France, responsible for the industrial foundry used for manufacturing GaN products. Proba-V's GaN-based X-band transmitter was an early prototype result from GREAT2, seizing a chance to have an early test of the technology in orbit. The GaN amplifier was incorporated into Proba-V's existing communication system by Syrlinks in France. Since then, while the transmitter has been proving its worth in space, the first industrial prototypes have successfully completed their testing for reliability and robustness.

"As a result of GREAT2 we were able to place the UMS GaN manufacturing process onto the European Preferred Parts List of the European Space Components Coordination – a list of recommended parts for space missions – in 2012," says Barnes. "This was two years earlier than originally planned," he adds. "This was along with obtaining early flight heritage on Proba-V, and the two achievements together have lent confidence to other ESA projects to make use of the technology."

ESA's Biomass mission – an Earth-observing satellite to track global forest biomass – is now planning to use European GaN technology to
produce mission-critical solid-state power amplifiers for its P-band synthetic aperture radar. "Work is currently ongoing to qualify high-power GaN power transistors assembled in hermetic packages for the Biomass mission," Barnes reports. "Beyond that, our long-term goal is to make space-qualified hermetically packaged GaN transistors commercially available on the open market, which would be a first for Europe."

Rubicon's Q1 growth in sapphire revenue for mobile devices balanced by weakness in LED market

Semiconductor Today

For first-quarter 2015, Rubicon Technology Inc of Bensenville, IL, USA (which makes monocrystalline sapphire substrates and products for the LED, semiconductor and optical industries) has reported revenue of $8.9m, down on $14.3m a year ago and level with last quarter.

"The sapphire market continues to be very challenging," says CEO William Weissman. "The market remains in a state of excess supply with fluctuations in demand, resulting in significant price pressure."

Core revenue was $5.1m, less than half of the $11.35m a year ago but up on $4.75m last quarter. This was mostly due to revenue for 2-inch sapphire cores (used primarily in the mobile device market), down from $8.5m a year ago but up from $3.2m last quarter to $4m. However, this growth was offset partly by revenue from 4-inch cores falling (for LEDs) falling further, from $2.85m a year ago and $1.55m last quarter to $1m. "We saw weakness in the LED market and some strengthening in the mobile device market," notes Weissman. "The LED market, which typically strengthened after Chinese New Year, this year remained soft throughout the quarter," he adds.

Wafer revenue was $1.9m, almost doubling from $1.1m a year ago but similar to last quarter. Of this, polished wafer revenue was $1.4m, up from $1m a year ago but roughly level with last quarter. Revenue for patterned sapphire substrates (PSS) has risen just from $0.1m a year ago to about $0.5m (also roughly level with last quarter) but remains limited to qualification levels.

Optical and R&D revenue totaled $1.9m, down slightly on last quarter's $2.2m but up slightly on $1.8m a year ago.

Crystal growth operations continued to run at full capacity, but wafer polishing and patterning operations remain under-utilized. Idle plant costs rose from $1.8m last quarter to $2.2m. However, operating expenses have been cut from $3.2m last quarter to $2.8m (due to lower bad debt expense and a decrease in consulting fees).

Raw material inventory balance declined sequentially by $1.6m, from $14.5m to $12.9m. "In addition to reducing our per-unit cost through our internal raw material process, we have also reduced the total quantities in inventory," says Weissman.

"We are still cycling through old more expensive raw material stock, so the current low cost of our internal raw material production is not yet fully reflected in our statement of operations," says Weissman. "As a result, the cost of raw material and our cost of goods sold is nearly double that of our current raw material production cost. The impact of this on EPS in the first quarter was about $0.03. These costs as well as our raw material inventory balance will continue to come down," he adds.

Despite the sustained raw material cost and the continued weakness in the LED market, net loss has been cut from $10.9m ($0.43 per share) a year ago and $9.4m ($0.36 per share) last quarter to $8.3m ($0.32 per share). Net cash used in operating activities has been cut from $4.5m a year ago to $3.9m. During the quarter, cash and short-term investments fell from $45m to $41m (with no debt).

Rubicon's key objectives for 2015 include aggressively pursuing the potential of its PSS product, targeting high-margin optical applications, and driving down product costs.

"We continue to work on furnace re-designs and process improvement to further reduce cost. We
also continue to improve on our proprietary raw material processes to reduce crystal growth cost," says Weissman. "We have now begun to convert our 83kg furnaces to 93kg, which not only produces more material at a nominally incremental cost but also reduces defects, which increases crystal yield. As we did with the conversion of our 311kg furnaces to 35kg, this will be done gradually according to our maintenance schedule," he adds.

"Our patterning operation is cost competitive and our patterning capability is strong," believes Weissman. "The area where we have greatest opportunity to reduce cost and where we must reduce cost is in polished wafers. We need to ensure that the incremental revenue from increasing PSS volumes generates positive cash flow in the near term and provides strong margins as the market improves. Addressing polished wafer cost therefore is a high priority. Over the past several months we have been working on a number of initiatives to reduce these costs, including the development of a new polishing platform. In coming the months we will be able to determine the cost-reduction impact of these initiatives," he adds.

"While we work on reducing polished wafer cost, we are focusing on PSS wafer sales rather than polished wafer sales," says chief financial officer Mardel A. Graffy. During Q1, the firm continued qualifying its large-diameter PSS wafers.

"The general lighting segment of the LED market is still in early stages of adoption and the LED industry is continuing to migrate to larger-diameter substrates," comments Graffy. "We are seeing the LED market begin to pick up and expect increased 4-inch core revenue in the second quarter," says Weissman. For second-quarter 2015, Rubicon expects revenue to be similar to the first quarter. While core sale volumes will likely be higher, 2-inch demand will be limited and pricing will be lower. In addition, PSS revenue will still be limited to qualification volumes. Loss per share is therefore also expected to be similar to Q1, with cost reductions offsetting the additional price pressure.

"While volume PSS orders have certainly been slower in coming than expected, we do have visibility to growing PSS volumes in the second half of the year," notes Weissman. "We believe that we will increase our PSS revenue over the course of this year." Utilization should increase as PSS wafer orders move from qualification to production volumes. "With increased wafer revenue in combination with reducing product costs, we expect a meaningful improvement in operating results by the end of the year," he adds. "Continuing to lower product cost is a major focus for us this year. It's our goal to ensure that Rubicon is positioned to drive strong margins when the markets strengthen and to ensure that we are cash flow positive by the end of this year, even as the pricing environment remains difficult," continues Weissman. "While it will be challenging to achieve these goals without some pricing improvement, we will be taking action over the next couple of quarters to reduce costs. This, along with increased PSS volumes, should reduce our cash burn."
More than **110 new patent applications** were published between **2015-06-02** and **2015-07-01**.

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**Fault tolerant design for large area nitride semiconductor devices**

Publ. Nb: US2015162252  
Patent Applicant: GaN Systems (CA)

A fault tolerant design for large area nitride semiconductor devices is provided, which facilitates testing and isolation of defective areas. A transistor comprises an array of a plurality of islands, each island comprising an active region, source and drain electrodes, and a gate electrode. Electrodes of each island are electrically isolated from electrodes of neighboring islands in at least one direction of the array. Source, drain and gate contact pads are provided to enable electrical testing of each island. After electrical testing of islands to identify defective islands, overlying electrical connections are formed to interconnect source electrodes in parallel, drain electrodes in parallel, and to interconnect gate electrodes to form a common gate electrode of large gate width \( W_g \). Interconnections are provided selectively to good islands, while electrically isolating defective islands. This approach makes it economically feasible to fabricate large area GaN devices, including hybrid devices.

**Small-sized light-emitting diode chiplets and method of fabrication thereof**

Publ. Nb: US2015179873  
Patent Applicant: Palo Alto Research Center (US)

Diode includes light emitting region, first metal layer, dielectric layer, and second metal layer. Light emitting diode includes n-type group III-nitride portion, p-type group III-nitride layer, and light emitting region sandwiched between n- and p-type layers. First metal layer may be coupled to p-type III-N portion and plurality of first terminals. First metal layer and p-type III-N portion may have substantially similar lateral size that is smaller than 200 micrometers. A portion of light emitting region and first metal layer may include a single via. Electrically-insulating layer may be coupled to first metal layer and sides of the single via. First terminals may be exposed from electrically-insulating layer. Second metal layer may include second terminal and may be coupled to electrically-insulating layer and to n-type III-N portion through the single via. The thickness of the diode excluding second terminal may be between 2 and 20 micrometers. Other embodiments are described.

Read more
**Nitride-based transistors having structures for suppressing leakage current**


A nitride-based transistor includes a semiconductor structure, a gate electrode and a leakage current suppression structure. The semiconductor structure includes a first nitride-based semiconductor layer doped with impurities of a first conductivity type, a second nitride-based semiconductor layer doped with impurities of a second conductivity type, and a third nitride-based semiconductor layer doped with impurities of the first conductivity type. The gate electrode overlaps the second nitride-based semiconductor layer. The leakage current suppression structure is disposed along edges of the semiconductor structure. The leakage current suppression structure includes a depletion layer in at least one of the first and third nitride-based semiconductor layers.

**Thin film gallium nitride structures grown on graphene**

Publ. Nb: US9064698  
Patent Applicant: IBM (US)

Thin film gallium nitride structures are fabricated by providing a semiconductor-carbon alloy substrate having a dielectric layer on a surface of the substrate, forming trenches in the dielectric layer to expose surface portions of the surface of the substrate, and forming an epitaxial graphene layer on the exposed surface portions of the surface of the substrate. A buffer layer of rare earth metal oxide material is grown epitaxially on the graphene layer. Gallium nitride structures are formed epitaxially on the metal oxide/graphene layers and within the trenches of the dielectric layer, limiting defects by aspect ratio trapping. A stressor layer is formed over the nitride structures. Removing the substrate below the graphene layer allows the nitride structures to be placed on a surrogate substrate.

**Nitride semiconductor based optical integrated circuit and method for manufacturing the same**

Publ. Nb: KR20150066148  

This invention about the optical integrated circuit specially, about the optical integrated circuit and the manufacturing method of Nitride semiconductor base is the thing the fact that. Such this invention, there to be in a optical integrated circuit of the Nitride semiconductor base which is embodied to on the identical borad, the borad. To be had to minute description board coat Japan, Nitride semiconductor as for under including radiation department. To be had to minute description board coat hit side, Nitride semiconductor as for
under including the dawn department. And about under connecting to be had minute description radiation department and the dawn department from on the minute description boral, Nitride semiconductor the low of including about under including could be composed a transmission department.

Read more

Nitride LED structure with double graded electron blocking layer

A group III nitride-based light emitting device includes an n-type semiconductor layer; a first p-type semiconductor layer; an active region; and an electron blocking region comprising AlGaN located between the active region and the first p-type semiconductor layer, and including at least an upgraded layer and a downgraded layer. An aluminium composition of the upgraded layer of the electron blocking region increases from an active region side to a first p-type semiconductor layer side of the electron blocking region, and an aluminium composition of the downgraded layer of the electron blocking region decreases from the active region side to the first p-type semiconductor layer side of the electron blocking region. The nitride-based light emitting device may be a light emitting diode or a laser diode.

Read more

Semiconductor device
Publ. Nb: WO2015079808

This invention provides a semiconductor device that exhibits improved reliability and yield, wherein even in a situation in which a plurality of semiconductor elements are arranged in close proximity to each other on a die pad of limited size, said semiconductor elements do not become affixed to the die pad at an angle. Said semiconductor device contains a MOSFET (11) that is affixed to a given surface of a die pad (2) via solder (12) and a GaN HEMT (13) that is affixed to the same surface of the die pad (2) via a silver paste (14). In a planar view, either a non-silver plated region (6) or a boundary between said non-silver plated region (6) and a silver plated region (5) is located between the MOSFET (11) and the GaN HEMT (13).

Read more
III-nitride nanowire LED with strain modified surface active region and method of making thereof  
Publ. Nb: WO2015095049  
Patent Applicant: Glo (SE)

A light emitting diode (LED) device includes a semiconductor nanowire core, and an In(Al)GaN active region quantum well shell located radially around the semiconductor nanowire core. The active region quantum well shell contains indium rich regions having at least 5 atomic percent higher indium content than indium poor regions in the same shell. The active region quantum well shell has a non-uniform surface profile having at least 3 peaks. Each of the at least 3 peaks is separated from an adjacent one of the at least 3 peaks by a valley, and each of the at least 3 peaks extends at least 2 nm in a radial direction away from an adjacent valley.  
Read more

Methods of fabricating micro- and nanostructure arrays and structures formed therefrom  
Publ. Nb: US2015170901  
Patent Applicant: Defense Threat Reduction Agency  
Dept of Defense United States Government (US), University of Maryland (US)

Methods of fabricating micro- and nanostructures comprise top-down etching of lithographically patterned GaN layer to form an array of micro- or nanopillar structures, followed by selective growth of GaN shells over the pillar structures via selective epitaxy. Also provided are methods of forming micro- and nanodisk structures and microstructures formed from thereby.  
Read more

Semiconductor light-emitting device  
Publ. Nb: US2015162495  
Patent Applicant: Panasonic (JP)
A nitride semiconductor light-emitting element 300 is a nitride semiconductor light-emitting element which has a multilayer structure 310, the multilayer structure 310 including an active layer which is made of an m-plane nitride semiconductor. The multilayer structure 310 has a light extraction surface 311a which is parallel to an m-plane in the nitride semiconductor active layer 306 and light extraction surfaces 311b which are parallel to a c-plane in the nitride semiconductor active layer 306. The ratio of an area of the light extraction surfaces 311b to an area of the light extraction surface 311a is not more than 46%.

Read more

**Electronic device**
Publ. Nb: DE102014117523, US2015162287, CN104701308
Patent Applicant: Infineon Technologies (AT)

An electronic device includes multiple semiconductor chips in a single housing. Such semiconductor chips may comprise different semiconductor materials, for example they may comprise GaN. Using bonding clips instead of bonding wires is an efficient way of connecting such semiconductor chips to a substrate.

Read more

**Semiconductor device and method for manufacturing same**
Patent Applicant: Denso (JP)

This semiconductor device comprises a switching device which is provided with: a substrate (1) that is configured from a semi-insulating material or a semiconductor; channel formation layers (2, 3) that are formed on the substrate and are configured from a compound semiconductor which is mainly composed of a group 3 nitride; a gate structure that is obtained by forming a gate electrode (6) on the channel formation layers with a gate insulating film (5) being interposed therebetween; and a source electrode (7) and a drain electrode (8) that are formed on the channel formation layers so as to sandwich the gate structure therebetween. If a region of the channel formation layers, where the switching device is formed, is defined as an element region and a region around the element region is defined as an element isolation region, a collapse suppressing layer (9), which is configured from an insulating material, is formed on the channel formation layers in the element region and a leakage suppressing layer (10), which is configured from an insulating material different from that of the collapse suppressing layer, is formed on the channel formation layers in the element isolation region.

Read more
A semiconductor die having improved thermal performance is disclosed. The semiconductor die includes a substrate having a device layer with a plurality of vias that pass through the substrate and the device layer, wherein individual ones of the plurality of vias have an open space volume of less than around about 70,000 cubic micrometers to around about 20,000 cubic micrometers. In at least one embodiment, the substrate of the semiconductor die is made of silicon carbide (SiC) and the device layer is made of gallium nitride (GaN).

Read more