# GANEXT

# Newsletter No. 21

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## GaN Technology for Optoelectronics & Electronics

Coordinated by **CRHEA-CNRS** research laboratory, this monthly newsletter is produced by **Knowmade** in collaboration with the managers of **GANEXT** groups. The newsletter presents a selection of newest scientific publications, patent applications and press releases related to **Optoelectronics** (LED, micro-LED, laser, photonics, etc.) and **Electronics** (Power, RF, advanced electronics, etc.) based on **III-Nitride semiconductors** (GaN, AlN, InN and alloys).

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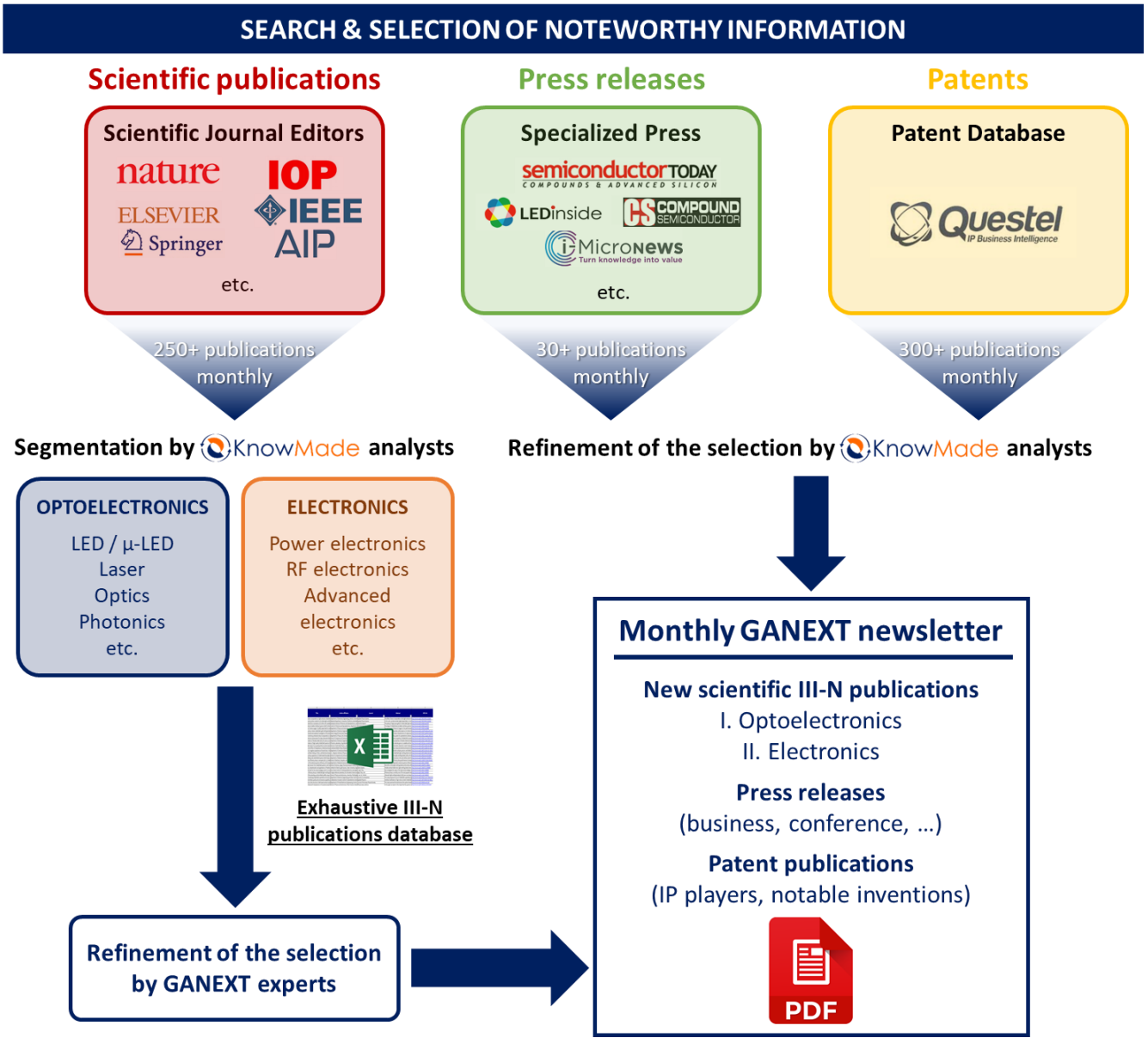
# METHODOLOGY



# SCIENTIFIC PUBLICATIONS

*Selection of new scientific articles*

## OPTOELECTRONICS

Group leader: Bruno Gayral (CEA)

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### Improvement of Porous GaN-Based UV Photodetector with Graphene Cladding

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Appl. Sci.
https://doi.org/10.3390/app112210833

This work presents the role of graphene in improving the performance of a porous GaN-based UV photodetector. The porous GaN-based photodetector, with a mean pore diameter of 35 nm, possessed higher UV sensitivity, about 95% better compared to that of the as-received (non-porous) photodetector. In addition, it exhibits a lower magnitude of leakage current at dark ambient, about 70.9 µA, compared to that of the as-received photodetector with 13.7 mA. However, it is also highly resistive in nature due to the corresponding electrochemical process selectively dissolute doped regions. Herein, two types of graphene, derived from CVD and the electrochemical exfoliation (EC) process, were cladded onto the porous GaN region. The formation of a graphene/porous GaN interface, as evident from the decrease in average distance between defects as determined from Raman spectroscopy, infers better charge accumulation and conductance, which significantly improved UV sensing. While the leakage current shows little improvement, the UV sensitivity was greatly enhanced, by about 460% and 420% for CVD and EC cladded samples. The slight difference between types of graphene was attributed to the coverage area on porous GaN, where CVD-grown graphene tends to be continuous while EC-graphene relies on aggregation to form films.

### Understanding the Luminescence Characteristics of Ultraviolet InGaN/AlGaN Multiple Quantum Wells with Different In Gradients

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Crystals
https://doi.org/10.3390/cryst11111390

The electroluminescence (EL) properties of InGaN/AlGaN ultraviolet light-emitting multiple quantum wells (MQWs) with identical average In content but different In gradients (In content increases linearly, along the growth direction) are investigated numerically. It is found that the luminescence efficiency is improved, and the EL spectral peak wavelength becomes longer for the MQW sample with a larger In gradient. Since the influence of In gradient is different for the conduction and valence bands in InGaN layers, the distribution of electrons and holes in QWs may be changed, leading to a redshift of EL spectra. In particular, when the In gradient increases, the overlap integral of electron-hole wavefunction in InGaN QWs increases, resulting in a higher radiative recombination rate and an enhanced EL intensity.

### InGaN-Based microLED Devices Approaching 1% EQE with Red 609 nm Electroluminescence on Semi-Relaxed Substrates

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Crystals
https://doi.org/10.3390/cryst11111364

In this paper, we report the successful demonstration of bright InGaN-based microLED devices emitting in the red spectral regime grown by metal organic chemical vapor deposition (MOCVD) on c-plane semi-

relaxed InGaN substrates on sapphire. Through application of an InGaN/GaN base layer scheme to ameliorate high defect density and maintain appropriate lattice constant throughout the growth, high-In quantum wells (QWs) can be grown with improved crystal quality. Improvement to the design of the growth scheme also yields higher power output resulting in an increase to the external quantum efficiency (EQE). Combined, these two improvements allow for an 80 × 80 µm2 microLED device emitting at 609 nm to achieve 0.83% EQE. Furthermore, the true In content of the QW is measured using atomic probe tomography (APT) to confirm the improved In incorporation during high temperature active region growth. These developments represent advancement toward the realization of bright, highly efficient red III-nitride LEDs to be used in RGB applications under one material system.

**Strain Compensation and Trade-Off Design Result in Exciton Emission at 306 nm from AlGaN LEDs at Temperatures up to 368 K**

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Materials
https://doi.org/10.3390/ma14216699

In this study, we suppressed the parasitic emission caused by electron overflow found in typical ultraviolet B (UVB) and ultraviolet C (UVC) light-emitting diodes (LEDs). The modulation of the p-layer structure and aluminum composition as well as a trade-off in the structure to ensure strain compensation allowed us to increase the p-AlGaN doping efficiency and hole numbers in the p-neutral region. This approach led to greater matching of the electron and hole numbers in the UVB and UVC emission quantum wells. Our UVB LED (sample A) exhibited clear exciton emission, with its peak near 306 nm, and a band-to-band emission at 303 nm. The relative intensity of the exciton emission of sample A decreased as a result of the thermal energy effect of the temperature increase. Nevertheless, sample A displayed its exciton emission at temperatures of up to 368 K. In contrast, our corresponding UVC LED (sample B) only exhibited a Gaussian peak emission at a wavelength of approximately 272 nm.

**Large-Area Monolayer MoS2 Nanosheets on GaN Substrates for Light-Emitting Diodes and Valley-Spin Electronic Devices**

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ACS Appl. Nano Mater.
https://doi.org/10.1021/acsanm.1c02662

Van der Waals heterostructures composed of atomically thin two-dimensional (2D) materials and three-dimensional (3D) materials provide a multidimensional material integration strategy, which combines materials with different characteristics leading to a wider degree of freedom than a single component, and offer a way for developing electronic and optoelectronic devices with multifunctionalities, such as high-frequency electronic devices, photodetectors, valley-spin electronic devices, and so on. This report demonstrates the direct growth of large-area monolayer MoS2 single-crystal nanosheets with a side length of more than 100 µm on 3D GaN substrates by the perylene-3,4,9,10-tetracarboxylic

acid tetrapotassium salt (PTAS) seed-assisted chemical vapor deposition (CVD) method. The seeding promoters changed the growth kinetics of MoS2 on the GaN substrate, which is different from the previously reported epitaxial growth behavior. The size of our synthesized single-crystal MoS2 nanosheets is 2 orders of magnitude larger than the reported epitaxially grown MoS2 on the GaN substrate. Meanwhile, the as-synthesized MoS2 by the seed-assisted CVD method has comparable crystal quality as that of the reported epitaxially grown MoS2 on the GaN substrate. Moreover, detailed characterizations indicate that noticeable charge transfer occurs between MoS2 and the GaN substrate, which suggests that the MoS2/GaN heterostructure has great potential applications in the field of light-emitting diodes (LED) and valley-spin electronic devices.

**A Self-Powered Transparent Photodetector Based on Detached Vertical (In,Ga)N Nanowires with 360° Omnidirectional Detection for Underwater Wireless Optical Communication**

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Nanomaterials
https://doi.org/10.3390/nano11112959

Underwater wireless optical communication (UWOC) is a wireless communication technology using visible light to transmit data in an underwater environment, which has wide applications. Based on lift-off (In,Ga)N nanowires, this work has proposed and successfully demonstrated a self-powered photoelectrochemical (PEC) photodetector (PD) with excellent transmissivity. The transparent functionality of the PD is critical for 360° omnidirectional underwater detection, which was realized by detaching the (In,Ga)N nanowires from the opaque epitaxial substrates to the indium tin oxide (ITO)/glass. It was also found that the insulating SiO2 layer can enhance the photocurrent by about 12 times. The core–shell structure of the nanowires is beneficial for generating carriers and contributing to the photocurrent. Furthermore, a communication system with ASCII code is set to demonstrate the PD detection in underwater communication. This work paves an effective way to develop 360° omnidirectional PDs for the wide applications in UWOC system and underwater photodetection.

**Effects of activation method and temperature to III-nitride micro-light-emitting diodes with tunnel junction contacts grown by metalorganic chemical vapor deposition**

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Applied Physics Letters
https://doi.org/10.1063/5.0073629

The optical and electrical characteristics of InGaN blue and green micro-light-emitting diodes (µLEDs) with GaN tunnel junction (TJ) contacts grown by metalorganic chemical vapor deposition (MOCVD) were compared at different activation temperatures among three activation methods from the literature, namely, sidewall activation, selective area growth (SAG), and chemical treatment before sidewall activation. The devices with chemical treatment before activation resulted in uniform electroluminescence and higher light output power, compared to the devices with sidewall activation and SAG. Moreover, the green µLEDs showed greater optical degradation at elevated activation temperatures, whereas the blue µLEDs yielded trivial difference with activation temperatures from 670 to 790 °C. The 5 × 5 µm2 devices with chemical treatment before activation and SAG yielded almost identical voltage at 20 A/cm2, and the voltage penalty significantly decreased with activation temperature in the case of devices with sidewall activation. The devices with chemical treatment before activation resulted in higher external quantum efficiency (EQE) and wall-plug efficiency (WPE) in low current density range compared to the devices with SAG. The enhancements in EQE and WPE were observed in different µLED sizes, suggesting that chemical treatment before sidewall activation enables the use

of TJ contacts grown by MOCVD and is advantageous for applications that require high brightness and efficiency.

**Deep ultraviolet emission from multiple quantum wells on flat N-polar AlN templates fabricated using periodical pulsed H2 etching**

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Japanese Journal of Applied Physics
https://doi.org/10.35848/1347-4065/ac2e7f

In a previous study, we successfully grew flat N-polar AlN layers on a c-plane sapphire substrate with a misorientation angle of 2.0° by metal-organic vapor phase epitaxy. However, its surface had undulations due to step bunching, and therefore further improvement of the surface flatness is required. In this study, we employed pulsed H2 etching during the growth of N-polar AlN layers to improve the surface flatness. Atomic force microscopy results indicated that the surface flatness was significantly improved, exhibiting a root mean square value of 0.4 nm. Further, the deep ultraviolet emission from AlGaN-based multiple quantum wells (MQWs) on the N-polar AlN layers was characterized, and the effect of the surface flatness on the optical characteristics was investigated. The surface flatness was found to play a crucial role in improving the optical characteristics of MQWs on N-polar AlN layers.

**Impact of potential fluctuation on temperature dependence of optical gain characteristics in InGaN quantum-well laser diodes**

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Japanese Journal of Applied Physics
https://doi.org/10.35848/1347-4065/ac2fef

The effects of the potential fluctuation (alloy compositional fluctuation and/or well-width fluctuation) in InGaN quantum wells (QWs) on the characteristics of InGaN-QW lasers, have been theoretically investigated, and it is found that the temperature dependence of the lasing threshold is strongly affected by the degree of fluctuation. Furthermore, we have experimentally measured the temperature dependence of stimulated-emission threshold excitation power density in photo-pump measurements, and have observed the predicted behavior of temperature dependence. It is considered that the temperature dependence of the lasing threshold could be used for the evaluation of the degree of the potential fluctuation in active layers of InGaN QW lasers.

**Effect of Defects on Strain Relaxation in InGaN/AlGaN Multiple-Quantum-Well Near-Ultraviolet Light-Emitting Diodes**

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physica status solidi a
https://doi.org/10.1002/pssa.202100418

Three similar-structure InGaN/AlGaN multiple-quantum-well near-ultraviolet (NUV) light-emitting diodes (LEDs) are utilized to investigate the microscopic effect of defects on strain relaxation. Consistent correlations among the crystal quality, the piezoelectric field (FPZ), the internal quantum efficiency (IQE), and the bandgap shrinkage of NUV LEDs are obtained by investigating the macroscopic characterizations. The difference in crystal quality (or the defect density) of NUV LEDs is found by the ideality factor, the emission microscope image, the Shockley–Read–Hall coefficient, and the IQE. Electroreflectance spectra are used to calculate FPZ of NUV LEDs. FPZ, the IQE, and the peak-wavelength shift at driving currents are increased with the samples' crystal quality compared to the reference sample. Also, FPZ, the IQE, and the peak-wavelength shift are decreased with the increase in samples' defect densities. A similar result is found for the bandgap shrinkage. This effect significantly indicates that the strain relaxation is induced by defects. Herein, a model that systematically explains the observed changes in macroscopic properties of NUV LEDs is proposed.

**Review on the Progress of AlGaN-based Ultraviolet Light-Emitting Diodes**

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Fundamental Research
https://doi.org/10.1016/j.fmre.2021.11.005

AlGaN-based materials have exhibited considerable potential for fabricating ultraviolet (UV) light-emitting diodes (LEDs) owing to their direct, wide, and adjustable energy bandgap. AlGaN-based devices have extensive applicability owing to their stable physico-chemical properties. With decades of research effort, significant progress has been achieved in enhancing the working efficiency of AlGaN-based LEDs by optimizing the crystalline quality, doping efficiency, and device design. In this review, methods to obtain high-quality AlGaN-based materials, achieve high doping efficiency, and design UV-LED structures are summarized and discussed. Finally, the issues that need to be addressed in AlGaN-based UV-LED devices are highlighted.

**Low-threshold wavelength-tunable ultraviolet vertical-cavity surface-emitting lasers from 376 to 409 nm**

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Fundamental Research
https://doi.org/10.1016/j.fmre.2021.11.001

Optically pumped wavelength-tunable vertical-cavity surface-emitting lasers (VCSELs) operating in the ultraviolet A (UVA) spectrum were demonstrated. The VCSELs feature double dielectric distributed brag reflectors and a wedge-shaped cavity fabricated using the substrate transfer technique and laser lift off, resulting in a graded cavity length in one device. A resonant period gain structure is used in the InGaN/GaN multi-quantum well active region to enhance the coupling between the cavity mode field and the active layers. The optical field inside the cavity is modulated by the cavity length; thus, tunable lasing at different wavelengths is realized at different points of a single VCSEL chip. The lasing wavelength extends from 376 to 409 nm, covering most of the UVA band below the band gap of GaN. The threshold pumping power density of the UVA VCSELs at different wavelengths ranges from 383 to 466 kW/cm2, which is among the lowest values for ultraviolet (UV) VCSELs. This study is promising for the development of small-footprint, power-efficient UV light sources.

**Transfer-free graphene-guided high-quality epitaxy of AlN film for deep ultraviolet light-emitting diodes**

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Journal of Applied Physics
https://doi.org/10.1063/5.0065328

We report on quasi-van der Waals epitaxy of high-quality AlN film guided by transfer-free graphene (Gr) with low wrinkle density (LWD-Gr) on sapphire. The surface wrinkle density of LWD-Gr is greatly reduced by 94% compared to conventional Gr with high wrinkle density (HWD-Gr). Also noteworthy is that AlN nucleation islands grown on LWD-Gr exhibit better crystalline orientation consistency and more feasibility to coalesce with each other, thus forming AlN film with lower stress and dislocation density. Finally, 285 nm deep ultraviolet (DUV) light-emitting diodes are fabricated on the high-quality AlN template with LWD-Gr, which shows stronger electroluminescence intensity than its counterpart without and with HWD-Gr. The insights granted by this research pave a new pathway for improving the performance of nitride-

based DUV optoelectronic devices through Gr engineering.

**Epitaxial growth of 2.5-µm quaternary AlInGaN for n-cladding layer in GaN-based green laser diodes**

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Fundamental Research
https://doi.org/10.1016/j.fmre.2021.09.016

The ridge morphology, which is related to random atomic step meandering, appears in thick AlInGaN films grown by metal organic chemical vapor deposition on both GaN templates and free-standing GaN substrates; this can be primarily attributed to the in-plane compressive strain in the thick layer. Therefore, a 2.5-µm Al0.08In0.0123GaN film with a slightly tensive strain was grown, with a regular and smooth step-flow morphology; the root mean square deviation of the film (with a size of 5 µm × 5 µm) was 0.56 nm.

**Catastrophic Optical Damage in Semiconductor Lasers: Physics and New Results on InGaN High-Power Diode lasers**

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physica status solidi rrl
https://doi.org/10.1002/pssr.202100527

Among the limitations known from semiconductor lasers, catastrophic optical damage (COD) is perhaps the most spectacular power-limiting mechanism. Here, absorption and temperature build up in a positive feedback loop that eventually leads to material destruction. Thus, this is truly an ultimate mechanism, and its continued suppression is a manifestation of progress in device design and manufacturing. After an overview of the current state of knowledge, we report on new investigations of COD using artificially µm-sized starting points created within the active zone in the cavity of 450-nm GaN semiconductor lasers. Defect growth mechanisms and characteristics were studied during 800-ns current pulses. The defect growth follows the highest light intensity. Secondary defect patterns are studied: complete destruction of the active zone and generation of a point defect cloud at least ∽10 µm into the remaining surrounding material. Extremely large angles (>90°) of damage growth are traced back to the material properties and the aging scenario. The results are compared to former experiments with GaAs-based lasers.

**Ultrasmall and ultradense InGaN-based RGB monochromatic micro-light-emitting diode arrays by pixilation of conductive p-GaN**

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Photonics Research
https://doi.org/10.1364/PRJ.439741

We describe 5 µm squircle InGaN-based red, green, and blue (RGB) monochromatic micro-light-emitting diodes (µLEDs) with an interpitch of 4 µm by pixilation of conductive p-GaN using a H2-plasma treatment. The p-GaN was passivated by H2 plasma and prevented the current's injection into the InGaN quantum wells below. We observed that InGaN-based red µLEDs exhibited a broader full width at half-maximum and larger peak wavelength blueshift at 11.5–115 A/cm2 than the green/blue µLEDs. The on-wafer light output power density of the red µLEDs at a wavelength of 632 nm at 115 A/cm2 was approximately 936 mW/cm2, the highest value reported thus far for InGaN-based red µLEDs. This value was comparable with that of the green/blue µLEDs at 11.5 A/cm2, indicating that the red µLEDs can satisfy the requirement of high brightness levels for specific displays. The color gamut based on InGaN RGB µLEDs covered 83.7% to 75.9% of the Rec. 2020 color space in the CIE 1931 diagram at 11.5 to 115 A/cm2.

**Defect Tolerance of Intersubband Transitions in Nonpolar GaN/(Al,Ga)N Heterostructures: A Path toward Low-Cost and Scalable Mid- to Far-Infrared Optoelectronics**

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PHYSICAL REVIEW APPLIED
https://doi.org/10.1103/PhysRevApplied.16.054040

We report on the impact of structural defects on mid-infrared intersubband (ISB) properties of GaN/(Al,Ga)N heterostructures grown by ammonia molecular beam epitaxy (NH3 MBE). Twenty-period GaN/(Al,Ga)N multi-quantum-well (MQW) heterostructures are grown on co-loaded a-plane freestanding GaN substrates and heteroepitaxial a-plane GaN on r-plane sapphire templates (a-GaN/r-sap) for three different quantum-well (QW) widths (3.0, 3.3, and 3.7 nm). Co-loaded structures grown on freestanding a-plane with no basal-plane stacking faults (BSFs), prismatic stacking faults (PSFs), and partial dislocations (PDs), with low threading dislocation (TD) densities of about 105cm−2 are compared with those grown on a-GaN templates on (10¯12) r-sapphire with BSF, PSF, PD, and TD densities of about 4 × 105 to 106cm−2, 5 × 103 to 2 × 104cm−2, about 9 × 1010 to 2 × 1011cm−2, and about 1010cm−2, respectively. Fourier-transform infrared absorption spectroscopy indicates ISB transition energies in the range of about 250–300 meV (wavelength range 4.1–4.8 μm) for MQWs with different QW widths. The ISB absorption spectra indicate about 5% smaller transition energies and only about 10%–20% larger spectral linewidths for structures grown on a-GaN/r-sapphire templates compared with those on freestanding GaN substrates. The strong defect tolerance in the nonpolar a-plane ISB structures could be due to the nature of defects and their energy levels with respect to the conduction-band minima, which do not affect the ISB properties. Our results pave the way toward the production of low-cost scalable nonpolar III-nitride MQW heterostructures for a variety of passive and active optical materials and devices based on intersubband transitions.

**Band Structure Engineering Based on InGaN/ZnGeN2 Heterostructure Quantum Wells for Visible Light Emitters**

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Cryst. Growth Des.
https://doi.org/10.1021/acs.cgd.1c00630

Band structure engineering based on InGaN/ZnGeN2 heterostructure quantum wells (QWs) is proposed to address the long-standing charge separation challenge in visible light emitters using polar InGaN QWs as active media. A nanometer-scale layer of ZnGeN2 is successfully incorporated in InGaN QWs via metalorganic chemical vapor deposition. Understanding the structural properties of the heterostructure QWs reveals that the growth conditions for the GaN barrier layers play an important role in the QW properties. Specifically, the structural quality of the QWs is improved by increasing the thickness and the growth temperature of the GaN barrier layers. Due to the large band offset at the InGaN/ZnGeN2 heterointerface, the position and thickness of the ZnGeN2 sub-layer within the InGaN QWs determine the potential minima and thus the carrier wave functions in both conduction and valence bands. This work demonstrates the effectiveness of emission wavelength tunability of InGaN/ZnGeN2/InGaN heterostructure QWs via tuning of the ZnGeN2 sub-layer properties. More significantly, the peak emission of InGaN/ZnGeN2/InGaN heterostructure QWs can be extended to longer wavelengths without increasing the In composition or the QW thickness. Results from this work provide a new route for addressing the low quantum efficiency of conventional InGaN QWs emitting at green and longer wavelengths.

**Recent progress in red light-emitting diodes by III-nitride materials**

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Semiconductor Science and Technology
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GaN-based light-emitting devices have the potential to realize all visible emissions with the same material system. These emitters are expected to be next-generation red, green, and blue displays and illumination tools. These emitting devices have been realized with highly efficient blue and green light-emitting diodes (LEDs) and laser diodes. Extending them to longer wavelength emissions remains challenging from an efficiency perspective. In the emerging research field of micro-LED displays, III-nitride red LEDs are in high demand to establish highly efficient devices like conventional blue and green systems. In this review, we describe fundamental issues in the development of red LEDs by III-nitrides. We also focus on the key role of growth techniques such as higher temperature growth, strain engineering, nanostructures, and Eu doping. The recent progress and prospect of developing III-nitride-based red light-emitting devices will be presented.

**On electrical analysis of Al-rich p-AlGaN films for III-nitride UV light emitters**

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In this work, an alternative scheme to estimate the resistivity and ionization energy of Al-rich p-AlGaN epitaxial films is developed using two large-area ohmic contacts. Accordingly, the resistivities measured using current–voltage measurements were observed to corroborate the Hall measurements in the Van der Pauw configuration. A free hole concentration of ∼1.5 × 1017 cm−3 and low ionization energy of ∼65 meV in Mg-doped Al0.7Ga0.3N films is demonstrated. Nearly an order of magnitude lower hydrogen concentration than Mg in the as-grown AlGaN films is thought to reduce the Mg passivation and enable higher hole concentrations in Al-rich p-AlGaN films, compared to p-GaN films. The alternate methodology proposed in this work is expected to provide a simpler pathway to evaluate the electrical characteristics of Al-rich p-AlGaN films for future III-nitride ultraviolet light emitters.

**Reduction of efficiency droop in c-plane InGaN/GaN light-emitting diodes using a thick single quantum well with doped barriers**

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Applied Physics Letters
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We report on c-plane InGaN/GaN single quantum well (QW) light-emitting diodes (LEDs) of different well widths (3 or 9 nm) with and without doped barriers. QW barriers were doped with the aim of reducing the internal electric field (FQW) in the QW to increase the electron-hole overlap, therefore increasing the recombination rates and resulting in the reduction of the efficiency droop. We, indeed, observed, through biased photocurrent spectroscopy, a reduction in FQW with doped barriers, with FQW being in the same direction of the p-n junction field at zero bias as opposed to the junction field for LEDs without doped barriers. Even with the improvement in the ground state wavefunction overlap, the ground state transition rate remains low for thick QWs. Transitions through excited states were observed for both thick QW LEDs with and without doped barriers. The thick QW LED without doped barriers displayed low external quantum efficiency (EQE), likely as a result of the carrier overflow due to the poor confinement of carriers in the excited states. On the other hand, for

LEDs with doped barriers, the flatter band in the QW resulting from the lower FQW reduces the energy separation between the eigenstates, leading to better confinement of carriers in the excited states. With doped barriers, we demonstrated a low efficiency droop 9-nm-thick single QW LED with a peak EQE of 42% at 40 A/cm2 and an EQE of 36% at 400 A/cm2.

**Role of oxygen diffusion in the dislocation reduction of epitaxial AlN on sapphire during high-temperature annealing**

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Recovery of epitaxial AlN films on sapphire at high temperatures is now an established process to produce pseudo-substrates with high crystalline perfection, which can be used to grow epitaxial structures for UV-light-emitting devices. To elucidate the elementary mechanisms taking place during the thermal treatment of MOVPE-grown films, we studied as-grown and annealed samples combining transmission electron microscopy techniques and secondary ion mass spectrometry (SIMS). By using SIMS, we find a temperature-dependent increase in the overall oxygen content of the films, which cannot be explained quantitatively with either simple bulk or pure pipe-diffusion from the sapphire substrate. Instead, we propose a lateral outdiffusion from the dislocation cores to explain qualitatively and quantitatively the presence of observed oxygen concentration plateaus. Based on the formation enthalpy of various atomic defects and complexes found in literature, we conclude that the di-oxygen/aluminum vacancy complex (VAl–2ON) is the dominant point defect controlling the annealing process. The formation of this defect at high temperatures promotes a dislocation core climb process, which causes the annihilation/fusion of the threading dislocation segments.

**Solar-blind ultraviolet photodetectors with thermally reduced graphene oxide formed on high-Al-content AlGaN layers**

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AIP Advances
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Solar-blind deep-ultraviolet (UV) photodetectors (PDs) with high responsivity and fast response have attracted significant attention in environmental, industrial, biological, and military applications. AlGaN is a representative semiconductor material in the field of solar-blind detection; semiconductor performance can be accelerated by combining it with high-transparency, high-stability contact electrode materials. In this study, solar-blind deep-UV metal–semiconductor–metal (MSM) PDs were fabricated based on two-dimensional reduced graphene oxide (rGO) contacts formed on various high-Al-content AlGaN semiconductors. A low dark current in the order of a few picoamperes and a fast photoresponse time of a few tens of milliseconds were confirmed. The investigation of the effects of front- and back-side illumination showed that the photocurrents and corresponding responsivities of the PDs drastically improved under back-side illumination. In detail, the peak locations of the responsivity–wavelength curves were downshifted from 290 nm with a responsivity of 0.0518 A/W for the rGO/Al0.5Ga0.5N MSM PD to 250 nm with a responsivity of 0.0113 A/W for the rGO/Al0.7Ga0.3N MSM PD under back-side illumination. These results indicate that rGO contacts on AlGaN provide a viable approach for developing solar-blind deep-UV PDs.

**Evolution of a dominant light emission mechanism induced by changes of the quantum well width in InGaN/GaN LEDs and LDs**

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Optics Express
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We examined electroluminescence from In0.17Ga0.83N/GaN quantum wells (QW) of light-

emitting diodes (LEDs) and laser diodes (LDs). For increasing QW width we observe transition from electron and hole ground-states recombination to excited states recombination. The effect is accompanied by partial (2.6 nm, 5.2 nm, 7.8 nm QW) or practically complete (10.4 nm QW) screening of the built-in electric field with increasing driving current for both types of emitters. The electric field magnitude was studied using an original high pressure method. The investigations are supported by simulations of the variation with driving current of i) electron and hole wavefunctions overlap affecting the recombination channel, ii) built-in electric field.

**Underwater optical wireless communications with InGaN LEDs grown with an asymmetric multiple quantum well for light emission or detection**

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IEEE Photonics Journal
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InGaN light-emitting diodes (LEDs) grown with an asymmetric multiple quantum well (MQW) are proposed for use in an optical link with an avalanche photodiode (APD) based receiver. In contrast to the high photoresponse of red AlGaInP LEDs in APDs, the proposed blue LEDs provide improved light output and enhanced system bandwidth for directed line-of-sight optical links passing through a 100-cm-long water tank. This improvement is due to the nonuniform carrier distribution within the InGaN MQWs being mitigated by using a thin GaN barrier near the n-GaN to facilitate hole transport capacity. In addition, bandwidth degradation resulting from APD module saturation can also be avoided by using these blue LEDs, successfully establishing a 300 Mbit/s LED-based underwater data link. The proposed InGaN LEDs (zero bias) under illumination exhibit a peak responsivity of 0.133 at = 370 nm, an ultraviolet (UV)-to-visible rejection ratio of 4849 and a 3-dB cut-off frequency of 33.3 MHz. Using violet UV laser diodes and the proposed LEDs respectively as the optical transmitter and receiver, an underwater optical link (L =100 cm) with a data transmission rate of up to 130 Mbit/s and a bit error rate of 4.2 109 is also demonstrated.

**275 nm deep ultraviolet AlGaN-based micro-LED arrays for ultraviolet communication**

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IEEE Photonics Journal
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In this work, we fabricated and characterized 44 parallel flip-chip AlGaN-based micro-LED arrays with varied mesa diameters of 120 m, 100 m, 80 m, and 60 m. The reported micro-LED arrays have a maximum bandwidth of 380 MHz and a peak wavelength of ~275 nm. It is found that the electrical and optical characteristics of AlGaN-based micro-LED arrays show strong size dependence for ultraviolet communication (UVC). The differential resistance increases from 28.8 to 112, the external quantum efficiency (EQE) is increased by ~30%, and the bandwidth doubles as the diameter of individual micro-LED decreases from 120 m to 60 m. Our research proves that tailoring the mesa size of parallel flip-chip AlGaN-based micro-LED arrays can further enhance its bandwidth and promote its application in UVC.

**Enhanced Optoelectronic Performance of Yellow Light-Emitting Diodes Grown on InGaN/GaN Pre-Well Structure**

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Nanomaterials
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InGaN-based long-wavelength light-emitting diodes (LEDs) are indispensable components for the next-

generation solid-state lighting industry. In this work, we introduce additional InGaN/GaN pre-wells in LED structure and investigate the influence on optoelectronic properties of yellow (~575 nm) LEDs. It is found that yellow LED with pre-wells exhibits a smaller blue shift, and a 2.2-fold increase in light output power and stronger photoluminescence (PL) intensity compared to yellow LED without pre-wells. The underlying mechanism is revealed by using Raman spectra, temperature-dependent PL, and X-ray diffraction. Benefiting from the pre-well structure, in-plane compressive stress is reduced, which effectively suppresses the quantum confined stark effect. Furthermore, the increased quantum efficiency is also related to deeper localized states with reduced non-radiative centers forming in multiple quantum wells grown on pre-wells. Our work demonstrates a comprehensive understanding of a pre-well structure for obtaining efficient LEDs towards long wavelengths.

**An injection-locked green InGaN diode laser**

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Microwave and Optical Technology Letters
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We designed a single-frequency green laser system that can deliver a 60-mW frequency-tunable single-longitudinal-mode laser beam, having a 6.5 MHz linewidth at around 519 nm. An external cavity diode laser can provide a wavelength-tunable single frequency laser beam, but its output power is limited. Therefore, an injection-locked laser was designed with a Fabry–Perot type green InGaN laser diode in an external Littrow-type cavity as the master laser and another laser diode of the same model as the slave laser. Injection locking can effectively enhance the output power and narrow the linewidth of the master laser. We found that the injection locking occurred at longitudinal mode matching between the master laser and slave laser diodes, which is located at a specific frequency for a periodical applied current. The side peaks of the injection locking due to the transverse mode mismatching were recorded and analyzed.

**High conductivity n-Al0.6Ga0.4N by ammonia-assisted molecular beam epitaxy for buried tunnel junctions in UV emitters**

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Optics Express
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Highly doped n-Al0.6Ga0.4N can be used to form tunnel junctions (TJs) on deep ultraviolet (UVC) LEDs and markedly increase the light extraction efficiency (LEE) compared to the use of p-GaN/p-AlGaN. High quality Al0.6Ga0.4N was grown by NH3-assisted molecular beam epitaxy (NH3 MBE) on top of AlN on SiC substrate. The films were crack free under scanning electron microscope (SEM) for the thickness investigated (up to 1 µm). X-ray diffraction reciprocal space map scan was used to determine the Al composition and the result is in close agreement with atom probe tomography (APT) measurements. By varying the growth parameters including growth rate, and Si cell temperature, n-Al0.6Ga0.4N with an electron density of 4×1019 /cm3 and a resistivity of 3 mΩ·cm was achieved. SIMS measurement shows that a high Si doping level up to 2×1020 /cm3 can be realized using a Si cell temperature of 1450 °C and a growth rate of 210 nm/hr. Using a vanadium-based annealed contact, ohmic contact with a specific resistance of 10−6 Ω·cm2 was achieved as determined by circular transmission line measurement (CTLM). Finally, the n-type AlGaN regrowth was done on MOCVD grown UVC LEDs to form UVC TJ LED. The sample was processed into thin film flip chip (TFFC) configuration. The emission wavelength is around 278 nm and the excess voltage of processed UV LED is around 4.1 V.

## ELECTRONICS

Group leader: Farid Medjoub (CNRS-IEMN)

*Information selected by Farid Medjoub (CNRS-IEMN), Jean-Claude De Jaeger (CNRS-IEMN), Matthew Charles (CEA-Leti) and Yvon Cordier (CNRS-CRHEA)*

### Substrate Effects on the Electrical Properties in GaN-Based High Electron Mobility Transistors

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Crystals
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We report the electrical characteristics of GaN-based high electron mobility transistors (HEMTs) operated on various substrates/films. For the detailed investigation and comparison of the electrical properties of GaN-based HEMTs according to the substrates/films, GaN-based HEMTs were processed using 4-inch sapphire substrates and separated from their original substrates through the laser lift-off technique. The separated AlGaN/GaN films including processed GaN-based HEMTs were bonded to AlN substrate or plated with a 100 µm-thick Cu at the back-side of the devices since AlN substrate and Cu film exhibit higher thermal conductivity than the sapphire substrate. Compared to the sapphire substrate, DC and RF properties such as drain current, transconductance, cut-off frequency and maximum oscillation frequency were improved, when GaN-based HEMTs were operated on AlN substrate or Cu film. Our systematic study has revealed that the device property improvement results from the diminishment of the self-heating effect, increase in carrier mobility under the gated region, and amelioration of sheet resistance at the access region. C(V) and pulse-mode stress measurements have confirmed that the back-side processing for the device transfer from sapphire substrate onto AlN substrate or Cu film did not induce the critical defects close to the AlGaN/GaN hetero-interface.

### Properties of AlN/GaN Heterostructures Grown at Low Growth Temperatures with Ammonia and Dimethylhydrazine

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Crystals
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The integration of different electronic materials systems together has gained increasing interest in recent years, with the III-nitrides being a favorable choice for a variety of electronic applications. To increase flexibility in integration options, growing nitrides material directly on semi-processed wafers would be advantageous, necessitating low temperature (LT) growth schemes. In this work, the growth of AlN and GaN was conducted via metalorganic chemical vapor deposition (MOCVD) using both NH3 and DMHy as N-precursors. The relationships between growth rate versus temperature were determined within the range of 300 to 550 °C. The growth of AlN/GaN heterostructures was also investigated herein, employing flow modulation epitaxy MOCVD at 550 °C. Subsequent samples were studied via atomic force microscopy, X-ray diffraction, TEM, and Hall measurements. Two-dimensional electron gases were found in samples where the LT AlN layer was grown with NH3, with one sample showing high electron mobility and sheet charge of 540 cm2/V·s and 3.76 × 1013 cm−2, respectively. Inserting a LT GaN layer under the LT AlN layer caused the mobility and charge to marginally decrease while still maintaining sufficiently high values. This sets the groundwork towards use of LT nitrides MOCVD in future electronic devices integrating III-nitrides with other materials.

**A novel AlGaN/GaN heterostructure field-effect transistor based on open-gate technology**

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Scientific Reports
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In this study, a novel AlGaN/GaN heterostructure field-effect transistor based on open-gate technology was fabricated. Sample transistors of different structures and sizes were constructed. Through measurements, it was found that by changing the width of the opening, the threshold voltage of the device could be easily modulated across a larger range. The open-gate device had two working modes with different transconductance. When the gate-source voltage VGS ≤ − 4.5 V, only the open region was conductive, and a new working mechanism modulated the channel current. Corresponding theoretical analysis and calculations showed that its saturation mechanism was related to a virtual gate formed by electron injection onto the surface. Also, the gate-source voltage modulated the open channel current by changing the channel electron mobility through polarization Coulomb field scattering. When used as class-A voltage amplifiers, open-gate devices can achieve effective voltage amplification with very low power consumption.

**The Influence of Design on Electrical Performance of AlGaN/GaN Lateral Schottky Barrier Diodes for Energy-Efficient Power Applications**

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Electronics
https://doi.org/10.3390/electronics10222802

In this paper, lateral AlGaN/GaN Schottky barrier diodes are investigated in terms of anode construction and diode structure. An original GaN Schottky diode manufacturing-process flow was developed. A set of experiments was carried out to verify dependences between electrical parameters of the diode, such as reverse and forward currents, ON-state voltage, forward voltage and capacitance, anode-to-cathode distance, length of field plate, anode length, Schottky contact material, subanode recess depth, and epitaxial structure type. It was found that diodes of SiN/Al0.23Ga0.77N/GaN epi structure with Ni-based anodes demonstrated two orders of magnitude lower reverse currents than diodes with GaN/Al0.25Ga0.75N/GaN epitaxial structure. Diodes with Ni-based anodes demonstrated lower VON and higher IF compared with diodes with Pt-based anodes. As a result of these investigations, an optimal set of parameters was selected, providing the following electrical characteristics: VON = 0.6 (at IF = 1 mA/mm), forward voltage of the diode VF = 1.6 V (at IF = 100 mA/mm), maximum reverse voltage VR = 300 V, reverse leakage current IR = 0.04 μA/mm (at VR = −200 V), and total capacitance C = 3.6 pF/mm (at f = 1 MHz and 0 V DC bias). Obtained electrical characteristics of the lateral Schottky barrier diode demonstrate great potential for use in energy-efficient power applications, such as 5G multiband and multistandard wireless base stations.

**Theoretical and Experimental Substractions of Device Temperature Determination Utilizing I-V Characterization Applied on AlGaN/GaN HEMT**

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Electronics
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A differential analysis of electrical attributes, including the temperature profile and trapping phenomena is introduced using a device analytical spatial electrical model. The resultant current difference caused by the applied voltage variation is divided into isothermal and thermal sections, corresponding to the instantaneous time- or temperature-dependent change. The average temperature relevance is explained in the theoretical section with respect to the thermal profile and major parameters of the device at the operating point. An ambient temperature variation method has been used to determine device average temperature under quasi-static state and

pulse operation, was compared with respect to the threshold voltage shift of a high-electron-mobility transistor (HEMT). The experimental sections present theoretical subtractions of average channel temperature determination including trapping phenomena adapted for the AlGaN/GaN HEMT. The theoretical results found using the analytical model, allow for the consolidation of specific methodologies for further research to determine the device temperature based on spatially distributed and averaged parameters.

**Van der Waals Heterostructure of Hexagonal Boron Nitride with an AlGaN/GaN Epitaxial Wafer for High-Performance Radio Frequency Applications**

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ACS Appl. Mater. Interfaces
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While two-dimensional (2D) hexagonal boron nitride (h-BN) is emerging as an atomically thin and dangling bond-free insulating layer for next-generation electronics and optoelectronics, its practical implementation into miniaturized integrated circuits has been significantly limited due to difficulties in large-scale growth directly on epitaxial semiconductor wafers. Herein, the realization of a wafer-scale h-BN van der Waals heterostructure with a 2 in. AlGaN/GaN high-electron mobility transistor (HEMT) wafer using metal–organic chemical vapor deposition is presented. The combination of state-of-the-art microscopic and spectroscopic analyses and theoretical calculations reveals that the heterointerface between ∼2.5 nm-thick h-BN and AlGaN layers is atomically sharp and exhibits a very weak van der Waals interaction without formation of a ternary or quaternary alloy that can induce undesired degradation of device performance. The fabricated AlGaN/GaN HEMT with h-BN shows very promising performance including a cutoff frequency (fT) and maximum oscillation frequency (fMAX) as high as 28 and 88 GHz, respectively, enabled by an effective passivation of surface defects on the HEMT wafer to deliver accurate information with minimized power loss. These findings pave the way for practical implementation of 2D materials integrated with conventional microelectronic devices and the realization of future all-2D electronics.

**Mechanism leading to semi-insulating property of carbon-doped GaN: Analysis of donor acceptor ratio and method for its determination**

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Carbon impurities in GaN form both acceptors and donors. Donor-to-acceptor ratios (DARs) determine the semi-insulating behavior of carbon-doped GaN (GaN:C) layers and are still debated. Two models are discussed; both can theoretically achieve semi-insulating behavior: the dominant acceptor model (DAM, DAR<1) and the auto-compensation model (ACM, DAR=1). We perform a capacitance–voltage analysis on metal/GaN:C/nGaN (n-doped GaN) structures, exhibiting Fermi-level pinning in GaN:C, 0.7 eV above the valence band maximum. This observation coupled with further interpretation clearly supports the DAM and contradicts the ACM. Furthermore, we reveal a finite depletion width of a transition region in GaN:C next to nGaN, where carbon acceptors drop below the Fermi level becoming fully ionized. Calculation of the potential drop in this region exhibits DAR values of 0.5–0.67 for GaN:C with total carbon concentrations of 1018 cm−3 and 1019 cm−3. Based on those results, we re-evaluate formerly published density functional theory (DFT)-calculated formation energies of point defects in GaN. Unexpectedly, growth in thermodynamic equilibrium with the bulk carbon phase contradicts our experimental analysis. Therefore, we propose the consideration of extreme carbon-rich growth conditions. As bulk carbon and carbon cluster formation are not reported to date, we consider a metastable GaN:C solid solution with the competing carbon bulk phase being kinetically hindered. DFT and

experimental results agree, confirming the role of carbon at nitrogen sites as dominant acceptors. Under N-rich conditions, carbon at gallium sites is the dominant donor, whereas additional nitrogen vacancies are generated under Ga-rich conditions.

**GaN-based power devices: Physics, reliability, and perspectives**

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Journal of Applied Physics
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Over the last decade, gallium nitride (GaN) has emerged as an excellent material for the fabrication of power devices. Among the semiconductors for which power devices are already available in the market, GaN has the widest energy gap, the largest critical field, and the highest saturation velocity, thus representing an excellent material for the fabrication of high-speed/high-voltage components. The presence of spontaneous and piezoelectric polarization allows us to create a two-dimensional electron gas, with high mobility and large channel density, in the absence of any doping, thanks to the use of AlGaN/GaN heterostructures. This contributes to minimize resistive losses; at the same time, for GaN transistors, switching losses are very low, thanks to the small parasitic capacitances and switching charges. Device scaling and monolithic integration enable a high-frequency operation, with consequent advantages in terms of miniaturization. For high power/high-voltage operation, vertical device architectures are being proposed and investigated, and three-dimensional structures—fin-shaped, trench-structured, nanowire-based—are demonstrating great potential. Contrary to Si, GaN is a relatively young material: trapping and degradation processes must be understood and described in detail, with the aim of optimizing device stability and reliability. This Tutorial describes the physics, technology, and reliability of GaN-based power devices: in the first part of the article, starting from a discussion of the main properties of the material, the characteristics of lateral and vertical GaN transistors are discussed in detail to provide guidance in this complex and interesting field. The second part of the paper focuses on trapping and reliability aspects: the physical origin of traps in GaN and the main degradation mechanisms are discussed in detail. The wide set of referenced papers and the insight into the most relevant aspects gives the reader a comprehensive overview on the present and next-generation GaN electronics.

**p-type AlN based heteroepitaxial diodes with Schottky, Pin, and junction barrier Schottky character achieving significant breakdown performance**

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Journal of Applied Physics
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The recent achievement of p-type AlN films via Be doping was utilized to achieve novel heteroepitaxial diodes with Schottky, Pin, and junction barrier Schottky (JBS) electrical behavior. Although the heteroepitaxial structures were quasi-vertical, which is subject to many issues lowering the breakdown voltage, the Pin diode achieved a breakdown voltage of ~25 V for a 200 nm thick unintentionally doped intrinsic layer indicating ~50% of the theoretical breakdown voltage performance for a similar homoepitaxial GaN pin diode. JBS and Schottky diodes were implemented using the inherent and intentional stress cracking properties of AlN grown on GaN films avoiding regrowth and plasma etching, both known to be technology impediments. The density of the intentional cracks and crystalline quality of the p-AlN films was controlled via Be doping and the total metal dose supplied during the metal modulated epitaxy shutter cycle resulting in differing degrees of grown stress. Since the intentional crack density determines the surface area ratio of the Schottky diode to the Pin diode, it is a key design parameter in optimizing device

performance. Furthermore, a novel current spreading layer was implemented to improve the current uniformity in these devices. The high breakdown voltage and good forward voltage characteristics of these devices shows potential to enable high-performance III-nitride high-power devices.

**Integration of high permittivity BaTiO3 with AlGaN/GaN for near-theoretical breakdown field kV-class transistors**

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Applied Physics Letters
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In this Letter, we discuss AlGaN/GaN HEMTs integrated with high permittivity BaTiO3 dielectric to enable enhanced breakdown characteristics. We show that using high permittivity BaTiO3 dielectric layers in the gate and drain access regions prevents premature gate breakdown, leading to average breakdown fields exceeding 3 MV/cm at a gate-to-drain spacing of 4 µm. The higher breakdown fields enable a high power figure of merit above 2.4 GW/cm2 in devices with a gate-to-drain spacing of 6 µm. This work demonstrates that electrostatic engineering using high-permittivity dielectrics can enable AlGaN/GaN HEMTs in approaching the material breakdown field limits.

**Cascaded Ni hard mask to create chlorine-based ICP dry etched deep mesas for high-power devices**

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Semiconductor Science and Technology
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A highly selective cascaded Ni hard mask without stress and film damage issues suitable for the formation of deep vertical mesas for high-power devices is presented. A Cl2/BCl3/Ar inductively coupled plasma dry etch was used to investigate the effect of photoresist, and patterned Ni hard masks applied via four different methods on the etch rate of GaN, and mask selectivity. Strain in the e-beam only deposited Ni films produced low yield due to poor adhesion. Electroplated Ni showed rough mask morphology. Sputtered Ni left damage/chemically reacted layers on the GaN under the mask. A cascaded 50 nm e-beam evaporated Ni followed by 2 µm of sputtered Ni mask method improved the yield to 100%, achieved high selectivity and retained an undamaged GaN surface morphology. The cascaded Ni hard mask successfully achieved GaN mesas up to 13 µm. The dry etching rates of the photoresist, GaN and Ni masks were 250, 275 and 13 nm min−1, respectively giving an etch selectivity of the GaN/Ni hard mask of ∼20, much higher than the etch selectivity of 1.1 for the photoresist. Furthermore, yield of the cascaded Ni hard mask was 100% making it suitable for commercial high-power electronics.

**Abnormal phenomenon of source-drain current of AlGaN/GaN heterostructure device under UV/visible light irradiation**

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We report an abnormal phenomenon that the source-drain current (ID) of AlGaN/GaN heterostructure devices decreases under visible light irradiation. When the incident light wavelength is 390 nm, the photon energy is less than the band gaps of GaN and AlGaN whereas it can causes an increase of ID. Based on the UV light irradiation, a decrease of ID can still be observed when turning on the visible light. We speculate that this abnormal phenomenon is related to the surface barrier height, the unionized donor-like surface states below the surface Fermi level and the ionized donor-like surface states above the surface Fermi level. For visible light, its photon energy is less than the surface barrier height of the AlGaN layer. The electrons bound in the donor-like surface states below the Fermi level are excited and trapped by the ionized donor-like surface states between the Fermi level and the conduction band of AlGaN. The electrons trapped in ionized donor-like surface states show a long relaxation time, and the newly ionized donor-like surface states below the surface Fermi level are filled

with electrons from the two-dimensional electron gas (2DEG) channel at AlGaN/GaN interface, which causes the decrease of ID. For the UV light, when its photon energy is larger than the surface barrier height of the AlGaN layer, electrons in the donor-like surface states below the Fermi level are excited to the conduction band and then drift into the 2DEG channel quickly, which cause the increase of ID.

**Review on the degradation of GaN-based lateral power transistors**

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e-Prime – Advances in Electrical Engineering, Electronics and Energy
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Several mechanisms may contribute to the degradation of GaN transistors; in this paper we discuss the main processes that limit the lifetime of GaN power devices, with focus on the following relevant aspects: (i) the degradation/breakdown induced by off-state bias; (ii) the origin of vertical leakage and breakdown; (iii) the failure of the gate stack in MIS-HEMTs and in transistors with p-type gate. The data reviewed in this paper help the reader understanding the main issues related to the development of GaN-based transistors, and give hints on possible strategies to improve device reliability. The signatures of the main deep levels in gallium nitride, which can influence the reliability of the devices, are critically reviewed and summarized.

**Room temperature asymmetric negative differential resistance characteristics of AlGaN/GaN resonant tunneling diodes grown by metal-organic chemical vapor deposition**

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Solid-State Electronics
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A large area AlGaN/GaN resonant tunneling diode (RTD) grown by metal–organic chemical vapor deposition (MOCVD) is manufactured. The device adopts air-bridge structure suitable for the terahertz (THz) band, and a commercially available high-frequency GaN technology is applied in the process of device fabrication. Negative differential resistance (NDR) characteristics of the device are observed under the bipolar bias voltage at room temperature, which exhibits clear anti-symmetry in the peak-to-valley current ratio (PVCR), peak voltage and peak current density. The work systematically investigates how the built-in electric field introduced by polarization effects modulates the resonant tunneling transport utilizing TCAD tool Silvaco-ATLAS, and analyzes the enhancement of the resonant tunneling under negative bias voltage of the RTD with low-aluminum content AlGaN as barriers. The AlGaN/GaN RTD with conventional double-barrier single (DBS) quantum well (QW) structure shows reproducible NDR characteristics under the bipolar bias voltage at room temperature, which facilitates the design and extensive study of complicated device structures.

**The Influence of Fe Doping Tail in Unintentionally Doped GaN Layer on DC and RF Performance of AlGaN/GaN HEMTs**

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IEEE Transactions on Electron Devices
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In this work, the performance of AlGaN/gallium nitride (GaN) high-electron mobility transistors (HEMTs) with different Fe doping tails was systematically investigated and compared. It is illustrated that the combination of the unintentionally doped (UID) GaN layer and a thinner Fe doping buffer layer would result in a faster slope rate of Fe concentration in the UID GaN layer. The devices with the fastest slope rate of Fe concentration in the UID GaN layer exhibited excellent large signal performance, including the saturated power density ( Psat ) of 9 W/mm and the power-added efficiency (PAE) of 65.6%. In addition, the Psat and the PAE of the device with the fastest slope rate of Fe concentration in UID GaN layer are 27.7% and 14.7%, which are higher than that of the device with the slowest slope rate of Fe concentration under the class AB operation conditions. Pulse I-V measurement results demonstrated that the buffer-related current collapse was more effectively suppressed in the 0.5-μm Fe doping buffer layer because of faster slope rate

of Fe concentration in UID GaN layer. Moreover, the frequency-dependent capacitance and conductance measurement results indicated that the current collapse was relevant to deep traps in the UID GaN layer introduced by Fe doping. By reducing the concentration of the deep traps caused by Fe doping, the device showed excellent characteristics of dc and RF. Furthermore, controlling the Fe doping tail was important for designing the GaN-based power amplifier with high Psat and PAE.

**Breakdown Electric Field of GaN p+-n and p-n+ Junction Diodes with Various Doping Concentrations**

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Breakdown characteristics in homoepitaxial GaN p-n junction diodes with p+-n and p-n+ junctions with relatively heavy doping concentrations are systematically investigated. The devices have vertical deep mesa etch termination, which enables uniform (nearly ideal) avalanche breakdown without electric field (E-field) crowding at the device edge. For p+-n junction, breakdown E-field of 3.0, 3.3 and 3.8 MV/cm and breakdown voltage (BV) of 340, 207 and 128 V were achieved at the donor concentrations of 7.5×1016, 1.5×1017, 3.1×1017 cm-3, respectively. For p-n+ junction, breakdown E-field of 3.2, 3.3 and 4.0 MV/cm and BV of 235, 180 and 110 V were achieved at the acceptor concentrations of 1.3×1017, 1.8×1017, 4.1×1017 cm-3, respectively. No significant difference of the breakdown characteristics between n-type and p-type voltage-blocking layers was observed. These results are consistent with numerical simulations using impact ionization coefficients (IICs) in GaN reported in our previous studies.

**Low-frequency noise characterization of AlGaN/GaN HEMTs with and without a p-GaN gate layer**

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Semiconductor Science and Technology
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In this paper, low-frequency noise characteristics of commercial AlGaN/GaN high electron mobility transistors with different substrates and devices with and without a p-GaN gate layer are measured and discussed. The noise power spectral density (PSD) of various devices are compared and analyzed under linear-region operation. The 1/f noise behavior exhibits carrier number fluctuation as the dominant cause. Devices with p-GaN gate layer fabricated on Si substrate show the highest normalized noise PSD. Results show that not only flicker noise (1/f noise) exists but that it also accompanied by generation–recombination noise (g–r noise) in the device on SiC substrate. The extracted g–r noise related traps show an activation energy of ~0.37 eV, which is mostly caused by spatial charges trapping/detrapping with the deep acceptor in the GaN buffer layer.

**Figures-of-Merit of Lateral GaN Power Devices: Modeling and Comparison of HEMTs and PSJs**

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IEEE Journal of the Electron Devices Society
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In this work, we propose a simple and yet accurate physical model to describe the figures-of-merit (FOMs) of lateral GaN power devices. While the performance limit of vertical devices is well understood, the FOMs of lateral devices are not properly described by current models. This work investigates the specific characteristics of the depletion in lateral devices, particularly focusing on the substantial potential of Polarization Super Junctions (PSJs) compared to conventional High-Electron-Mobility Transistors (HEMTs). Our results show that PSJs can result in more than a 10-fold decrease in specific on-resistance for the same breakdown voltage compared to HEMTs, which can be further improved by the use of multi-channel

heterostructures. In addition, we demonstrate that PSJs lead to a significant reduction of the RON×Eoss figure-of-merit, both in the case of negligible and dominating parasitic contributions. This model enables a proper evaluation of the main figures-of-merit of lateral GaN power devices and shows the potential of PSJs to reduce both the DC and switching losses in power devices.

**Investigation on the Degradation Mechanism for GaN Cascode Device under Repetitive Hard-Switching Stress**

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The degradations of electrical parameters for depletion mode GaN devices in the cascode configuration under repetitive hard-switching stress are investigated in detail. With the help of TCAD simulations and comprehensive experimental analysis, two different mechanisms behind the degradations are demonstrated. Under a relatively low Vds hard-switching condition, hot electron injection is proved to be the only influence factor, which results in the increase of Rdson under low gate bias voltage. Furthermore, under the low Vds switching condition, influence of different stages on the degradation trend of the device is verified. It is found that the turn-on procedure has a greater degradation risk due to higher energy consumption. However, when Vds is high during hard-switching, the surface trapping effect is triggered due to high electric field at the end of gate field plate, and finally results in the device degradation trend. It results in the increase of the Rdson under high gate bias condition. Therefore, considering the stability and safety of power systems which adopt cascode devices as switches, shorter turn-on time or a soft-switching operation condition should be considered in the design.

**A New High-Frequency HEMT GaN Extrinsic Capacitance Extraction Technique**

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IEEE Microwave and Wireless Components Letters
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In this letter, a new extraction technique is proposed to determine the GaN high-electron-mobility transistor (HEMT) extrinsic capacitances using a small-signal model equivalent circuit with 21 elements under cold pinchoff operating conditions. This technique is based on an analytical representation of the various capacitances. The proposed approach achieved successful results through close agreement with published data, up to 60 GHz.

**Analysis of Electrical Properties in Ni/GaN Schottky Contacts on nonpolar/semipolar GaN free-standing Substrates**

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Journal of Alloys and Compounds
https://doi.org/10.1016/j.jallcom.2021.162817

This work focuses on the electrical properties of Ni/n-GaN Schottky barrier diodes (SBDs) fabricated on GaN bulk substrates with different crystal orientations. For the SBDs on a-plane, m-plane, and s5-plane GaN, the Schottky barrier heights (SBHs) exhibited magnitudes of 0.65 eV, 0.69 eV, and 0.75 eV, respectively. The relatively small SBH of a-plane devices results in a relatively larger reverse leakage current than that of m-plane and s5-plane. In addition, the carrier concentrations extracted by C–V characteristics are comparable for the GaN substrates with different crystal orientations. The temperature-dependent I–V characteristics indicate how the barrier inhomogeneity of the Ni/GaN Schottky contacts on the

a-plane GaN is smaller than the others. Based on the XPS spectra results, the discrepancy in Schottky contact characteristics stems from the different polarization charges and/or surface oxides of the different crystal planes. The low GaOx density on a-plane GaN surface contributes to the minimum barrier inhomogeneity of the corresponding SBD devices.

**Profitability of low-temperature power electronics and potential applications**

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Cryogenics
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This article presents an investigation of the profitability of cryogenic power electronics at different cooling and ambient temperatures. Thermodynamic fundamentals of low-temperature refrigeration processes are considered and the Carnot efficiencies of state-of-the-art refrigerators are evaluated in order to establish the necessary power loss reduction for energetic profitability of low-temperature to cryogenic power electronic systems down to 77 K. In this context, special attention is paid to two loss contributions in a power electronic system which, based on investigations on active and passive components, show the greatest potential for loss reduction at low temperatures. These are the on-state losses of Si and GaN transistors and the DC winding losses of inductors. The analysis shows that over the entire low temperature range, the loss reduction in a cryogenic converter can hardly compensate for the electrical power required to provide the necessary cooling capacity when cooling against an ambient temperature of 300 K.

**Analysis of RF performance of novel Sc-doped GaN high-electron-mobility transistors with air-bridge structure**

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Results in Physics
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We analysis the RF performance of novel Sc-Doped GaN high-electron-mobility transistors (HEMTs) with asymmetric air-bridge structure by TCAD software. The maximum oscillating frequency (fMAX) which has been achieved in this work is 41.2 GHz and the cutoff frequency (fT) reached 30.2 GHz, while the HEMT with conventional structure attained to only 12.9 GHz and 9 GHz respectively. This work has been performed on novel p-GaN HEMT device. The air-bridge is designed to be asymmetrical in width and the ScAlN layer is innovatively placed between the AlGaN and GaN layers as part of the heterojunction. It is found that the thickness change of scandium layer will bring great influence on a higher transconductance (from 9.22 × 10−3 S/mm to 3.187 × 10−2 S/mm), lower electron concentration (from 5.01 × 1019/cm3 to 3.16 × 1018/cm3) and higher electron velocity (from 5.52 × 107cm/s to 2.30 × 108cm/s) of the device. In addition, the combined influence of air bridge and scandium layer structure on the capacitance and other parameters were analyzed, which propose a useful approach for improving the DC and RF characteristic of GaN HEMTs.

**On the operating speed and energy efficiency of GaN-based monolithic complementary logic circuits for integrated power conversion systems**

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Fundamental Research
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Gallium nitride (GaN)-based power conversion systems exhibit striking competitiveness in realizing compact and high-efficiency power management modules. Recently emerging GaN-based p-channel field-effect transistors (FETs) and monolithic integration techniques enable the implementation of GaN-based complementary logic (CL) circuits and thereby offer an additional pathway to improving the system-level energy efficiency and functionality. In this article, holistic analyses are conducted to evaluate the potential benefits of introducing GaN CL circuits into the integrated power systems, based on the material limit of GaN and state-of-the-art experimental results. It is revealed that the propagation delay of a single-stage CL gate based on the commercial p-GaN gate power HEMT (high-electron-mobility transistor) platform could be as short as sub-nanosecond, which sufficiently satisfies

the requirement of power conversion systems typically with operating frequencies less than 10 MHz. With the currently adopted n-FET-based logic gates (e.g., directly coupled FET logic) replaced by CL gates, the power consumption of peripheral logic circuits could be substantially suppressed by more than 103 times, mainly due to the elimination of the pronounced static power loss. Consequently, the energy efficiency of the entire system could be substantially improved.

**Dependence of Electrical Characteristics on Epitaxial Layer Structure of AlGaN/GaN HEMTs Fabricated on Freestanding GaN Substrates**

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IEEE Transactions on Electron Devices
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This article reports a systematic study on the effects of the epitaxial layer structure on the electrical characteristics of AlGaN/GaN high electron mobility transistors (HEMTs) fabricated on freestanding GaN substrates. First, GaN-on-GaN HEMTs were fabricated comprising channel and buffer layers unintentionally doped with Fe atoms those were diffused from the substrate. Their electrical characteristics were compared with GaN-on-SiC HEMTs. The tradeoff relation between maximum drain current and the breakdown characteristics was improved in GaN-on-GaN devices than in GaN-on-SiC devices. A small current collapse was observed in GaN-on-GaN devices despite a high Fe density in the channel. This suggested an influence of Fe diffusion on the frequency dispersion to be comparatively limited. Second, GaN-on-GaN HEMTs were fabricated using a thin undoped channel layer grown on Fe-doped GaN substrate directly or through an Fe diffusion stopper layer. Without the stopper layer, the buffer leakage was significantly increased by reducing the channel thickness, and a 100-nm-thick channel device showed nonpinch-off characteristics. On the other hand, samples with the stopper layer exhibited no buffer leakage and a complete pinchoff up to 200 V. In addition, a sample with an intentional C doping to the buffer layer showed a relatively large current collapse, suggesting a major contribution of C-doping to the frequency dispersion of GaN-on-GaN HEMTs.

**A 1-42 GHz GaN Distributed Amplifier With Adjustable Gain by Voltage-Controlled Switch**

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IEEE Microwave and Wireless Components Letters
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A 1-42 GHz gain-variable distributed amplifier is presented in the letter using a 0.13-µm gallium nitride (GaN) process. The amplifier can achieve a gain tuning range of about 3 dB over the entire frequency band by voltage-controlled switching. The chip area of the amplifier is about 1.9 x 1.1 mm². The average output power of the amplifier is greater than 27.5 dBm over the entire bandwidth. A wider gain tuning range can be achieved by adding more voltage-controlled switches.

**A Highly Integrated PCB Embedded GaN Full-Bridge Module with Ultra-Low Parasitic Inductance**

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IEEE Transactions on Power Electronics
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To fully take the high-frequency advantage of gallium nitride (GaN) devices, this article presents a face-up integrated power module based on the printed circuit board (PCB) embedding technology to tackle the challenges caused by conventional discrete solutions. The proposed GaN module highly integrates a GaN-bare-dies-based full bridge, driving circuits, and decoupling capacitors, in which the advanced bismaleimide-triazine (BT) material is used as the packaging material and the copper-filled laser microvias are used for low-parasitic-inductance and high-thermal-conductivity interconnection. Careful electro-thermal co-design and optimization of power loop is conducted to make the trade-off between power loop inductance and thermal performance. The proposed full bridge power module achieves the lowest power loop inductance of about 0.305 nH in power modules with the same power level. The

maximum thermal resistances from the embedded GaN bare dies to top and bottom surface are 3.39 /W and 0.42 /W, respectively. Benefitting from the ultra-low power loop parasitic inductances, the switching speed of GaN devices reaches to 57.5 V/ns, while the voltage overshoot is not higher than 5.35% of the DC bus voltage. The superior performance of the proposed integrated GaN module makes it a promising application prospect in high frequency high power density converters.

**Releasable AlGaN/GaN 2D Electron Gas Heterostructure Membranes for Flexible Wide-Bandgap Electronics**

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Advanced Electronic Materials
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The development of transferrable free-standing semiconductor materials and their heterogeneous integration to arbitrary substrates open up new possibilities in improving device performance, exploring nonconventional manufacturing approaches, and offering a pathway to soft, conformal, and flexible electronics. In this work, flexible AlGaN/GaN high-electron mobility transistors (HEMTs) are demonstrated, which are transfer-printed from AlGaN/GaN on insulator to a flexible substrate using a novel releasing strategy based on the fast, facile, and reliable transfer process. Flexible AlGaN/GaN HEMTs possess good electrical performance such as the maximum saturated drain current density and transconductance of 110 mA mm−1 and 42.5 mS mm−1, respectively. Moreover, a significant piezoelectric behavior is observed when the device is under strain, resulting from the piezoelectric-induced polarization at the heterostructure interface. Owing to an additional strain-induced piezoelectric effect by the mechanical bending, the performance of AlGaN/GaN HEMT can be further improved. The results demonstrate that the device has great potential in applications for the next-generation flexible electronics, such as wearable systems, intelligent microinductor systems, and smart systems that can sense or feedback external mechanical stimuli.

**Analysis of semi-insulating carbon-doped GaN layers using deep-level transient spectroscopy**

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Electrically active defects in carbon-doped GaN layers were studied with a metal/carbon-doped GaN (GaN:C)/Si-doped GaN (GaN:Si) MIS structure. The GaN:C layers were grown with three different carbon doping concentrations (NC). A semi-vertical metal/semi-insulator/n-type semiconductor (MIS) device was fabricated to perform deep-level transient spectroscopy (DLTS) measurements. Two electron traps E1 and E2 with energy level at EC – (0.22–0.31) eV and EC – (0.45–0.49) eV were observed. E1 and E2 are associated with a nitrogen vacancy VN-related defect in the strain field of extended defects and a nitrogen antisite defect, respectively. By changing the reverse bias voltage of the DLTS measurement, the location and relative defect concentration of the E1 and E2 traps could be verified. A dominant electron trap E3 with an unusual capture cross section was only observed in devices with an NC = 2 × 1019 cm−3 GaN:C layer. This may charge carriers from a defect band and lead to the charge redistribution in the GaN:C layer when forward biased. A hole trap H1 with energy level at EV + 0.47 eV was found for the pulse bias in the forward ON-state. H1 is suggested to correspond with the CN induced 0/+ donor level. By analyzing the schematic band diagrams across the MIS structure, the carrier transport and defect charging mechanisms underlying the DLTS

transient measurements are illustrated. The identification of the trap states in the carbon-doped GaN with different NC gives further understanding on the carbon doping impact on electric characteristics of GaN power devices made on Si substrates.

**High-performance normally-off recessed tri-gate GaN MIS-FETs in micrometer scale**

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Semiconductor Science and Technology
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In this study, a normally-off AlGaN/GaN metal–insulator–semiconductor field-effect transistor (MIS-FET) based on the combination of tri-gate and recessed MIS gate is fabricated and characterized. The recessed tri-gate MIS-FET is manufactured by micro-level trenches, defining the fin-shaped channel and improving the gate control capability. The recessed surface is cleaned by a diluted buffered oxide etch, HCl solution, and tetramethylammonium hydroxide treatment before a 20 nm Al2O3 deposition by atomic layer deposition. After deposition, post-deposition annealing was carried out. Recessed tri-gate MIS-FET demonstrates a high threshold voltage of 3.1 V, a high drain current of 1121 mA mm−1, and an on/off current ratio of 2 × 108. A smaller on-resistance of 5.4 Ω mm compared with recessed planar MIS-FET of 12.7 Ω mm is achieved. Besides, the devices show a low I–V hysteresis. All experimental results confirm micro-level trenches realize the advantages of the recessed tri-gate structures, which supports a promising technique to pursue the normally-off operation of GaN high electron mobility transistors.

**Effect of Schottky barrier height on quantitative analysis of deep-levels in n-type GaN by deep-level transient spectroscopy**

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Deep-level transient spectroscopy (DLTS) using Schottky barrier diodes (SBDs) is widely used for quantitative analysis of deep levels. This study focuses on the dependence of Schottky barrier height on apparent time constants and concentrations of electron traps in n-type GaN. DLTS using SBDs with various barrier heights was carried out. Experimental data show that large reverse leakage currents due to low barrier heights resulted in underestimation of time constants and concentrations. Theoretical calculations considering the impact of leakage currents reproduced experimental results well. Based on the calculations, we suggest a minimum required barrier height where accurate time constants and concentrations can be evaluated.

**A Novel Nitrogen Ion Implantation Technique for Turning Thin Film "Normally On" AlGaN/GaN Transistor into "Normally Off" Using TCAD Simulation**

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Membranes
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This study presents an innovative, low-cost, mass-manufacturable ion implantation technique for converting thin film normally on AlGaN/GaN devices into normally off ones. Through TCAD (Technology Computer-Aided Design) simulations, we converted a calibrated normally on transistor into a normally off AlGaN/GaN transistor grown on a silicon <111> substrate using a nitrogen ion implantation energy of 300 keV, which shifted the bandgap from below to above the Fermi level. In addition, the threshold voltage (Vth) was adjusted by altering the nitrogen ion implantation dose. The normally off AlGaN/GaN device exhibited a breakdown voltage of 127.4 V at room temperature because of impact ionization, which showed a positive temperature coefficient of 3 × 10−3 K−1. In this study, the normally off AlGaN/GaN device exhibited an average drain current gain of 45.3%, which was confirmed through an analysis of transfer characteristics by changing the gate-to-source ramping. Accordingly, the proposed technique enabled the successful simulation of a 100-µm-wide device that can generate a saturation drain current of 1.4 A/mm at a gate-to-source voltage of 4 V, with a mobility of 1487 cm2V−1s−1. The advantages of the

proposed technique are summarized herein in terms of processing and performance.

**The Second Source Harmonic Optimization in Continuous Class-GF Power Amplifiers**

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IEEE Microwave and Wireless Components Letters
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In this letter, the second source harmonic in continuous-mode class GF (CCGF) is optimized to flatten the power amplifier's (PA) frequency response over a wideband. A new design space is explored by considering the effects of controlling the input nonlinearity of the gate-source capacitance ( Cgs ) on the drain current waveforms under continuous-mode drain voltage waveforms. A wideband CCGF PA is designed and fabricated using a commercial 10-W gallium nitride (GaN) device and low-temperature co-fired ceramic (LTCC) technology. Results of the measurement show a flat frequency response from 3.3 to 4.3 GHz with variations less than ±0.4 dB for 40 dBm output power, and 17 dB large signal gain at 3-dB compression point. A drain efficiency of 66 ± 2% is achieved over the entire bandwidth.

**Fabrication of Superconducting Nb–AlN–NbN Tunnel Junctions Using Electron-Beam Lithography**

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Electronics
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Mixers based on superconductor–insulator–superconductor (SIS) tunnel junctions are the best input devices at frequencies from 0.1 to 1.2 THz. This is explained by both the extremely high nonlinearity of such elements and their extremely low intrinsic noise. Submicron tunnel junctions are necessary to realize the ultimate parameters of SIS receivers, which are used as standard devices on both ground and space radio telescopes around the world. The technology for manufacturing submicron Nb–AlN–NbN tunnel junctions using electron-beam lithography was developed and optimized. This article presents the results on the selection of the exposure dose, development time, and plasma chemical etching parameters to obtain high-quality junctions (the ratio of the resistances below and above the gap Rj/Rn). The use of a negative-resist ma-N 2400 with lower sensitivity and better contrast in comparison with a negative-resist UVN 2300-0.5 improved the reproducibility of the structure fabrication process. Submicron (area from 2.0 to 0.2 μm2) Nb–AlN–NbN tunnel junctions with high current densities and quality parameters Rj/Rn > 15 were fabricated. The spread of parameters of submicron tunnel structures across the substrate and the reproducibility of the cycle-to-cycle process of tunnel structure fabrication were measured.

**High Frequency, High Efficiency, and High Power Density GaN-Based LLC Resonant Converter: State-of-the-Art and Perspectives**

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Appl. Sci.
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Soft switching for both primary and secondary side devices is available by using LLC converters. This resonant converter is an ideal candidate for today's high frequency, high efficiency, and high power density applications like adapters, Uninterrupted Power Supplies (UPS), Solid State Transformers (SST), electric vehicle battery chargers, renewable energy systems, servers, and telecom systems. Using Gallium-Nitride (GaN)-based power switches in this converter merits more and more switching frequency, power density, and efficiency. Therefore, the present paper focused on GaN-based LLC resonant converters. The converter structure, operation regions, design steps, and drive system are described precisely. Then its losses are discussed, and the magnets and inductance characteristics are investigated. After that, various interleaved topologies, as a solution to improve power density and decrease current ripples, have been discussed. Also, some challenges and concerns related to GaN-based LLC converters have been reviewed. Commercially available power transistors based on various technologies, i.e., GaN HEMT, Silicon (Si) MOSFET, and Silicon Carbide (SiC) have been

compared. Finally, the LLC resonant converter has been simulated by taking advantage of LTspice and GaN HEMT merits, as compared with Si MOSFETs.

**Enhancement in Analog/RF and Power Performance of Underlapped Dual-Gate GaN-Based MOSHEMTs with Quaternary InAlGaN Barrier of Varying Widths**

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Journal of Electronic Materials
https://doi.org/10.1007/s11664-021-09324-6

An underlapped dual-gate (U-DG) quaternary In0.05Al0.75Ga0.2N/GaN metal–oxide–semiconductor high-electron-mobility transistor (MOS-HEMT) and a conventional ternary Al0.3Ga0.7N/GaN MOS-HEMT device with the same structure are analyzed and compared by investigating their analog/radiofrequency (RF) and power performance. Quaternary InAlGaN heterostructures, having higher polarization charge density, exhibit almost three times higher two-dimensional electron gas (2DEG) concentration, thus showing 171.8% higher saturation drain current density (Id) compared with ternary AlGaN having an equal barrier width of 18 nm, at the same working voltage of 1 V, thus validating the improved analog performance. The influence of the InAlGaN barrier layer on all the performance parameters is studied by varying its thickness for three different widths (18 nm, 13 nm, and 7 nm). The 10.8% higher fT and 9.1% higher fMAX values of the InAlGaN MOS-HEMT with respect to the AlGaN counterpart prove the former's superiority for use in high-frequency amplifiers. These percentage improvements increase to 18.3% and 54.6%, respectively, for the smaller quaternary barrier width of 7 nm. Large-signal analysis for the 7-nm InAlGaN/GaN MOS-HEMT at 100 GHz indicates a higher gain with 87.5% output power efficiency compared with 42.5% for the 18-nm AlGaN/GaN MOS-HEMT at the same input of 45 dBm, demonstrating that the thinner-barrier quaternary MOS-HEMTs is a better candidate for use in sophisticated high-power devices.

**A GaN Complementary FET Inverter With Excellent Noise Margins Monolithically Integrated With Power Gate-Injection HEMTs**

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IEEE Transactions on Electron Devices
https://doi.org/10.1109/TED.2021.3126267

A GaN complementary field-effect transistor (FET) inverter monolithically integrated with power gate-injection high-electron-mobility transistors (HEMTs) was realized on a Si substrate. The GaN p-channel and n-channel logic devices and power devices were fabricated based on a p-GaN/AlGaN/GaN epi-structure. Through optimization of epi-layer thickness and doping, excellent low-level noise margin (NM L ) of 1.47 V and high-level noise margin (NM H ) of 0.98 V were achieved at a supply voltage VDD of 3 V at room temperature. A maximum current density ( ID,max ) of 0.36 mA/mm/220 mA/mm at VDS of -3 V/3 V and a threshold voltage VTH of -2.0 V/+2.3 V were achieved in the p-channel and n-channel FETs, respectively. A propagation delay of an inverter stage τpd in a ring oscillator was measured to be 1.67 µs. The power gate-injection HEMT has an on-resistance Ron of 18.7 Ω ·mm and a breakdown voltage (BV) of 900 V. These results show the great potential of the developed GaN complementary FET technology in the applications of GaN power modules.

**A Generic Theory for Design of Efficient Three-Stage Doherty Power Amplifiers**

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IEEE Transactions on Microwave Theory and Techniques
https://doi.org/10.1109/TMTT.2021.3126885

An analytical load--pull-based design methodology for three-stage Doherty power amplifiers (PAs) is presented and demonstrated. A compact output combiner network, together with the input phase delays, is derived directly from transistor load--pull data and the design requirements. The technique

opens up a new design space for three-stage Doherty PAs with reconfigurable high-efficiency power back-off levels. The method is designed to enable high transistor power utilization by maintaining full voltage and current swings of the main and auxiliary amplifier cells. Therefore, a wide efficiency enhancement range can be achieved also with symmetrical devices. As a proof of concept, a 2.14-GHz 30-W three-stage Doherty PA with identical gallium nitride (GaN) HEMT active devices is designed, fabricated, and characterized. The prototype PA is able to linearly reproduce 20-MHz long-term evolution signals with 8.5- and 11.5-dB peak-to-average power-ratio (PAPR), providing average efficiencies of 56.6% and 46.8% at an average output power level of 36.8 and 33.8 dBm, respectively. Moreover, an average efficiency as high as 54.5% and an average output power of 36.3 dBm have been measured at an adjacent power leakage ratio of -45.7 dBc for a 100-MHz signal with 8.5 dB of PAPR, after applying digital predistortion linearization.

**Influence of GaN/ZrO2 interfacial layer defects on 8-nm GaN-SOI-FinFET for reliable RFIC design**

Applied Science and Humanity Department ADGITM, New Delhi, India
ECE Department, Jaypee Institute of Information Technology, Noida, India

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This work presents, the reliability of GaN/ZrO2 (Gallium Nitride/Zirconium dioxide) interfacial layer defects on 8-nm Gallium Nitride (GaN) Silicon-on-Insulator (SOI) FinFET (GaN-SOI-FinFET). Positive, negative, and neutral interface trap charges are considered in all the results and simultaneously compared with SOI-FinFET with an 8-nm gate length for the evaluation of device reliability. It is found that the proposed device is more immune to interfacial trap defects and reflected in terms of drain current (Id), device efficiency (gm/Id), transconductance (gm), subthreshold slope (SS), electric field, surface potential, and threshold voltage at an ultra-low voltage (VDS = 0.1 V). Further, the performance degradation of GaN-SOI-FinFET is calculated by various linearity figures of merits (FOMs) such as higher-order transconductance coefficients (gm2 and gm3), voltage, and current intercept points (VIP2, VIP3, and IIP3). Moreover, device reliability is also performed by evaluating intermodulation and harmonic distortions (IMD3, HD2, and HD3). The proposed device shows better reliability in the presence of interfacial traps and paves the way for high-performance low power, high linearity, and lesser harmonic distortions performance for RFIC design.

# PRESS RELEASE

*Technical and economic information selected by Knowmade*

## ELECTRONICS

### The RF GaN Device Market: A Roller-Coaster Ride

*Microwave Journal*

In as little as five years, analysts at Yole Développement (Yole) predict the already mighty RF GaN device market will mushroom from some $900 million to $2.4 billion (see Figure 1). Three decades of investment from defense organizations around the world has placed this high power density, high efficiency material firmly on the compound semiconductor map, with GaN devices routinely used in military radar and electronic warfare. As defense agencies look to commercial applications to pay back their billion-dollar investments, 5G/LTE telecoms applications are already providing a return on the investment. At least for now.

**BASE STATION ADOPTION**

China's Huawei started using GaN RF devices in its 4G LTE remote radio heads (RRH) in 2014. The telecom behemoth had decided to trade low-cost Si LDMOS for GaN's high power density and wide bandwidth and other OEMs followed. Today, the power of GaN is being harnessed by the 5G infrastructure market. Tried-and-tested GaN on SiC technology is widely used in 5G sub-6 GHz RRH base stations and is expected to maintain its stronghold for some time.

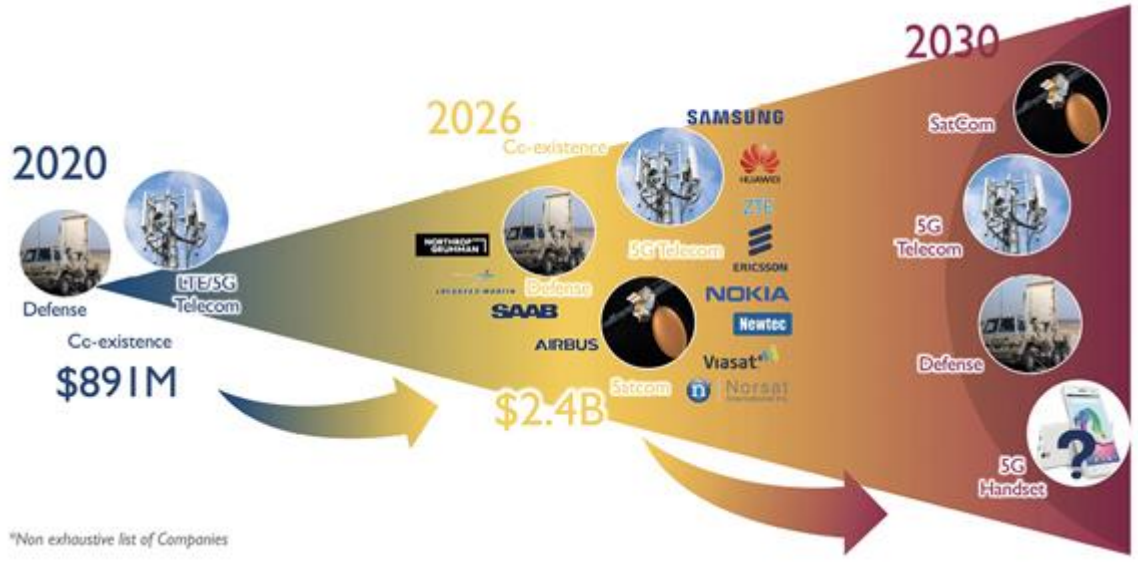



**Figure 1 GaN RF device market evolution from 2020 to 2030. Source: GaN RF Market: Applications, Players, Technology, and Substrates 2021 report, Yole Développement, 2021.**

In part due to the monumental 5G network sharing deal between operators in China, the technology is also being adopted in 5G sub-6 GHz active antenna systems (AASs). To deploy more efficient antenna types, the Chinese operators ditched cheaper LDMOS transistors for higher performing GaN on SiC devices in these sub-6 GHz AAS deployments, a decision that kick-started GaN adoption elsewhere. Today, other OEMs have realized the value

that GaN can bring to 5G wireless infrastructure and are moving to six-inch GaN on SiC wafer production in a bid to reduce the technology's high price tag.

In 2020, NXP, the Netherlands-based semiconductor manufacturer and key LDMOS player, opened a six-inch GaN on SiC facility in Arizona, signaling strong customer interest in GaN RF devices for a cost-effective price. This year, longtime GaN on SiC partners, Sumitomo Electric Device Innovations (SEDI) of Japan and U.S. semiconductor manufacturer, II-VI, opened a six-inch fab in New Jersey to churn out power transistors for 5G base stations at a more cost-competitive price. As NXP and SEDI/II-VI ramp up production, U.S. semiconductor makers Wolfspeed, Qorvo and other fabs are acting to transition to six-inch GaN on SiC production—clear signs the technology is set to capture market share from LDMOS (see Figure 2).

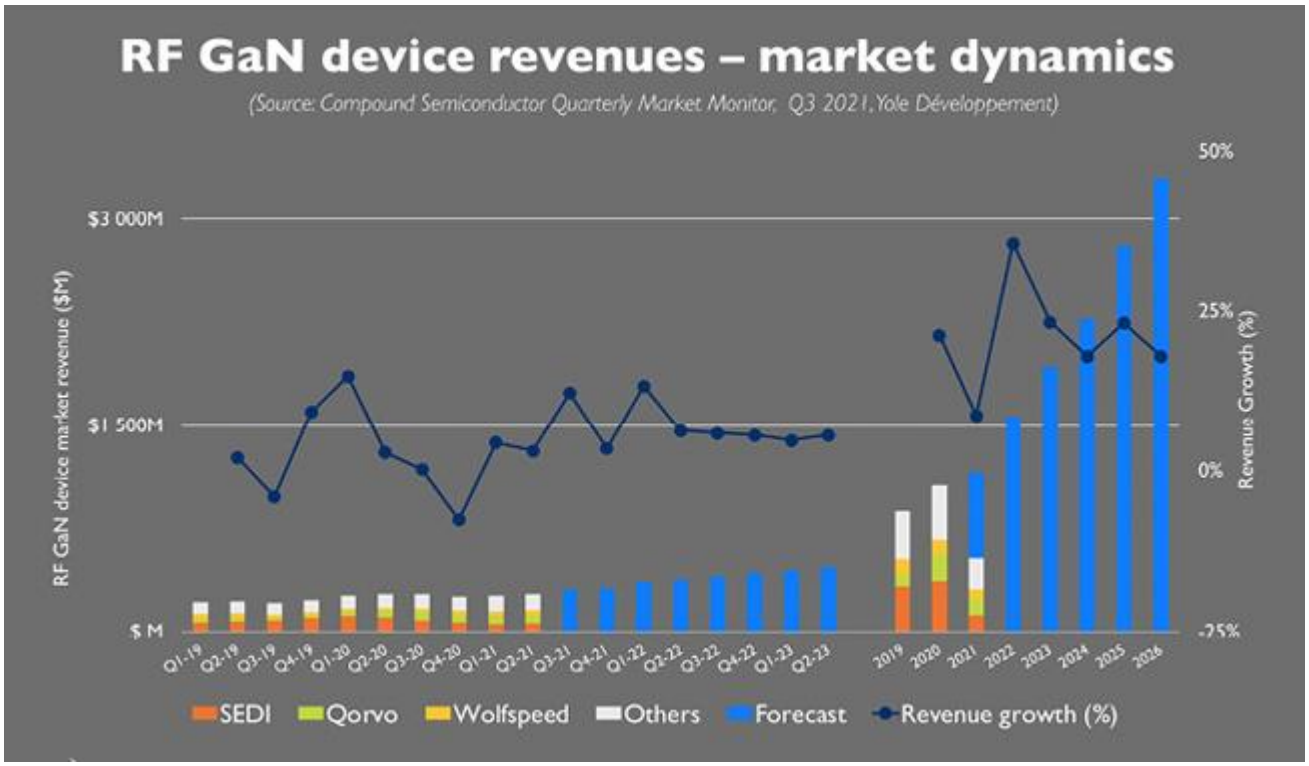



**Figure 2 Historic GaN RF device revenue and forecast growth. Source: Compound Semiconductor Quarterly Market monitor, Q3 2021, Yole Développement.**

**INTERNATIONAL TENSIONS**

But what about the ongoing trade conflict between the U.S. and China? How is this affecting the GaN RF device market? Like the U.S., the Chinese government is determined to make the most of its GaN investments and grow commercial 5G applications. While U.S. sanctions have stymied China's progress, the restrictions have also pushed the government to encourage development of a home-grown, internal GaN ecosystem.

At the beginning of the tensions, Huawei and ZTE stockpiled devices so they could continue to build base stations and other network infrastructure. Since, many organizations up and down the supply chain have been funneling investments into GaN. Examples include wafer manufacturers and foundries SICC and HiWafer, integrated device manufacturers (IDM) CETC and Dynax and Huawei's own design house, HiSilicon (see Figure 3). Importantly for China, industry feedback indicates that tier one suppliers are now producing quality systems with Chinese components. Given this, the rest of the world is monitoring China's progress very closely.


**Figure 3 Global GaN RF device suppliers. Source: GaN RF Market: Applications, Players, Technology, and Substrates 2021 report, Yole Développement, 2021.**

**GaN HANDSET PAs?**

There's more to come for GaN. In the longer term, 5G handsets could also harbor many opportunities for the GaN RF device market.

Today, GaAs is the leading power amplifier (PA) technology in smartphones, such as the iPhone 13, and will retain its dominance particularly in sub-6 GHz handsets. But industry trends are changing. The move to large bandwidth, higher power density and efficiency and greater integration, to save space in the handset's RF front-end, mean GaN is beginning to appeal to OEMs, especially for the mmWave bands. Indeed, at least one major semiconductor player is qualifying 5G handset PAs designed with GaN for several OEMs. In the coming years, the industry may see the first adoption of a GaN PA in luxury phones that use the increasingly popular n77 to n79 C-Band, as an alternative to mmWave and the traditional sub-6 GHz cellular bands.

What might happen next? If more OEMs around the world demand GaN PAs, more foundries will fabricate the technology and the momentum will build. If GaN PAs are widely adopted for mmWave front-ends in handsets, the technology's success is likely sealed.

**SiC OR Si?**

Along the way, the rivalry between GaN on SiC and GaN on Si wafers will play out. With cheap, large diameter Si substrates, GaN on Si presents a bright opportunity for OEMS to develop relatively cheap GaN-based devices and systems built on the foundation of an established, scalable wafer supply. Keen to explore this opportunity, MACOM and STMicroelectronics joined forces to develop a GaN on Si platform in 2018. Infineon is also developing GaN on Si for RF applications. Earlier this year, U.S. defense giant Raytheon and Global Foundries announced a collaboration to transfer Raytheon's GaN on CMOS process to Global Foundries for commercialization.

While these are significant industry developments and GaN on Si may deliver the cheaper PAs that high volume, cost-sensitive 5G handsets will demand, the technology does not benefit from the billion-dollar defense investments awarded to GaN on SiC. Consequently, the GaN on Si supply chain is not yet developed, and technology development spans from epitaxy to modules. Still, the pros and cons of GaN on Si and GaN on SiC are

becoming clearer for the industry; for now, the technology choice depends on the OEM's strategy and view of the trade-offs.

**TO THE SKIES**

Satellite communication (satcom) offers another promising avenue for GaN. While destined to be a niche, low volume market, satcom has been attracting many industry players keen to apply GaN to applications such as very small aperture terminal (VSAT) satellite broadband. Here, GaN PAs from Qorvo, Wolfspeed and others have been replacing traveling wave tube amplifiers, improving reliability and lowering the system costs of transmit-receive ground stations. Myriad large-scale projects have been springing up across the U.S. and Europe, driving the development of solid-state GaN PAs for VSAT and other applications.

In the future, GaN's radiation hardness and its high power efficiency and power density will see the technology increasingly used in satellites. Key industry players including Canada's Norsat International, the European Space Agency and GaN device manufacturers UMS, Qorvo and OMMIC are all investigating GaN for satellites.

**STALWART DEFENSE**

Space aside, the reliable defense market will be a strong supporter of GaN for many years. Billion-dollar projects from U.S. government agencies and prime contractors such as Northrop Grumman, Lockheed and Raytheon, as well as defense semiconductor suppliers Wolfspeed and Qorvo, will continue to fund technology development and insertion in programs. These efforts will require a secure and robust supply chain that will benefit the commercial telecom and other markets to follow. Similar scenarios are playing out in Asia and Europe, where organizations such as Thales, SAAB and BAE Systems are all working on GaN technologies that will also feed the commercial telecoms markets.

**MANY QUESTIONS**

While the future of the GaN RF device market is bright, the level of success hinges on yet-to-be determined dynamics. For GaN on SiC, the smooth transition to six-inch wafers will be important for its near-term success. As NXP, SEDI/II-VI and other players make the transition, will the production of quality wafers proceed as planned? If not, will this dampen GaN on SiC's adoption by 5G? Meanwhile will handset manufacturers opt for GaN on Si PAs in their 5G devices? What happens if these industry players abandon both GaN options and retain GaAs or adopt alternative technologies, such as SOI, which offer sufficient performance? What will be the impact of the deepening tensions between the U.S. and China?

Only time will reveal how the RF GaN roller-coaster ride ends. Throughout the ride, Yole Développement will scrutinize market developments, analyze the strategic questions and share our view of the likely outcomes.

## GaN Systems raises $150m in growth capital funding

*SemiconductorToday*

GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of gallium nitride-based power switching semiconductors for power conversion and control applications) has announced a US$150m growth capital funding round to accelerate innovation and adoption of GaN technology across its automotive, consumer, industrial and enterprise markets.

The fundraising round was led by Fidelity Investments (celebrating 75 years since its founding, with US$4.2 trillion in assets under administration), joined by new strategic investor Vitesco Technologies (an international developer and manufacturer of powertrain technologies for sustainable mobility) plus existing investors including BMW i Ventures.

GaN Systems says it will use the new funding to fuel the rapid market penetration of GaN as global power electronics companies shift from legacy silicon devices to small, low-cost, efficient power systems.

Vitesco has announced a broad strategic partnership with GaN Systems to enable GaN solutions across the electric vehicle (EV) platform. This follows GaN Systems' announcement in September of a capacity agreement with BMW.

"By combining our automotive know-how with our partner's GaN expertise, we will be able to reap the benefits of comprehensive wide-bandgap technology in the car," says Thomas Stierle, member of the executive board and head of Vitesco Technologies' Electrification Technology business unit.

"The demand for higher-performing, more efficient power electronics is growing exponentially, and traditional silicon solutions cannot keep up," says GaN Systems' CEO Jim Witham. "Gallium nitride takes the baton from legacy silicon to enable smaller platforms to run cooler and use fewer materials," he adds, claiming that GaN Systems is the only GaN power transistor company currently shipping to automotive, consumer, industrial and data-center customers. "Our relationships with industry leaders and our $8bn pipeline tell us that the GaN inflection is here, and the time is now to accelerate investment in the business."

With more than 200 billion device field hours, global companies (including industry leaders like Dell, Samsung, HARMAN, Siemens, Signify and Philips) rely on GaN Systems' transistors to reduce levels of CO2 emissions and increase the utility and energy efficiency of their power systems. GaN Systems says that, with just a small change in the electronics design, its transistors enable design engineers to significantly decrease the size, weight and power lost by 4x while reducing overall system costs.

## Navitas and Anker sign strategic partnership for next-gen mobile fast chargers

*SemiconductorToday*

Gallium nitride (GaN) power integrated circuit firm Navitas Semiconductor of El Segundo, CA, USA and Dublin, Ireland and consumer electronics firm Anker Innovations of Changsha, Hunan, China have signed a new strategic partnership.

Founded in 2014, Navitas introduced what it claimed to be the first commercial GaN power integrated circuits. Its proprietary GaNFast power ICs monolithically integrate GaN power field-effect transistors (FETs) and GaN drive plus control and protection circuits in a single SMT package. Since GaN is reckoned to run up to 20x faster than silicon, GaNFast power ICs are said to deliver up to 3x faster charging or 3x more power in half the size and weight, and with up to 40% energy savings compared with silicon chips. Integrated in over 130 mobile chargers, over 30 million GaNFast power ICs have been shipped with zero reported field failures.

Anker and Navitas have an established relationship, starting in 2017 when Anker was one of the first companies to create fast-charger prototypes and then qualify the new GaN technology. The 2019 Anker PowerCore Fusion PD combination charger and portable power bank used Navitas' GaNFast power ICs to reach higher levels of efficiency and power density.

"Having engineering teams from Anker and Navitas sitting side by side on a daily basis will greatly improve the efficiency of the product development process, translating into faster and better chargers for our customers," believes Anker Innovations' CEO Steven Yang.

The new agreement dedicates engineering teams from both Navitas and Anker to be co-located at Anker offices to develop and launch GaNFast chargers to accelerate time-to-market. The initial focus will be on next-generation mobile chargers but will expand into the high-growth energy-storage markets. The deal also provides a longer

planning horizon for co-operative marketing across all media platforms and in-person events, such as January's Consumer Electronics Show (CES) in Las Vegas.

"As both a long-term customer and investor in Navitas, Anker has demonstrated a passion for innovation and vision for the future of charging," says Navitas' co-founder & CEO Gene Sheridan. "Mobile charging is a $2bn target market for GaN power ICs, and working with Anker on energy storage is aligned with our renewable/solar energy expansion strategy."

The first two fast chargers released under the new partnership are the 30W USB-C and 65W 2C+A chargers in Anker's collaboration with the 'League of Legends' multi-player online battle arena video game, played on phones, tablets and laptops. With fast action and intensive, detailed graphics, the game has a high draw on battery power, and fast charging – with portability – is crucial.

At only 28mm x 29mm x 32mm, the 30W USB-C 'Jinx' is a similar size to the original 5W so-called 'sugar-cube' phone charger and 70% smaller than the standard silicon-based 30W.

The 65W 2C1A 'Yasuo' charger has 2x USB-C and 1x USB-A port to simultaneously charge three devices (such as a phone, headphones and a laptop) with enough power for high-performance gaming laptops.

## Transphorm turns profit as quarterly product revenue grows 30% year-on-year

*SemiconductorToday*

For fiscal second-quarter 2022 (to end-September 2021), Transphorm Inc of Goleta, near Santa Barbara, CA, USA — which designs and manufactures JEDEC- and AEC-Q101-qualified gallium nitride (GaN) field-effect transistors (FETs) for high-voltage power conversion applications — has reported revenue of $11.3m, up from $3.2m last quarter and $1.9m a year ago.

Growth was driven by a combination of licensing revenue related to ongoing development work with a manufacturing partner plus record product sales from ramping shipments of GaN devices for a broad range of power conversion applications, including fast chargers and adapters, gaming, data center and crypto-mining. Product revenue rose sequentially for a seventh consecutive quarter and grew 30% year-on-year to a quarterly record.

"We continued to ramp device shipments in support of expanded design-ins going into production," says president & co-founder Primit Parikh. "Product revenue in the first half of fiscal 2022 has exceeded the revenue contribution from products for the full fiscal year of 2021, driven by growing traction with our GaN devices in fast chargers and adaptors as well as high-power gaming, server and crypto-mining applications. Additionally, we continued to lay the foundation for significant future growth highlighted by the recently achieved automotive qualification of our SuperGaN Gen IV FET device. With strong customer momentum and strong blue-chip strategic partnerships, we expect continued product revenue growth in the coming quarters."

Highlights during the quarter included continued momentum on adaptor and fast-charger market penetration, including partnerships with leading controller and integrated driver makers. Also, Transphorm achieved automotive qualification of its SuperGaN Gen IV multi-kilowatt-class power FET device. The firm was also awarded a $1.4m GaN development contract by the US Defense Advanced Research Projects Agency (DARPA).

On a non-GAAP basis, operating expenses were $4.45m, up from $3.5m a year ago but cut slightly from $4.59m last quarter.

Net income was $3.6m ($0.09 per share), compared with net losses of $5.3m ($0.13 per diluted share) last quarter and $5.3m ($0.15 per diluted share) a year ago. Cash and equivalents remained $2.5m at the end of the September quarter.

During the quarter, Transphorm completed the transaction for its AFSW wafer fab in Aizu Wakamatsu, Japan to be acquired by GaNovation, its joint venture formed recently with its new Palo Alto-based strategic financial partner JCP Capital. The AFSW fab was previously a JV with Fujitsu Semiconductor Ltd (FSL).

After the end of the quarter, in October, strategic partner Yaskawa Electric Corp of Kitakyushu, Japan (a manufacturer of low- and medium-voltage variable-frequency drives, servo motors, machine controllers and industrial robots) converted 100% of its $15.6m Transphorm convertible notes into common stock at $5 per share.

In subsequent private placement transactions completed in early November, the firm closed $33m of equity financing at $5 per share, comprising follow-on investments of $5m by KKR and $10m by Sino-American Silicon Products (SAS) as well as participation by institutional investors. This followed the closing of a $5m initial private placement by SAS in August.

“Through a series of successful transactions over the past few months, we have significantly strengthened our balance sheet and cash position while also realizing a $50m increase in shareholder equity since June,” notes chief financial officer Cameron McAulay. “In part as a result of our stronger financial position, we believe the company is now positioned to meet the qualification requirements for uplisting Transphorm’s common stock to the NASDAQ, an ambition we will continue to pursue aggressively in the coming months.”

## GaN power IC firm Navitas doubles sales volume year-on-year in Q3

*SemiconductorToday*

For third-quarter 2021, gallium nitride (GaN) power integrated circuit firm Navitas Semiconductor of El Segundo, CA, USA and Dublin, Ireland has reported revenue of $5.6m, up 61% on $3.5m a year ago, reflecting the expansion of its product and end-customer base. Total sales volume rose by 103%, from 3 million to 6.1 million GaN ICs shipped. In total, over 30 million have now been shipped, with zero reported field failures.

Founded in 2013, Navitas introduced what it claimed to be the first commercial GaN power integrated circuits. Its proprietary GaNFast power ICs monolithically integrate GaN power field-effect transistors (FETs) and GaN drive plus control and protection circuits in a single SMT package. GaNFast power ICs have been integrated in over 135 mobile chargers, including fast chargers from Xiaomi, Dell, Lenovo, LG, Amazon, OPPO, Anker, Belkin and dozens of other major OEMs. An additional 150 GaN chargers are in development across all mobile customers worldwide.

On a non-GAAP basis, gross margin has grown from 37.6% a year ago to 46.2% in Q3/2021. However, net loss was $6.6m ($0.39 per share), up from $3.8m ($0.26 per share) a year ago.

After using cash to fund operations, meet working capital requirements, for capital expenditures and strategic investments, total cash and cash-equivalents fell by $27.8m during the quarter to $11.1m. Total debt outstanding rose by $1.7m to $7.7m.

“We expect to continue to incur net operating losses and negative cash flows from operations and we expect our R&D expenses, general and administrative expenses and capital expenditures will continue to increase,” says the

firm. “We expect our expenses and capital requirements to increase in connection with our ongoing initiatives to expand our operations, product offerings and end-customer base.”

After the quarter, on 19 October, Navitas completed its de-SPAC business combination with Live Oak Acquisition Corp II - a publicly traded special-purpose acquisition company (SPAC). Navitas’ common shares and warrants begin trading on 20 October on the Nasdaq Global Market (under the ticker symbols ‘NVTS’ and ‘NVTSW’), when CEO & co-founder Gene Sheridan rang the opening bell at the Nasdaq MarketSite. Gross proceeds raised in the business combination transaction were $325m. With about 117.7 million shares outstanding, Navitas has about $260m in cash and cash equivalents to support growth.

Navitas expects that the additional capital will accelerate product development and expansion from its industry-leading position in GaN mobile fast chargers into consumer, enterprise, solar and electric vehicle (EV) markets, as well as providing funds for non-organic growth. “We expect our historical focus on near-term working capital and liquidity to shift to more strategic and forward-looking capital optimization plans,” says Navitas. “The influx of capital from the business combination is sufficient to finance our operations, working capital requirements and capital expenditures for the foreseeable future.” The firm’s personnel strength has grown by about 50%, to about 150 staff worldwide. Also, new offices and teams in China and Europe are addressing expansion markets.

For fourth-quarter 2021, revenue is expected to grow about 60% year-on-year to $7.4m (plus or minus 5%). Gross margin should be about 44%.

“Worldwide GaN penetration in the $2bn fast-charger market is estimated at only 2-3% so far, so we expect a fast revenue ramp ahead in mobile plus the higher-power expansion markets of data center, solar and EV,” says co-founder & CEO Gene Sheridan. “Couple that with next-gen technology introductions, growing team strength and more than 130 patents issued or pending, and we have an extraordinary opportunity in front us is to become the next-generation power semiconductor leader.”

## TI Wins Four Awards at EE Awards Asia and Accelerates the Momentum of GaN Technology

*eetimes*

Texas Instruments Inc. (TI), a leading designer and manufacturer of analog and embedded processing chips targeted at the industrial, automotive, personal electronics, communications equipment, and enterprise systems markets, has won four awards—EV Power Semiconductor Supplier and Energy-Saving Power Semiconductor Provider in both Taiwan and Asia divisions of this year’s EE Awards Asia —for its LMG3525R030-Q1 gallium nitride (GaN) device.

**Addressing Industry Challenges**

The power electronics industry is evolving rapidly. Along with this evolution are key trends driving change in power management: power density, low electromagnetic interference (EMI), low quiescent current (IQ), isolation, and low-noise and high-precision.

To help customers address these issues, TI has strategically invested in gallium nitride (GaN) technology, a new power semiconductor that leverages superior device switching properties to reduce power loss, increase efficiency, and improve the power density of AC/DC and DC/DC power supplies. These are universal improvements for any power supply ranging from consumer adapters to server and telecom PSUs, to automotive onboard charging systems for electric vehicles (EVs).

TI recently introduced the LMG3525R030-Q1, the industry’s first automotive GaN FET with integrated driver, protection, and active power management. These advancements help customers get the most out of their system

and make it as easy as possible to use by delivering twice the power density and the highest efficiency in automotive onboard chargers and industrial power supplies.

TI also has released a major advancement in EV battery management systems (BMS)—a high-performance solution for wireless BMS, featuring a new automotive battery monitor and balancer to help engineers achieve battery safety goals and maximize distance per charge in wired and wireless BMS.

**Unique Technology Solutions**
TI won the awards in recognition of its GaN technology solutions' focus on maximizing efficiency, driving high levels of robustness and reliability, and maximizing capacity while minimizing cost.

Featuring increased integration and switching frequency, TI's GaN devices also have >40 million device hours of system reliability testing to address failure mechanisms and maximize lifetime.

TI invested in internal manufacturing capacity to best control supply, quality, and cost. The company is also continuing to invest in highly integrated GaN devices that further the ability to improve efficiency and power density, targeted at a broad range of end user applications. This includes power levels ranging from tens of watts for low-power applications to 22kW for EVs, to help support engineers who want to consider GaN to build power systems that are smaller, lighter, and more efficient.

Most recently, TI announced its GaN technology and C2000 real-time microcontrollers (MCUs) are being combined with Delta Electronics' high-efficiency power electronics expertise in the design of an enterprise server power-supply unit (PSU) featuring an 80% improvement in power density with 1% better efficiency—up to 99.2%—for data center applications, compared to enterprise server power supplies using a traditional architecture.

## SEI launches high-power GaN devices for X-band radar

*SemiconductorToday*

Japan's Sumitomo Electric Industries Ltd and its group company Sumitomo Electric Device Innovations USA Inc of San Jose, CA, USA, a provider of radio frequency (RF), wireless and optical communications solutions, has introduced its line of high-power gallium nitride (GaN) products for X-band radar applications.

Next-generation X-band radars face significant size, weight, power and cost (SWAP-C) challenges, notes the firm. Among the challenges are the RF power amplifier designs used in these radar systems.

Since GaN provides very high power and bandwidth that improves performance and is a proven and reliable technology for radar applications, Sumitomo Electric has hence developed a line of high-power GaN X-band devices that enable RF solid-state power amplifiers to meet the SWAP-C challenges of these new radars while also improving reliability versus tube amplifiers.

The new product line comprises five new X-band GaN devices (with efficiencies of 37-38%):

- the 8.5-9.5GHz SGC8595-300B-R (with output power of 270W below 9.17GHz and 235W above 9.17GHz, and gain of 8.3dB below 9.17GHz and 7.7dB above 9.17GHz) in a hermetic metal/ceramic flange mount package;
- the 9.0-10.0GHz SGC0910-300B-R (with output power of 270W below 9.6GHz and 235W above 9.6GHz, and gain of 8.3dB below 9.6GHz and 7.7dB above 9.6GHz) in a hermetic metal/ceramic flange mount package;

- the 9.8-10.5GHz SGC1011-300B-R (with output power of 250W below 10.3GHz and 235W above 10.3GHz, and gain of 8.0dB below 10.3GHz and 7.4dB above 10.3GHz) in a hermetic metal/ceramic flange mount package;
- the 9.2-9.5GHz SGM6906VU (with output power of 43.7W, and gain of 21.4dB) in a hermetically sealed SMT package;
- the 8.5-10.1GHz SGM6901VU (with output power of 24W below 10.1GHz and 21.4W above 10.1GHz, and gain of 23.3dB) in a hermetically sealed SMT package.

## Navitas concludes $30m forward-purchase transaction

*SemiconductorToday*

Gallium nitride (GaN) power integrated circuit firm Navitas Semiconductor of El Segundo, CA, USA and Dublin, Ireland has concluded a prepaid, forward-purchase transaction, resulting in the removal of restrictions affecting $30m of cash on the company's balance sheet and 3,000,000 outstanding shares of Navitas common stock.

As previously disclosed, on 6 October, Navitas (then known as Live Oak Acquisition Corp II (LOKB)) entered into a prepaid forward-purchase agreement with an affiliate of privately held, SEC-registered alternative investment advisory firm Atalaya Capital Management LP. Per the agreement, Atalaya had the right to purchase up to 3,000,000 LOKB shares from shareholders who had redeemed shares, or indicated an interest in redeeming shares, prior to the closing of LOKB's business combination transaction with Navitas. The agreement provided for Atalaya to sell the shares it purchased to Navitas within two years, at the redemption price in effect prior to closing. Atalaya also had the right to sell the shares to others during the two-year term, concluding the forward purchase obligations with Navitas in an amount corresponding to the number of shares sold.

On 18 November, Atalaya notified Navitas that it had sold all 3,000,000 shares covered by the agreement in open-market transactions. As a result, a total of about $30m has been remitted to Navitas, free of any restrictions.

## Navitas drives Xiaomi's new ultrafast-charging Note 11 Pro+ smartphone

*SemiconductorToday*

Gallium nitride (GaN) power integrated circuit firm Navitas Semiconductor of El Segundo, CA, USA and Dublin, Ireland says that its GaNFast power ICs with GaNSense technology are being used to ultrafast-charge Xiaomi's new Note 11 Pro+ flagship smartphone. The worldwide launch of Navitas' GaNSense technology was held recently, on 14 November, at the China Power Supply Society's (CPSS) Conference in Shanghai.

Xiaomi's power management and graphene Li-ion battery technology allows ultrafast-charging, with a powerful 120W capability to charge the 4500mAhr battery from 0-100% in only 17 minutes. GaNSense technology delivers what is claimed to be the smallest, most efficient, most portable 120W charger to enable this performance.

Founded in 2014, Navitas introduced what it claimed to be the first commercial GaN power integrated circuits. Its proprietary GaNFast power ICs monolithically integrate GaN power field-effect transistors (FETs) and GaN drive plus control and protection circuits in a single SMT package. Since GaN is reckoned to run up to 20x faster than silicon, GaNFast power ICs are said to deliver up to 3x faster charging or 3x more power in half the size and weight, and with up to 40% energy savings compared with silicon chips.

New GaNSense technology delivers another 10% energy saving plus autonomous system-parameter sensing and high-speed protection features for maximum reliability. This enables the GaN power IC to detect and protect in less than 30ns.

The Xiaomi 120W measures only 55mm x 55mm x 28.4mm (86cc), weighs just 138g and achieves what is claimed to be an industry-leading power density of 1.4W/cc. Two NV6134 GaNFast power ICs with GaNSense technology are used in the 120W charger: one in the front-end boost power-factor correction (PFC) section, and the other in the downstream high-frequency quasi-resonant (HFQR) DC-DC stage, utilizing a high-speed, low-profile planar transformer.

"These ultra-fast chargers require double the GaN content per charger, which of course doubles the revenue opportunity for Navitas," notes Charles Zha, VP & general manager of Navitas China. "By our estimates, we project this ultra-fast charger category will represent up to half of the GaN potential in mobile chargers over the next few years."

## HG makes strategic investment in GaN Systems

*SemiconductorToday*

宏光照明控股有限公司
Hongguang Lighting Holdings Company Limited

Hong Kong-based HG Semiconductor Ltd says that its subsidiary FastSemi Holding Ltd has invested in GaN Systems Inc of Ottawa, Ontario, Canada (a fabless developer of gallium nitride-based power switching semiconductors for power conversion and control applications), and agreed to invest by subscribing for series F-2 convertible preference shares in GaN Systems as a strategic investor.

GaN Systems' current growth capital funding round (to raise $150m) is aimed at accelerating innovation and adoption of GaN technology across its automotive, consumer, industrial and enterprise markets. HG's strategic investment is also joined by existing investor BMW i Ventures, along with Fidelity, Vitesco Technologies and others. Following this investment, HG will be able to nominate an independent board observer from Canada to be on the board of GaN Systems.

HG's activities encompass the design, development, manufacturing, subcontracting services and sale of LED beads, LED lighting products, fast-charging products and a new generation of GaN-based products. Leveraging its industrial expertise in LED manufacturing, HG has been accelerating its R&D and expanding its business to various kinds of semiconductors including GaN-based products, through the integration of design, manufacturing and sale of chips. In particular, the firm strategically holds a 21.86% stake in VisIC Technologies Ltd of Ness Ziona, Israel (a fabless supplier of GaN-based power conversion devices), leveraging their respective strengths to jointly develop GaN-based chips and products.

To further deepen its presence in the GaN sector, HG says it aims to capitalize on the extensive experience, resources and expertise of GaN Systems, developing its GaN business to become a leading player in the sector.

"The group expects this strategic investment will lay a solid foundation for its future development and prospects in its GaN semiconductor business. Upon completion of the investment, we expect both the group and GaN Systems may have the opportunity to pool our respective advantages to each other, creating synergistic effects," says HG's chairman & executive director Zhao Yi Wen. "In particular, GaN Systems can provide dedicated technical support (from Ottawa, California and Taiwan) to the group for process definition and qualification of GaN device manufacturing to achieve best-in-class yield targets and targeted qualifications. Such technical support may include elements of the developed process that are proprietary to GaN Systems only, and alignment on intellectual property strategy for resulting process know how," he adds. "The group will also be able to obtain technical support for reference design in Internet data center (IDC) power systems, electric vehicle (EV) and solar inverter applications from GaN Systems on most-favored-nation terms. Furthermore, GaN Systems also proposes

to qualify the subsidiary of the group as a foundry partner to GaN Systems and enter into a licence agreement whereby the group may use certain GaN technology of GaN Systems for manufacturing its semiconductors components."

## HG completes share placement to boost R&D

*SemiconductorToday*

Hong Kong-based HG Semiconductor Ltd has completed a placing of 14,346,000 shares (about 2.55% of its issued share capital) to not less than six placees at a price of HK$6.20 per share.

After deduction of the professional fee and other related expenses, net proceeds amounted to about HK$86.2m. The group intends to apply about HK$64.3m for strengthening its R&D capabilities in LEDs, mini-LEDs, fast charging products, and gallium nitride (GaN) devices and related semiconductor products. Net proceeds will also be used for the set-up of R&D centers, recruitment of R&D professionals, as well as the procurement of equipment and materials with the aim of developing and acquiring patents and technology. Meanwhile, the remaining HK$21.9m will be used to provide general working capital and improve the financial position of the group.

HG says that, leveraging its industrial expertise in semiconductor manufacturing, it has been expanding its business to various kinds of semiconductors including GaN-related products. In view of its long-term strategy to further develop its business in the GaN sector, HG says that it is setting up a new factory in the Xuzhou Economic and Technological Development Zone, comprising 7000m2 of cleanroom space and 850m2 of office area. A production line for manufacturing electronic products including GaN-related products will be installed in the Xuzhou Factory, the facilities of which will be further upgraded to full automation in the future.

The firm's management has added core members to its Technology and Manufacturing team. Among them, Xuzhou Factory general manager Dr Chen Zhen has over 20 years of experience in R&D, production and management in GaN-based optoelectronics devices, including full-band solid-state light-emitting devices as well as proprietary technology for 8-inch silicon-based GaN epitaxial growth. Chen has applied for more than 30 domestic and foreign patents, and served as a reviewer for more than 10 international journals.

Moreover, Xuzhou Factory operation deputy general manager Lu Juilin has over 30 years of experience in semiconductor industry and foundry technology and management, with experience in managing 8-inch to 12-inch fab management and 55nm to 0.5µm chip manufacturing process factory management experience. He is also experienced in building new factories and worked as factory manager for Semiconductor Manufacturing International Corp (SMIC) and Hua Hong Semiconductor Ltd (HHS).

Senior consultant Dr Chang Ru Gin is the founder and former CEO of SMIC. Xuzhou Factory research deputy general manager Dr Thomas Hu has more than 20 years of experience in GaN device design and fabrication, in particular GaN high-electron-mobility transistors (HEMTs). Hu is experienced in semiconductor process control, fab operation and management and is in charge of new process recipe development, process optimization, new product development, product quality control and yield improvement for GaN HEMT devices and products. It is expected that the core members of the Technology and Manufacturing team will enhance the R&D capabilities of the group.

"The strategic investments of the group in VisIC Technologies and GaN Systems [fabless developers of GaN-based power conversion devices based in Israel and Canada, respectively] announced earlier on [in August and November, respectively] also represent our commitment venturing into the third-generation semiconductor industry, further enhancing our third-generation semiconductor design and manufacturing capabilities," says HG's chairman & executive director Zhao Yiwen. "With new appointments of experienced and professional core

members of the Technology and Manufacturing team, we strongly believe that the team, who are all world-class seasoned professional in the semiconductor industry, can capitalize on their factory management, project management and technical experience to design and produce leading-edge semiconductor products," he adds.

## EPC launches 100V, 23mΩ eGaN power transistor for high-power-density power conversion and LiDAR

*SemiconductorToday*

Efficient Power Conversion Corp (EPC) of El Segundo, CA, USA – which makes enhancement-mode gallium nitride on silicon (eGaN) power field-effect transistors (FETs) and integrated circuits for power management applications – has launched the EPC2070, a 100V GaN transistor with a maximum on-resistance RDS(on) of 23mΩ and a 34A pulsed output current for high efficiency power conversion in a 1mm x 1.1mm footprint.

Applications demanding higher efficiency and power density no longer have to choose between size and performance, says EPC. In addition, the low cost of the EPC2070 brings the performance of GaN FETs at a price comparable to silicon MOSFETs. Applications benefiting from this performance, small size and low cost include 48V input power converters up to 60W for computing and telecom systems, time of flight (ToF) modules using vertical-cavity surface-emitting lasers (VCSELs) for camera modules, laptops and smart phones, LED lighting, and Class-D audio.

"The ability of eGaN-based power devices to operate efficiently at high frequency widens the performance and cost gap with silicon," says CEO Alex Lidow. "The 100V, EPC2070 is a great addition to our fifth-generation family of products offering designers the ability to go to higher power densities than what is possible with silicon MOSFETs."

The EPC90141 development board is a 100V maximum device voltage half-bridge with onboard gate drives, featuring the EPC2070 eGaN FETs. The 2" x 2" (50.8mm x 50.8mm) board is designed for optimal switching performance and contains all critical components for easy evaluation of the EPC2070.

The EPC2070 eGaN FET is priced at $0.67 each for 2500 units. The EPC90141 development board is priced at $123.75/each. Both the EPC2070 and EPC90141 are available for purchase from distributor Digi-Key Corp.

## Navitas opens design center in China focused on enabling GaN-based data-centers

*SemiconductorTodayNavitas*

Gallium nitride (GaN) power integrated circuit firm Navitas Semiconductor of El Segundo, CA, USA and Dublin, Ireland has announced its expansion into higher-power markets with the opening of a new Design Center dedicated to bringing next-generation GaN power ICs and associated high-efficiency, high-power-density systems to enable data centers around the world to upgrade from silicon to GaN, thereby significantly improving energy savings, reducing electricity costs and cutting CO2 emissions.

Founded in 2014, Navitas introduced what it claimed to be the first commercial GaN power integrated circuits. Its proprietary GaNFast power ICs monolithically integrate GaN power field-effect transistors (FETs) and GaN drive plus control and protection circuits in a single SMT package. Since GaN is reckoned to run up to 20x faster than silicon, GaNFast power ICs are said to deliver up to 3x faster charging or 3x more power in half the size and weight.

The new Design Center in Hangzhou, China hosts a team of power system designers with capabilities across electrical, thermal and mechanical design, software development, and complete simulation and prototyping

capabilities. Data-center power customers will be supported worldwide by the new team, from concept to prototype, through to full qualification and mass production.

The Design Center will develop schematics, layouts and firmware for full-function, productizable data-center power supplies. Solutions for the highest power density and highest efficiency will bring GaN into mainstream data centers, Navitas reckons. Additionally, multiple partnerships will be created for magnetics, thermal substrates, and other materials to assist customers in optimizing their power supply designs.

Navitas estimates that an upgrade from legacy silicon to new GaN could deliver energy savings up to 40%, and save $1.9bn/year in data-center electricity costs worldwide. Data-center supplies are rated to meet tough efficiency criteria, with the extreme 'Titanium' grade demanding 96% efficiency at 50% load. These new benchmarks are not only enabled by GaN technology but also demanded by legislation such as the European Union's 'Directive 2009/125/EC, 2019 Annex', which states that new data-center power supplies must meet the 'Titanium' level of efficiency from 1 January 2023.

"The Navitas Data Center team has the new technical skills of GaN power ICs plus the experience of real power supply design and qualification," says Charles Zha, VP & general manager of Navitas China. "The first proof point is a 1.2kW 'Titanium plus' design that not only exceeds the highest efficiency standards for data-center power supplies but is also value-engineered to be lower cost than legacy silicon designs. After this, it's on to 2.2kW and 3kW platforms."

The 1.2kW design was developed in collaboration with Boco and FRD of Hangzhou, and the power supply is now under evaluation for mass production in 2022. "GaNFast power ICs are easy-to-use, digital-in, power-out building blocks that have accelerated time-to-prototype and first-time-right designs," comments Boco's CEO Golden Yin. "GaNFast power ICs are essential to achieving Titanium Plus efficiency, a critical milestone for next-generation data-center power supplies," says Ray Gu, general manager of FRD's Power Supply business unit. "This will help FRD strengthen its product portfolio and provide comprehensive solutions to enterprise customers," he adds.

"As data and communications continue their exponential growth, it is critical for data centers to upgrade to GaNFast power ICs to reduce costs, maximize energy savings and reduce CO2 emissions," says Navitas' co-founder & CEO Gene Sheridan. "As a critical expansion market, we recruited ahead of our recent IPO funding, and that faith in our data-center design team is already paying dividends. By working in collaboration with data-center engineers around the world, we can accelerate adoption of GaN-based data centers and make a significant impact on energy savings, electricity costs and CO2 emissions."

Manufacturing a GaN power IC has up to a 10x lower CO2 footprint than for a silicon chip, it is reckoned. Considering use-case efficiency, material size and weight benefits, then each GaN power IC shipped can save 4kg of CO2, the firm adds. Overall, GaN is expected to address a 2.6Gton/year reduction in CO2 emissions by 2050.

## OPTOELECTRONICS

### Court orders search and seizure of products from suspected infringers of Seoul Viosys' patents in Europe

*SemiconductorToday*

LED product maker Seoul Viosys Co Ltd – an affiliate of Sensor Electronic Technology Inc (SETi) and a subsidiary of South Korea's Seoul Semiconductor – says that, in September, the Judicial Court of Paris, France ordered a search and seizure against a multi-national electric retailer and its suppliers for distributing UV LED sterilizers suspected of infringing Seoul Viosys' patents.

Seoul Viosys had filed a patent infringement complaint with the French court. Under the French court's order, bailiffs seized products from the business offices of those companies located in Paris and Lille to secure evidence of suspected infringement.

As developers of second-generation technologies, Seoul Viosys and its affiliates say they have obtained permanent injunctions and orders of recall against products infringing their patented technologies.

For example, SSI (currently Mediana Electronics) was the subject of a search and seizure for supplying South Korea's largest companies with white LED chips, infringing Seoul Semiconductor's technology in order to generate hundreds of billions of Korean won in sales revenues, says the firm. SSI's employees were arrested for stealing Seoul's technology.

Recently, Seoul Viosys and its strategic partners also obtained a series of permanent injunctions or judgments for patent infringement in the USA and Europe against various UV LED makers (such as RayVio, Everlight, Bolb, Epileds and LED Engin) and they continue to pursue additional enforcements against some of those manufacturers.

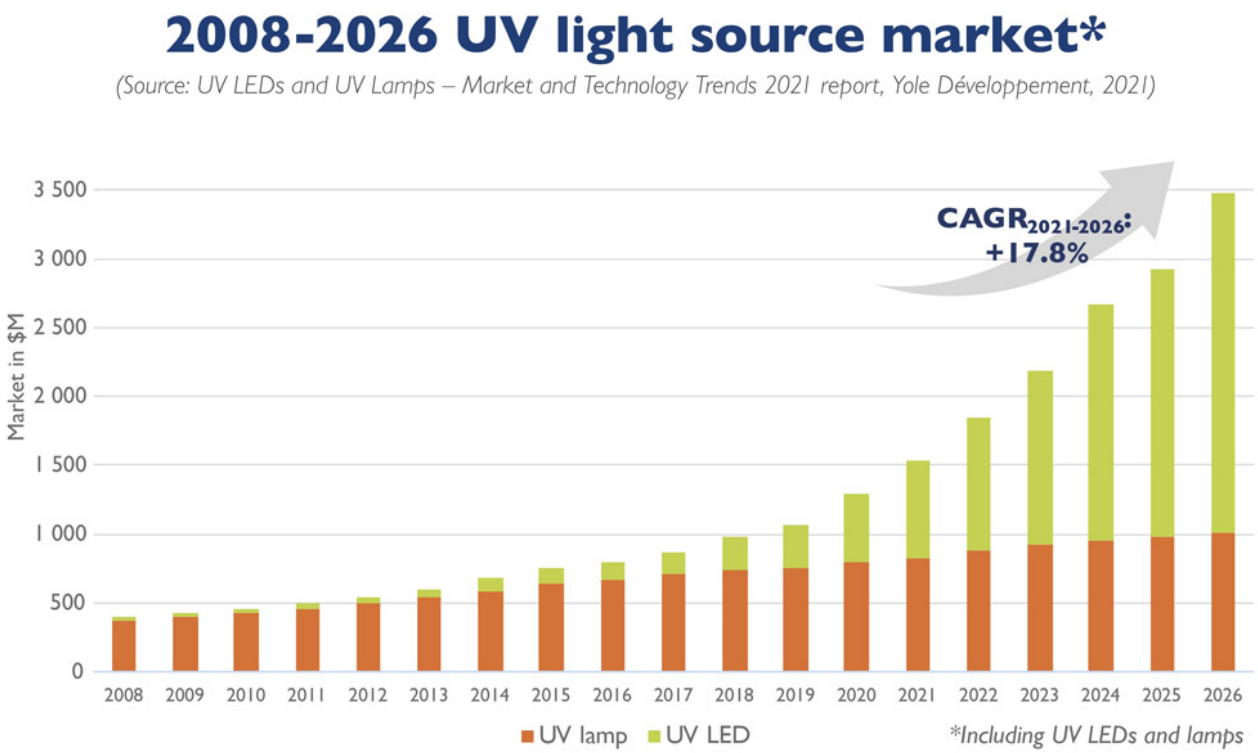
Seoul Viosys has been collaborating for over 20 years with SETi, a pioneer in UV LED technology. Together, the firms co-developed Violeds technology, which can effectively disinfect water, air space and surfaces, including the elimination of 99.437% of the SARS-CoV-2 virus in less than 1 second. Seoul Viosys expects the probability of infection to be reduced to 3% in an indoor environment when using Violeds. Violeds technology also has applications in deodorization and 3D printing. Based on its technology, Seoul Viosys supplies LED solutions for refrigerators, air conditioners, washing machines and water purifiers to the top three global companies in Korea, the USA and China.

### UV LED market to grow to $2.466bn in 2026, driven by impact of COVID-19

*SemiconductorToday*

The UV lighting market is expected to rise at a compound annual growth rate (CAGR) of 17.8% from 2021-to $3.5bn in 2026, with the UV LED market in particular growing to $2.466bn, forecasts market analyst firm Yole Développement in its new report 'UV LEDs and UV Lamps – Market and Technology Trends 2021'.

The UV lighting market overall was about $400m in 2008. By 2015 UV LEDs alone were worth $100m. In 2019, the total market reached $1bn as UV LEDs spread into UV curing and disinfection. The COVID-19 pandemic then drove demand, increasing total revenue by 30% in just one year. Yole hence expects the UV lighting market to be $1.5bn in 2021 before rising at a 17.8% CAGR, doubling or tripling to $3.5bn in 2026.




"The COVID-19 pandemic has created some perfect use-cases for UV lighting technologies to spread throughout a rapidly changing disinfection market," says Pars Mukish, business unit manager, Solid-State Lighting & Display, at Yole.

Indeed, SARS-COV-2, the virus that causes COVID-19, has one of the highest reproduction/transmissibility rates among all viruses that have emerged. To reduce the spread of the disease, light in the UVC wavelength band (which can deactivate bacteria and viruses through physical methods) has gained unprecedented attention. Overall, there will be a 'before' and an 'after' the COVID-19 pandemic for the UV lighting industry, says Yole.

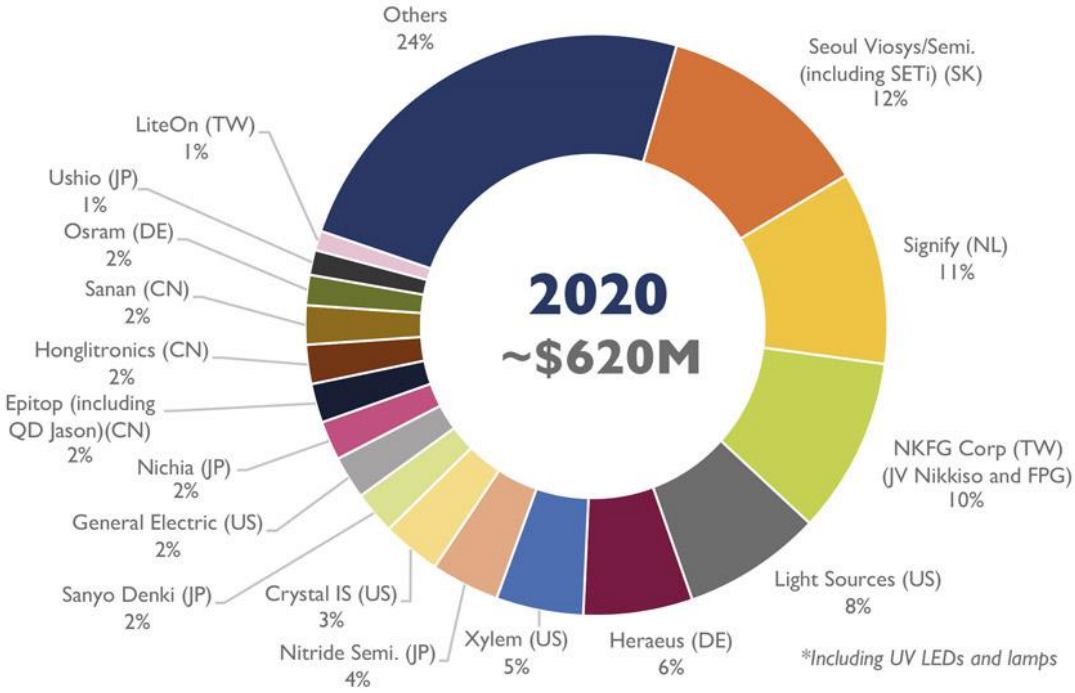
"Indeed, the health crisis due to the SARS-CoV-2 virus has generated unprecedented demand for the design and manufacture of disinfection systems using optical UV rays," notes Joël Thomé, CEO of photonics innovation services provider PISEO (a partner of Yole), which has released the report 'UV-C LEDs in the Time of COVID-19 - Update November 2021'. "LED manufacturers have seized this opportunity, and we are currently seeing an explosion in UV-C LED products."

The COVID-19 pandemic has strongly impacted the UV industry in general, notes the report 'UV LEDs and UV Lamps – Market and Technology Trends 2021'. On the one hand UV lamps are historic, established and mature technologies in the UV lighting market. Business before the COVID-19 pandemic was driven mostly by polymer curing with UVA wavelength light and water disinfection with UVC light. On the other hand, UV LED technologies are still emerging. Until recently, business was mostly driven by UVA LEDs. It was only a few years ago that UVC LEDs reached the performance and cost specifications of early adopters and started generating revenue.

"Both technologies will benefit, but on different timelines," says Pierrick Boulay, senior technology & market analyst, Solid-state Lighting, at Yole. "In the very short term, UV lamps might dominate end-systems because they are already established and easy to integrate. However, this proliferation of applications is a catalyst for the UV LED industry that will further push the technology and its performance forward. In the middle-to-long term, several end-systems might further adopt UV LED technology".

## 2020 UVC light source market shares for disinfection applications*

*(Source: UV LEDs and UV Lamps – Market and Technology Trends 2021 report, Yole Développement, 2021)*




Numerous industries and players supply UV lamps and UV LEDs. Signify, Light Sources, Heraeus and Xylem/Wedeco are the top four UVC lamp players, while Seoul Viosys and NKFG are currently leading the UVC LED industry. There are few overlaps between the two industries. Yole expects this to remain the case even though some UVC lamp players, such as Stanley and Osram, are diversifying their activities into the UVC LED field. In total, PISEO has identified 15 more UV-C LED manufacturers compared with 2020.

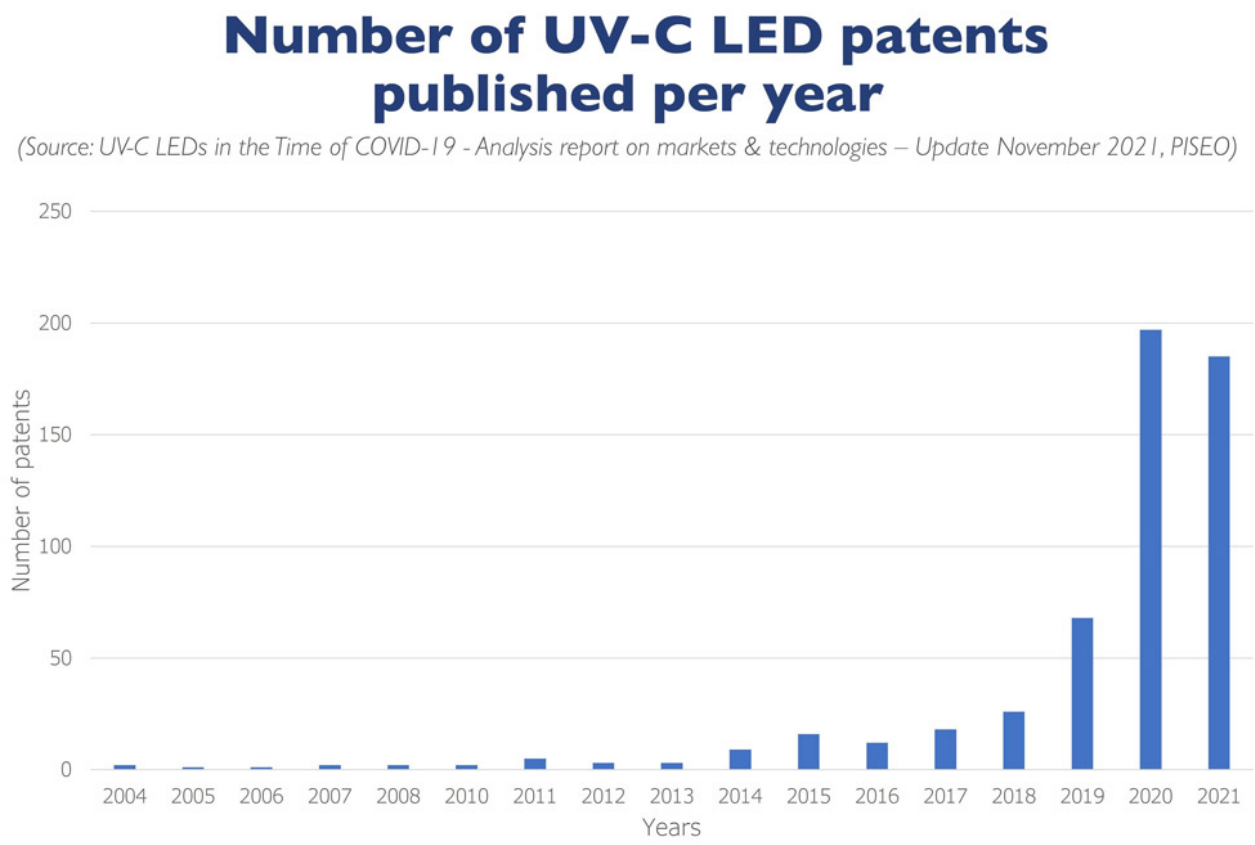
Overall, the UVC LED industry is likely to be the most transformed by recent trends. The industry has waited more than 10 years for this moment to happen. All the players are now ready to grab a piece of this booming market, says Yole.

**UV-C LED-related patents**

The number of UV-C LED-related patents filed in the last two years has exploded, illustrating the dynamism of research in this area, states PISEO. In its new UV-C LED report, PISEO offers a particular focus on the key patents of four LED makers, highlighting the main challenges of the rollout of this technology: intrinsic efficacy and cost. Yole also offers a complementary analysis of the patent landscape. The need for disinfection and the opportunity to use small light sources enabled the creation of increasingly compact systems. This evolution, including new form factors, has clearly generated renewed interest on the part of LED makers.

Wavelength is also a key parameter for germicidal efficiency and optical risk assessment. “Although currently relatively scarce and expensive, several system manufacturers, such as Signify and Acuity Brands, are taking a close interest in sources emitting a 222nm wavelength due to the harmlessness of this optical radiation on the human body,” notes Matthieu Verstraete, Innovation Leader and Electronics & Software Architect at PISEO. Several products have already been placed on the market, and there are more to come that integrate excimer sources made by the company Ushio. PISEO’s specialists therefore review the state of medical research, the

technology of sources emitting at 222nm, the germicidal effect of this wavelength, the regulatory environment, and the roadmaps produced.




## SemiLEDs' full-year revenue falls 23%

*SemiconductorToday*

For its fiscal full-year 2021 (to end-August), LED chip and component maker SemiLEDs Corp of Hsinchu, Taiwan has reported revenue of $4.7m, down 23% on fiscal 2020's $6.1m. However, fiscal fourth-quarter 2021 revenue of $1.4m is level with both last quarter and a year ago.

Full-year gross margin fell from 26% in fiscal 2020 to 22% in fiscal 2021. Most recently, gross margin dropped from 46% last quarter to 11%, although this is still up on just 8% a year ago.

Full-year operating margin declined from -34% in fiscal 2020 to -83% for fiscal 2021. This includes quarterly operating margin worsening from -41% last quarter to -135% in fiscal Q4.

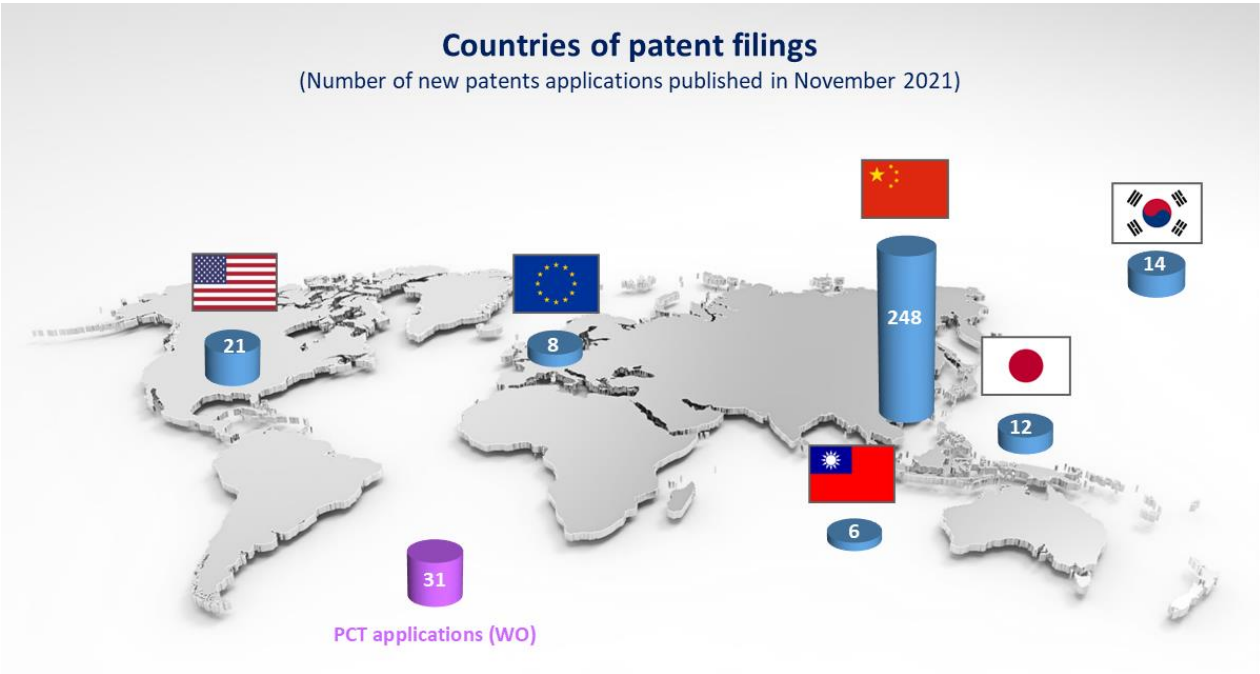
Net loss grew from $64,000 ($0.02 per diluted share) last quarter to $1.835m ($0.42 per diluted share), taking full-year net loss from $544,000 ($0.15 per diluted share) in fiscal 2020 to $2.85m ($0.68 per diluted share) for fiscal 2021.

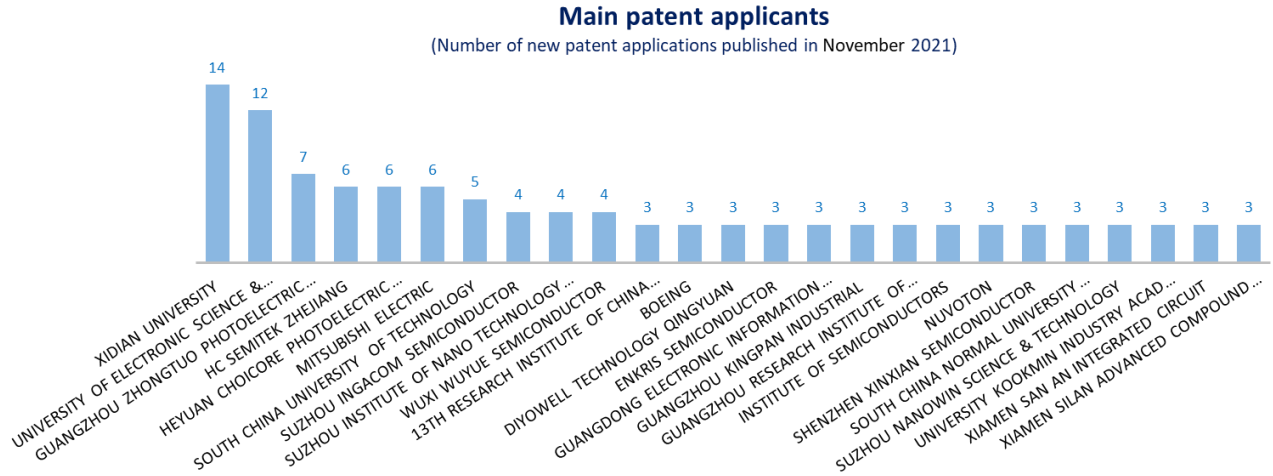
During fiscal Q4, cash and cash equivalents rose from $1.7m to $4.83m.

SemiLEDs says that, given the continuing uncertain impact of COVID-19 on the economy and the firm, it is unable to forecast revenue for fiscal first-quarter 2021 (to end-November) at this time.

# PATENT APPLICATIONS

More than **310 new patent families** related to GaN technology were published in **November 2021**.



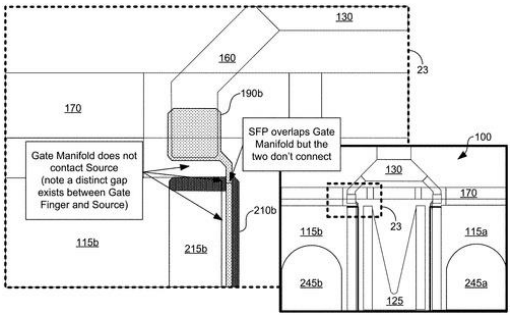

Other patent applicants: 38th Research Institute China Electronics Technology, Amosense, BOE Technology Group, Chongqing Konka Photoelectric Technology Research Institute, Fudan University, Fujian Prima Optoelectronics, Hangzhou Silan Azure, Hebei University of Technology, Huawei, Hunan University, Huzhou VEECD Opto Technology, Infineon Technologies, Innoscience Technology, Jiangsu Third Generation Semiconductor Research Institute, Jiangxi Zhao Chi Semiconductor, Kyocera, Nanchang Guiji Semiconductor Technology, Nanchang University, Nanjing GMinnovation Technology, Nanjing Xingan Technology, Nippon Telegraph & Telephone, Nupower Electronic, Samsung Electronics, Shenzhen Gallium Core Semiconductor Technology, Shenzhen Third Generation Semiconductor Research Institute, Shenzhen Yajingyuan Technology, Shenzhen Zhenmaojia Semiconductor, Soochow University, Sun Yat Sen University, University South Science & Technology China, Wuhu Qidi Semiconductor, Wuxi Haijing Semiconductor Technology, Xiangneng Hualei Optoelectronic Corppration, Zhongshan Institute of Modern Industrial Technology South China University of Technology, Aixier Huizhou Technology, Anhui Feimu Material, Anhui University of Technology, Anhui Xinta Electronic Technology, Asahi Kasei, Beifa, Beihai Huike Photoelectric Technology, Beijing Institute of Radio Measurement, Beijing Lyuneng Xinchuang Electronic Technology, Beijing Nuomishixian Electronic Technology, Beijing Qinghe Jingyuan Semiconductor Technology, Beijing Satellite Manufacturing Factory, Beyond Shidai Smartor Technology Beijing, British Business Prich Semiconductor, Central South University, Chengdu Changdao Technology, Chengdu Haohanxinguang Microelectronics Technology, Chengdu University of Information Technology, Chengdu Vistar Opteolectronics, China Electronic Science & Technology, China Electronics Technology, China University of Geosciences Beijing, Chip Foundation Technology, Chongqing HKC Optoelectronics Technology, Chongqing University, Citic Mobile Communication Technology, Continental Innosecco Suzhou Semiconductor, Cree, Danmarks Tekniske Universitet, Dongguan Dingli Daily Necessities Technology, Dongxu, Epinovatech, Facebook Technologies, Fatri United Testing & Control Technologies, Focus Lightings Science & Technology, Fraunhofer, Fuji Electric, Fujian Institute of Research on the Structure of Matter Chinese Academy of Sciences, Fujian JRSEMI Technology, Fujitsu, Fuyang Electronic Information Research Institute.

## Notable new patent applications

### Improved layout techniques and optimization for power transistors

**Publication number:** US20210359092, WO2021/230895, TW202143087
**Patent applicant:** Macom

Various embodiments are disclosed for improved and structurally optimized transistors, such as RF power amplifier transistors. A transistor may include a drain metal portion raised from a surface of a substrate, a drain metal having a notched region, a gate manifold body with angled gate tabs extending from the gate manifold, and/or a source-connected shielding. The transistor may include a high-electron-mobility transistor (HEMT), a gallium nitride (GaN)-on-silicon transistor, a GaN-on-silicon-carbide transistor, or other type of transistor.




### Fabricating a silicon carbide and nitride structures on a carrier substrate

**Publication number:** US20210358747, CA3113032, KR10-2021-0141343, CN113671771
**Patent applicant:** Boeing

A method, apparatus, and system for forming a semiconductor structure. A first oxide layer located on a set of group III nitride layers formed on a silicon carbide substrate is bonded to a second oxide layer located on a carrier substrate to form an oxide layer located between the carrier substrate and the set of group III nitride layers. The silicon carbide substrate has a doped layer. The silicon carbide substrate having the doped layer is etched using a photo-electrochemical etching process, wherein a doping level of the doped layer is such that the doped layer is removed and a silicon carbide layer in the silicon carbide substrate remains unetched. The semiconductor structure is formed using the silicon carbide layer and the set of group III nitride layers.

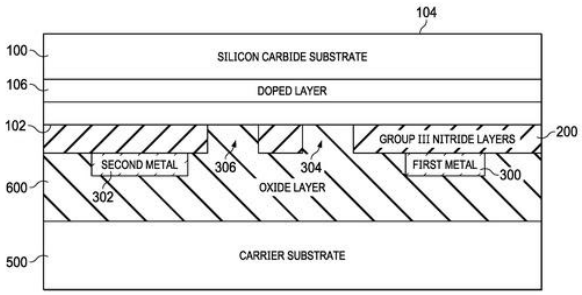
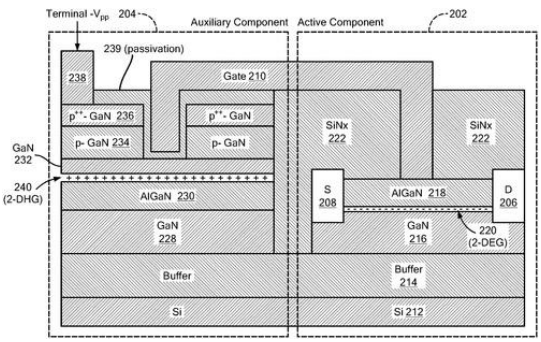


FIG. 6

### Semiconductor device with linear parasitic capacitance

**Publication number:** US20210343703
**Patent applicant:** MIT

A semiconductor device having relatively linear and constant parasitic capacitance of an operation range includes a first component having a negatively charged carrier channel and a second component comprising a positively charged carrier channel. The first component has source terminal and a drain terminal. The second component has bias terminal. Both components share a gate terminal that is electrostatically coupled to the negatively charged carrier channel of the first component and the positively charged carrier channel of the second component to produce a capacitance profile that stays relatively linear and constant as a voltage at the gate terminal changes.

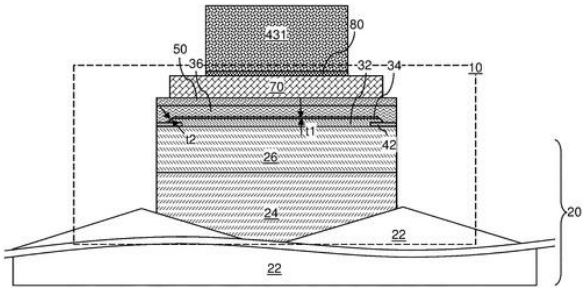


## Semiconductor device containing stress relaxation layer and method of making thereof

**Publication number:** US20210343901

**Patent applicant:** Nanosys (Glo)

A LED structure includes a first material layer, a second material layer, and a stress relaxation layer (dielectric layer) having a thickness of 0.5 nm or less between the first material layer and the second material layer.

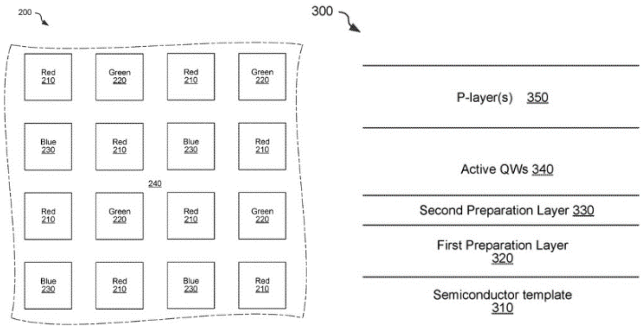



## LEDs with aluminum-containing layers integrated therein and associated methods

**Publication Number:** US20210343897, WO2021/226121

**Patent Applicant:** Raxium

A light-emitting diode (LED) structure includes an active region that has at least one aluminum-containing quantum well (QW) stack that emits light from the LED structure when activated. The LED structure exhibits a modified internal quantum efficiency value, which is higher than a LED structure that does not include aluminum within a QW stack. The LED structure also exhibits a modified peak wavelength, which is longer than an unmodified peak wavelength of the unmodified LED structure.

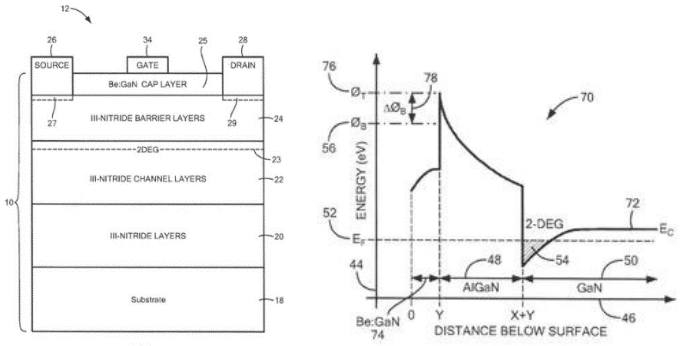



## Depletion mode HEMT semiconductor device having beryllium doped schottky contact layers

**Publication Number:** US20210367055, WO2021/236199

**Patent Applicant:** Raytheon

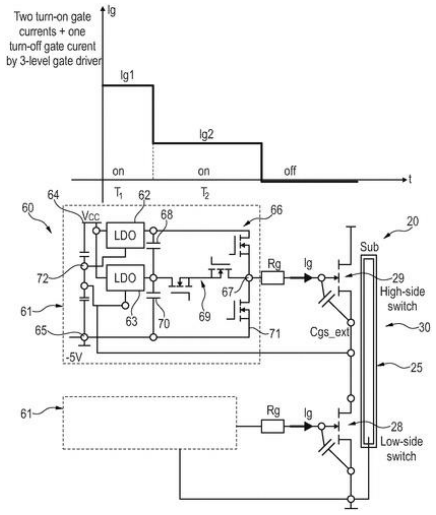
A semiconductor device having a substrate (18), a pair of Group Ill-Nitride layers (22, 24) on the substrate forming: a heterojunction with a 2 Dimensional Electron Gas (2DEG) channel in a lower one (22) of the pair of Group Ill-Nitride layers, a cap beryllium doped Group Ill-Nitride layer (25) on the upper one (24) of the pair of Group Ill-Nitride layers; and an electrical contact (34) in Schottky contact with a portion of the cap beryllium doped, Group Ill-Nitride layer.



## Switching circuit, gate driver and method of operating a transistor device

**Publication Number:** EP3905523, US20210344340, CN113595539

**Patent Applicant:** Infineon

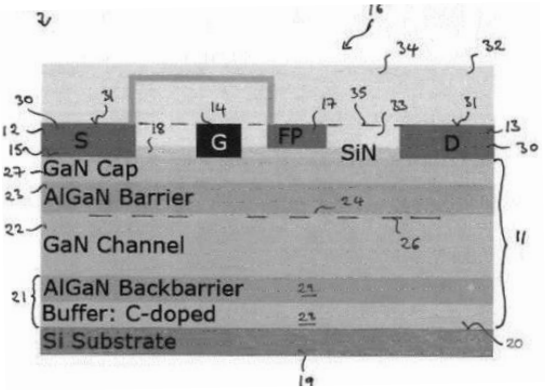



In an embodiment, a switching circuit is provided that comprises a Group III nitride-based semiconductor body comprising and a first monolithically integrated Group III nitride-based transistor device a second monolithically integrated Group III nitride-based transistor device that are coupled to form a half-bridge circuit and are arranged on a common foreign substrate comprising a common doping level. The switching circuit is configured to operate the half-bridge circuit at a voltage of at least 300V.

## Group III-nitride-based transistor device

**Publication Number:** WO2021/219740, EP3905335, EP3905336, EP3905337

**Patent Applicant:** Infineon




A Group III nitride-based transistor device is provided that has a gate drain capacitance (CGD) , a drain source capacitance (CDS) and a drain source on resistance (RDSon). A ratio of the gate drain capacitance (CGD) at a drain source voltage (VDS) of 0V, CGD(0V), and the gate drain capacitance CGD at a value of VDS > OV, CGDV, is at least 2:1, wherein VDS is less than 20V.

## Radiation-hard, temperature tolerant, GaN HEMT devices for radiation sensing applications

**Publication Number:** WO2021/217253

**Patent Applicant:** National Research Council (NRC)

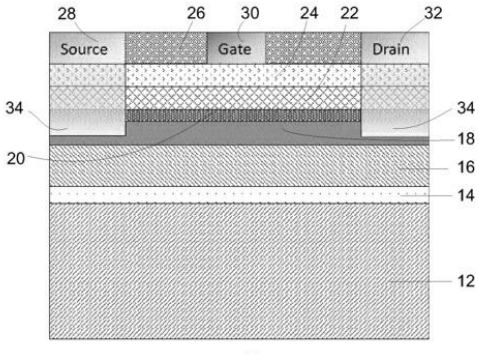


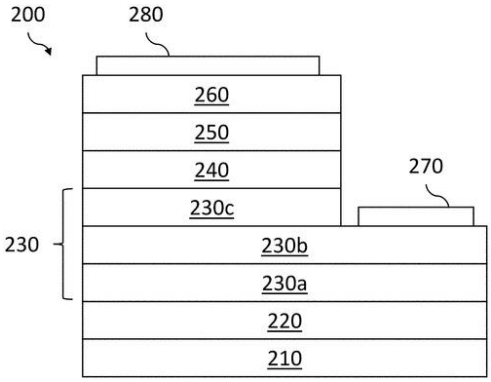
Figure 1a

A semiconductor high electron mobility transistor (HEMT)-based device configured to detect ionizing radiation, wherein the device comprises: a substrate; a nucleation layer formed on the substrate; a gallium nitride (GaN) buffer layer arranged on the nucleation layer; a GaN channel layer arranged on the GaN buffer layer; an aluminum nitride (AlN) spacer layer arranged on the GaN channel layer; a barrier layer arranged on the AlN spacer layer; a GaN cap layer arranged on the barrier layer; an electrically insulating silicon nitride (SiNx) passivation layer arranged on the GaN cap layer; a source, a drain and a gate, wherein the source and the drain are formed on the GaN cap layer; wherein charge carriers generated by the radiation in the underlying GaN layers are collected in the GaN channel layer and multiplied by impact ionization by a high electric field at the gate edge facing the drain contact.

## Buried contact layer for UV light emitting device

**Publication Number:** US20210343896, WO2021/220158, TW202143508
**Patent Applicant:** Silanna UV Technologies

In some embodiments, a light emitting structure comprises a layered semiconductor stack comprising a first set of doped layers, a second layer, a light emitting layer positioned between the first set of doped layers and the second layer, and an electrical contact to the first set of doped layers. The first set of doped layers can comprise a first sub-layer, a second sub-layer, and a third sub-layer, where the third sub-layer is adjacent to the light emitting layer. The electrical contact to the first set of doped layers can be made to the second sub-layer. The first, second and third sub-layers can be doped n-type, and an electrical conductivity of the second sub-layer can be higher than an electrical conductivity of the first and third sub-layers. In some cases, the second sub-layer can absorb more light emitted from the light emitting layer than the first or third sub-layers.




## Color LEDs with integrated optical filtering elements

**Publication Number:** WO2021/221924
**Patent Applicant:** Lumileds

A red LED includes a semiconductor LED layer having an active InGaN layer with intrinsic emission spectrum having LDom in a range of from 580 nm to 620 nm. A filter is positioned over the semiconductor LED layer to filter shorter wavelengths of the intrinsic emission spectrum and shift LDom by between 5 nm to 20 nm to a longer wavelength.

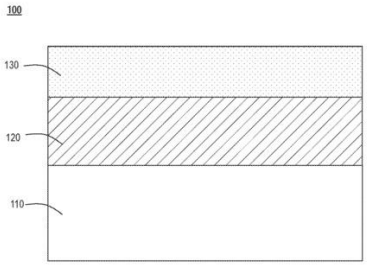
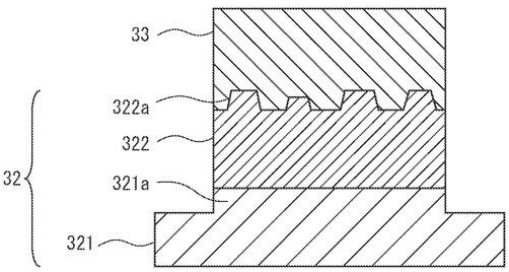


FIG. 1

## Nitride semiconductor element

**Publication Number:** US20210366703, CN113725732
**Patent Applicant:** Asahi Kasei

Provided is a nitride semiconductor element that does not cause element breakdown even when driven at high current density. A nitride semiconductor element includes an active layer, an electron block layer formed above the active layer, an AlGaN layer formed on the electron block layer, and a cover layer covering an upper surface of the AlGaN layer and formed of AlGaN or GaN having a lower Al composition ratio than in the AlGaN layer, in which the AlGaN layer includes protrusions provided on a surface opposite to the active layer, and the cover layer covers the protrusions. The AlGaN layer is preferably formed of AlGaN having an Al composition ratio decreasing in a direction away from the active layer, and the protrusions preferably have a frustum shape.



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