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Nano-cathodoluminescence reveals the effect of electron damage on the optical properties of nitride optoelectronics and the damage threshold
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Nano-cathodoluminescence (Nano-CL) reveals optical emission from individual InGaN quantum wells for applications in optoelectronic devices. We show the luminescent intensity decays over time with exposure to the electron beam for energies between 80 and 200 keV. Measurements of the CL intensity over time show an exponential decline in intensity, which we propose is due to the formation of nitrogen Frenkel defects. The measured CL damage decreases with reductions in the electron accelerating voltage and we suggest that the electron induced structural damage may be suppressed below the proposed damage threshold. The electron beam induced damage leads to a non-radiative region that extends over the measured minority carrier diffusion length. Nano-CL may thus serve as a powerful technique to study III-nitride optoelectronics.

Optical properties and internal quantum efficiency of InGaN/GaN core-shell microrods for solid state lighting
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OSRAM Opto Semiconductors GmbH, Regensburg, Germany

J. Appl. Phys http://dx.doi.org/10.1063/1.4964871

We investigate, via temperature and excitation density dependent quasi-resonant confocal micro-luminiscence, the optical properties and internal quantum efficiency (IQE) of InGaN/GaN single quantum wells (QWs) on Ga-polar GaN microrods selectively grown by continuous flow metal organic vapor phase epitaxy on patterned SiO2/n-GaN/sapphire template. Seven samples were grown with different growth parameters for the InGaN/GaN QW. The homogeneity of their optical properties is analyzed by mappings along the m-plane facet of the microrods in order to get insight on the growth mechanisms of the shell. Excitation density dependent measurements show that the IQE is affected by the high doping level of the core, which is required to grow such high aspect-ratio structures. Local IQEs between 15±1 % near the tip and 44±5 % near the base of microrods are estimated from measurements at room and low temperature. By comparison with results reported on planar c-plane QWs, we conclude that the radiative recombination rate is the main limitation for the emission efficiency.

Radiative recombination mechanisms in polar and non-polar InGaN/GaN quantum well LED structures
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We study the photoluminescence internal quantum efficiency (IQE) and recombination dynamics in a pair of polar and non-polar InGaN/GaN quantum well (QW) light-emitting diode (LED) structures as a function of excess carrier density and temperature. In the polar LED at 293 K, the variation of radiative and non-radiative lifetimes is well described by a modified ABC type model which accounts for the background carrier concentration in the QWs due
to unintentional doping. As the temperature is reduced, the sensitivity of the radiative lifetime to excess carrier density becomes progressively weaker. We attribute this behaviour to the reduced mobility of the localised electrons and holes at low temperatures, resulting in a more monomolecular like radiative process. Thus we propose that in polar QWs, the degree of carrier localisation determines the sensitivity of the radiative lifetime to the excess carrier density. In the non-polar LED, the radiative lifetime is independent of excitation density at room temperature, consistent with a wholly excitonic recombination mechanism. These findings have significance for the interpretation of LED efficiency data within the context of the ABC recombination model.

Ultraviolet light emitting diodes using III-N quantum dots

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Materials Science in Semiconductor Processing
http://dx.doi.org/10.1016/j.mssp.2016.02.014

(AI,Ga)N-based quantum dots (QDs) grown on Al0.5Ga0.5N by molecular beam epitaxy have been studied as the active region for the fabrication of ultra-violet (UV) light emitting diodes (LEDs). In the first part, using both “polar” (0001) and “semipolar” (11̅2̅2) surface orientations, the structural and optical properties of different QD structures are investigated and compared. In particular, their propensity to get an emission in the UV range is analyzed in correlation with the influence of the internal electric field on their optical properties. In a second part, (0001) and (11̅2̅2)-oriented LEDs using GaN/Al0.5Ga0.5N QD as active regions have been fabricated. Their main current-voltage characteristics and electroluminescence properties are discussed, with a focus on the LED emission wavelength range reached for both surface orientations: it is shown that a large part of the UV-A region can be covered, with longer wavelengths-from 415 to 360 nm-for the “polar” LEDs, and shorter ones-from 345 to 325 nm-for the “semipolar” LEDs. In addition, the influence of the internal electric field on the QD-LEDs working operation is shown.

Demonstration of InGaN-based orange LEDs with hybrid multiple-quantum-wells structure

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Applied Physics Express
http://dx.doi.org/10.7567/APEX.9.111003

We demonstrate the effectiveness of a hybrid multiple-quantum-wells (MQWs) structure in InGaN-based orange light-emitting diodes (LEDs) grown by metalorganic vapor phase epitaxy. The hybrid MQWs-LED is composed of orange InGaN double QWs and a blue-green InGaN single QW. Using the hybrid MQWs structure, the orange LEDs exhibited electroluminescence spectra with narrow full widths at half maximum of 51 nm at 20 mA. The light output power and external quantum efficiency of the InGaN-based orange LEDs were 0.23 mW and 0.6%, respectively, at 20 mA.

Effective suppression of efficiency droop in GaN-based light-emitting diodes: role of significant reduction of carrier density and built-in field

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Scientific Reports
http://dx.doi.org/10.1038/srep34586

A critical issue in GaN-based high power light-emitting diodes (LEDs) is how to suppress the efficiency droop problem occurred at high current injection while improving overall quantum efficiency, especially in conventional c-plane InGaN/GaN quantum well (QW), without using complicated bandgap engineering or unconventional materials and structures. Although increasing thickness of each QW may decrease carrier density in QWs, formation of additional strain and defects as well as increased
built-in field effect due to enlarged QW thickness are unavoidable. Here, we propose a facile and effective method for not only reducing efficiency droop but also improving quantum efficiency by utilizing c-plane InGaN/GaN QWs having thinner barriers and increased QW number while keeping the same single well thickness and total active layer thickness. As the barrier thickness decreases and the QW number increases, both internal electric field and carrier density within QWs are simultaneously reduced without degradation of material quality. Furthermore, we found overall improved efficiency and reduced efficiency droop, which was attributed to the decrease of the built-in field and to less influence by non-radiative recombination processes at high carrier density. This simple and effective approach can be extended further for high power ultraviolet, green, and red LEDs.

**Broadband full-color monolithic InGaN light-emitting diodes by self-assembled InGaN quantum dots**

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Scientific Reports
http://dx.doi.org/10.1038/srep35217

We have presented broadband full-color monolithic InGaN light-emitting diodes (LEDs) by self-assembled InGaN quantum dots (QDs) using metal organic chemical vapor deposition (MOCVD). The electroluminescence spectra of the InGaN QDs LEDs are extremely broad span from 410 nm to 720 nm with a line-width of 164 nm, covering entire visible wavelength range. A color temperature of 3370 K and a color rendering index of 69.3 have been achieved. Temperature-dependent photoluminescence measurements reveal a strong carriers localization effect of the InGaN QDs layer by obvious blue-shift of emission peak from 50 K to 300 K. The broadband luminescence spectrum is believed to be attributed to the injected carriers captured by the different localized states of InGaN QDs with various sizes, shapes and indium compositions, leading to a full visible color emission. The successful realization of our broadband InGaN QDs LEDs provide a convenient and practical method for the fabrication of GaN-based monolithic full-color LEDs in wafer scale.
Examination of Iron Doped Gallium Nitride as a Near-IR Laser Material
University Research Foundation, United States
U.S. Naval Research Laboratory, United States
Kyma Technologies, United States

https://doi.org/10.1364/ASL.2016.JTh2A.31

Iron doped Gallium Nitride is a promising candidate for high power laser operation at 1µm. We report novel spectroscopic characterization on samples with iron doping densities ranging from 1.0 x 10¹⁶cm⁻³ to 9.0 x 10¹⁹cm⁻³.

AlGaN/AlN integrated photonics platform for the ultraviolet and visible spectral range
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Optics Express
https://doi.org/10.1364/OE.24.025415

We analyze a photonic integrated circuit (PIC) platform comprised of a crystalline AlₓGa₁₋ₓN optical guiding layer on an AlN substrate for the ultraviolet to visible (UV-vis) wavelength range. An Al composition of x~0.65 provides a refractive index difference of ~0.1 between AlₓGa₁₋ₓN and AlN, and a small lattice mismatch (< 1%) that minimizes crystal dislocations at the AlₓGa₁₋ₓN/AlN interface. This small refractive index difference is beneficial at shorter wavelengths to avoid extra-small waveguide dimensions. The platform enables compact waveguides and bends with high field confinement in the wavelength range from 700 nm down to 300 nm (and potentially lower) with waveguide cross-section dimensions comparable to those used for telecom PICs such as silicon and silicon nitride waveguides, allowing for well-established optical lithography. This platform can potentially enable cost-effective, manufacturable, monolithic UV-vis photonic integrated circuits.

Enhancement of 1.5 µm emission under 980 nm resonant excitation in Er and Yb co-doped GaN epilayers
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http://dx.doi.org/10.1063/1.4964843

The Erbium (Er) doped GaN is a promising gain medium for optical amplifiers and solid-state high energy lasers due to its high thermal conductivity, wide bandgap, mechanical hardness, and ability to emit in the highly useful 1.5 µm window. Finding the mechanisms to enhance the optical absorption efficiency at a resonant pump wavelength and emission efficiency at 1.5 µm is highly desirable. We report here the in-situ synthesis of the Er and Yb co-doped GaN epilayers (Er + Yb:GaN) by metal-organic chemical vapor deposition (MOCVD). It was observed that the 1.5 µm emission intensity of the Er doped GaN (Er:GaN) under 980 nm resonant pump can be boosted by a factor of 7 by co-doping the sample with Yb. The temperature dependent PL emission at 1.5 µm in the Er + Yb:GaN epilayers under an above bandgap excitation revealed a small thermal quenching of 12% from 10 to 300 K. From these results, it can be inferred that the process of energy transfer from Yb³⁺ to Er³⁺ ions is highly efficient, and non-radiative recombination channels are limited in the Er + Yb:GaN epilayers synthesized in-situ by MOCVD. Our results point to an effective way to improve the emission efficiency of the Er doped GaN for optical amplification and lasing applications.
InGaN/GaN Dot-in-Nanowire Lasers on Silicon
Department of Electrical Engineering and Computer Science University of Michigan, Ann Arbor, MI 48109, USA

Frontiers in Optics 2016
https://www.osapublishing.org/viewmedia.cfm?uri=LS-2016-LTu1H.2&seq=0

The fabrication and characteristics of monolithic edge-emitting InGaN/GaN dot-in-nanowire array diode lasers on (001)Si will be presented.

Ultraviolet Second Harmonic Generation in Aluminum Nitride Microring Resonators
Rochester Institute of Technology, United States
Frontiers in Optics 2016
https://www.osapublishing.org/abstract.cfm?URI=fio-2016-FTh5G.6

Aluminum nitride, with a bandgap of 6.2 eV, and a χ(2) of ~10's of pm/V can generate ultraviolet photons. This article describes using aluminum nitride microring resonators to produce second harmonic photons below 400nm.

Second-harmonic generation in aluminum nitride microrings with 2500%/W conversion efficiency
Department of Electrical Engineering, Yale University, New Haven, Connecticut 06511, USA

Optica
https://doi.org/10.1364/OPTICA.3.001126

Photonic integrated circuits hold promise as miniaturized and scalable platforms for classical and quantum photonic information processing. Second-order nonlinearity (∇χ(2)∇χ(2)) is the basis of many important applications such as second-harmonic generation, spontaneous parametric down-conversion, and optical parametric oscillation. Here, we present systematical investigation and optimization of the second-harmonic generation in a dual-resonant aluminum nitride microring resonator. By optimizing the quality factor, independently engineering the coupling conditions for dual-band operation, and perfectly fulfilling phase-match conditions through thermal tuning, we demonstrate a second-harmonic generation efficiency of 2500% W−12500% W−1 in the low-pump-power regime. To the best of our knowledge, this is a state-of-the-art value among all the integrated photonic platforms. We also study the high-power regime where the pump power depletion is non-negligible. A conversion efficiency of 12% is realized with 27 mW pump power. Our high-efficiency second-harmonic generator enables integrated frequency conversion and frequency locking between visible and infrared systems, and our approach can also apply to other photonic platforms.

High reflectivity III-nitride UV-C distributed Bragg reflectors for vertical cavity emitting lasers
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J. Appl. Phys.
http://dx.doi.org/10.1063/1.4963831

UV-C distributed Bragg reflectors (DBRs) for vertical cavity surface emitting laser applications and polariton lasers are presented. The structural integrity of up to 25 layer pairs of AlN/Al0.65Ga0.35N DBRs is maintained by balancing the tensile and compressive strain present between the single layers of the multilayer stack grown on top of an Al 0.85Ga0.35N template. By comparing the structural and optical properties for DBRs grown on low dislocation density AlN and AlGaN templates, the criteria for plastic relaxation by cracking thick nitride Bragg reflectors are deduced. The critical thickness is found to be limited mainly by the accumulated strain energy during the DBR growth and is only negligibly affected by the dislocations. A reflectance of 97.7% at 273 nm is demonstrated. The demonstrated optical quality and an ability to tune the resonance wavelength of our resonators and microcavity structures open new opportunities for UV-C vertical emitters.
**GaN-on-Si laser diode: open up a new era of Si-based optical interconnections**

State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, China

Science Bulletin
http://dx.doi.org/10.1007/s11434-016-1192-x

As Si-based electronics technology approaches its scaling limits, it arises great interest in optical interconnections via Si photonics. However, Si with an indirect band-gap structure can hardly emit light. The lack of an efficient on-chip laser source remains as the major roadblock of Si photonics for decades, which recently has drawn renewed research interest. It is highly desirable to grow III-V semiconductor laser directly on Si for a monolithic integration with Si photonics to take the full advantage of low-cost large-scale fabrication platforms.

**Optically pumped vertical-cavity surface-emitting laser at 374.9 nm with an electrically conducting n-type distributed Bragg reflector**

Center for Compound Semiconductors and School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250, U.S.A.

Applied Physics Express
http://dx.doi.org/10.7567/APEX.9.111002

An optically pumped vertical-cavity surface-emitting laser with an electrically conducting n-type distributed Bragg reflector was achieved at 374.9 nm. An epitaxially grown 40-pair n-type AlGaN/GaN distributed Bragg reflector was used as the bottom mirror, while the top mirror was formed by a dielectric distributed Bragg reflector composed of seven pairs of HfO2/SiO2. A numerical simulation for the optical mode clearly demonstrated that a high confinement factor was achieved and the threshold pumping power density at room temperature was measured as 1.64 MW/cm2. The achieved optically pumped laser demonstrates the potential of utilizing an n-type distributed Bragg reflector for surface-emitting optical devices.

**Waveguide (WG) architectures of 420 nm emitting InGaN/GaN diode lasers**

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Applied Physics Express
http://dx.doi.org/10.7567/APEX.9.111002

Waveguide (WG) architectures of 420 nm emitting InGaN/GaN diode lasers are analyzed by photoluminescence and photocurrent spectroscopy using a nearfield scanning optical microscope that scans along their front facets. The components of the 'optical active cavity', quantum wells, WGs, and cladding layers are individually inspected with a spatial resolution of ~100 nm. Separate analysis of the p- and n-
sections of the WG was achieved, and reveals defect levels in the p-part. Moreover, it is demonstrated that the homogeneity of the n-WG section directly affects the quantum wells that are grown on top of this layer. Substantially increased carrier capture efficiencies into InGaN/GaN-WGs compared to GaN-WGs are demonstrated.
Nanoscale fissure formation in AlxGa1−xN/GaN heterostructures and their influence on Ohmic contact formation

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Radiation resistance of wide-bandgap semiconductor power transistors

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Nanoscale surface fissures on AlxGa1−xN/GaN (15 nm/1 µm) heterostructures grown by metalorganic vapour phase epitaxy (MOVPE) were imaged using tapping-mode atomic force microscopy (AFM) and electron channelling contrast imaging (ECCI). Fissure formation was linked to threading dislocations, and was only observed in samples cooled under H2 and NH3, developing with increasing barrier layer Al content. No strain relaxation was detected regardless of fissure formation up to barrier layer Al composition fractions of x = 0.37. A reduction of measured channel carrier density was found in fissured samples at low temperature. This instability is attributed to shallow trap formation associated with fissure boundaries. For Ti/Al/Ni/Au Ohmic contact formation to high Al content barrier layers, fissures were found to offer conduction routes to the 2DEG that allow for low resistance contacts, with fissure-free samples requiring additional optimisation of the metal stack and anneal conditions to achieve contact resistivity of order those measured in fissured samples. In addition, the effects of fissures were found to be detrimental to thermal stability of sheet and contact resistance, suggesting that fissure formation compromises the integrity of the 2DEG.

Radiation resistance of state-of-the-art commercial wide-bandgap power transistors, 1700 V 4H-SiC power MOSFETs and 200 V GaN HEMTs, to the total ionization dose was investigated. Transistors were irradiated with 4.5 MeV electrons with doses up to 2000 kGy. Electrical characteristics and introduced defects were characterized by current–voltage (I–V), capacitance–voltage (C–V), and deep level transient spectroscopy (DLTS) measurements. Results show that already low doses of 4.5 MeV electrons (>1 kGy) cause a significant decrease in threshold voltage of SiC MOSFETs due to embedding of the positive charge into the gate oxide. On the other hand, other parameters like the ON-state resistance are nearly unchanged up to the dose of 20 kGy. At 200 kGy, the threshold voltage returns back close to its original value, however, the ON-state resistance increases and transconductance is lowered. This effect is caused by radiation defects introduced into the low-doped drift region which decrease electron concentration and mobility. GaN HEMTs exhibit significantly higher radiation resistance. They keep within the datasheet specification up to doses of 2000 kGy. Absence of dielectric layer beneath the gate and high concentration of carriers in the two dimensional electron gas channel are the reasons of higher radiation resistance of GaN HEMTs. Their degradation then occurs at much higher doses due to electron mobility degradation.
In this paper, some aspects of the electrical characterization of trapping phenomena occurring at interfaces between insulators and wide band semiconductors (WBG) are presented, with a focus on the SiO2/SiC and SiO2/GaN systems. In particular, time resolved capacitance, current measurements, and parallel conductance measurements as a function of frequency were correlated to investigate trapping states in SiC and GaN MOS-structures, allowing to distinguish between slow and fast states in these systems.

Furthermore, gate current measurements enabled us to get insights into the near interface traps (NITs) present inside the SiO2 layer. Evidently, in these systems, although post-oxide deposition annealing treatments can reduce the interface traps (down to the $10^{11}–10^{12} \text{cm}^{-2} \text{eV}^{-1}$ range), the presence of the NITs is responsible for an anomalous behavior of the current conduction, penalizing the threshold voltage stability. Time-dependent current and conductance measurements, performed in appropriate bias ranges, enabled to determine the density of NITs ($1 \times 10^{11} \text{cm}^{-2}$). The impact of the observed trapping phenomena on the SiO2/SiC(GaN) transistor operation is briefly discussed.

**Electric field dependence of optical phonon frequencies in wurtzite GaN observed in GaN high electron mobility transistors**

In this study, we explore the electric field dependence of the optical phonon frequencies in GaN high electron mobility transistors (HEMTs). We use density functional theory to calculate the zone center $E_2$ (high), $A_1$ (LO), and $E_2$ (low) modes to shift by $-1.39 \text{cm}^{-1}/(\text{MV/cm})$, $2.16 \text{cm}^{-1}/(\text{MV/cm})$, and $-0.36 \text{cm}^{-1}/(\text{MV/cm})$, respectively, due to an electric field component along the $c$-axis. This is an order of magnitude larger than the shifts associated with the inverse piezoelectric (IPE) effect. We then measure changes in the $E_2$ (high) and $A_1$ (LO) Raman peak positions with $\approx 1 \mu\text{m}$ spatial resolution in GaN HEMTs biased in the pinched OFF state and show good agreement between the strain, stress, and electric field components derived from the measurements and our 3D electro-mechanical model. This study helps to explain the reason the pinched OFF state is a suitable reference for removing the contributions of the electric field and the IPE-induced stress from the temperature rise in the ON state and suggests that the IPE-induced stress in the GaN buffer is an order of magnitude smaller than previously believed.
effect and suggest that this is a general phenomenon occurring in all wurtzite and zincblende crystals. The total electric field dependence of the optical phonon frequencies in piezoelectric crystals is a critical consideration in accurately characterizing the stress, strain, electric field, and temperature distributions in microelectronic devices via micro-Raman spectroscopy.

Highly-stable and low-state-density Al2O3/GaN interfaces using epitaxial n-GaN layers grown on free-standing GaN substrates
Research Center for Integrated Quantum Electronics (RCIQE), Hokkaido University, Sapporo 060-0814, Japan

Interface characterization was carried out on Al2O3/GaN structures using epitaxial n-GaN layers grown on free-standing GaN substrates with relatively low dislocation density (<3 × 10⁶ cm⁻²). The Al2O3 layer was prepared by atomic layer deposition. The as-deposited metal-oxide-semiconductor (MOS) sample showed a significant frequency dispersion and a bump-like feature in capacitance-voltage (C–V) curves at reverse bias, showing high-density interface states in the range of 10¹² cm⁻¹ eV⁻¹. On the other hand, excellent C–V characteristics with negligible frequency dispersion were observed from the MOS sample after annealing under a reverse bias at 300 °C in air for 3 h. The reverse-bias-annealed sample showed state densities less than 1 × 10¹¹ cm⁻¹ eV⁻¹ and small shifts of flat-band voltage. In addition, the C–V curve measured at 200 °C remained essentially similar compared with the room-temperature C–V curves. These results indicate that the present process realizes a stable Al2O3/GaN interface with low interface state densities.

Normally-off p-GaN/AlGaN/GaN high electron mobility transistors using hydrogen plasma treatment
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In this letter, we report a method by introducing hydrogen plasma treatment to realize normally-off p-GaN/AlGaN/GaN HEMT devices. Instead of using etching technology, hydrogen plasma was adopted to compensate holes in the p-GaN above the two dimensional electron gas (2DEG) channel to release electrons in the 2DEG channel and form high-resistivity area to reduce leakage current and increase gate control capability. The fabricated p-GaN/AlGaN/GaN HEMT exhibits normally-off operation with a threshold voltage of 1.75 V, a subthreshold swing of 90 mV/dec, a maximum transconductance of 73.1 mS/mm, an ON/OFF ratio of 1 × 10⁷, a breakdown voltage of 393 V, and a maximum drain current density of 188 mA/mm at a gate bias of 6 V. The comparison of the two processes of hydrogen plasma treatment and p-GaN etching has also been made in this work.

Investigating compositional effects of atomic layer deposition ternary dielectric Ti-Al-O on metal-insulator-semiconductor heterojunction capacitor structure for gate insulation of InAlN/GaN and AlGaN/GaN
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Gate insulation/surface passivation in AlGaN/GaN and InAlN/GaN heterojunction field-effect transistors is a major concern for passivation of surface traps and reduction of gate leakage current. However, finding the most appropriate gate dielectric materials is challenging and often
involves a compromise of the required properties such as dielectric constant, conduction/valence band-offsets, or thermal stability. Creating a ternary compound such as Ti-Al-O and tailoring its composition may result in a reasonably good gate material in terms of the said properties. To date, there is limited knowledge of the performance of ternary dielectric compounds on AlGaN/GaN and even less on InAlN/GaN. To approach this problem, the authors fabricated metal-insulator-semiconductor heterojunction (MISH) capacitors with ternary dielectrics Ti-Al-O of various compositions, deposited by atomic layer deposition (ALD). The film deposition was achieved by alternating cycles of TiO2 and Al2O3 using different ratios of ALD cycles. TiO2 was also deposited as a reference sample. The electrical characterization of the MISH capacitors shows an overall better performance of ternary compounds compared to the pure TiO2. The gate leakage current density decreases with increasing Al content, being ~2–3 orders of magnitude lower for a TiO2:Al2O3 cycle ratio of 2:1. Although the dielectric constant has the highest value of 79 for TiO2 and decreases with increasing the number of Al2O3 cycles, it is maintaining a relatively high value compared to an Al2O3 film. Capacitance voltage sweeps were also measured in order to characterize the interface trap density. A decreasing trend in the interface trap density was found while increasing Al content in the film. In conclusion, our study reveals that the desired high-κ properties of TiO2 can be adequately maintained while improving other insulator performance factors. The ternary compounds may be an excellent choice as a gate material for both AlGaN/GaN and InAlN/GaN based devices.

The effects of the surface and bulk traps on current collapse in AlGaN/GaN high electron mobility transistor were investigated by the transient behaviors of the devices. The results proved that the traps at the surface had little effect on current collapse when the device was well passivated, but the traps in the buffer layer played an important role. Two bulk trap levels were observed in these devices. In addition, the effects of light illumination on the bulk traps were studied in detail. It was found that light illumination enhanced the resumption of the current collapse after the field stress. The contribution of lights illumination with various wavelengths to the current collapse was also investigated to study the trap energy levels.

Identification of the primary compensating defect level responsible for determining blocking voltage of vertical GaN power diodes
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Avogy, Inc., San Jose, California 95134, USA

Electrical performance and characterization of deep levels in vertical GaN P-i-N diodes grown on low threading dislocation density (~104 - 106 cm−2) bulk GaN substrates are investigated. The lightly doped n drift region of these devices is observed to be highly compensated by several prominent deep levels detected using deep level optical spectroscopy at Ec-2.13, 2.92, and 3.2 eV. A combination of steady-state photocapacitance and lighted capacitance-voltage profiling indicates the concentrations of these deep levels to be Nt = 3 × 1012, 2 × 1015, and 5 × 1014 cm−3, respectively. The Ec-2.92 eV level is observed to be the primary compensating defect in as-grown n-type metal-organic chemical vapor deposition GaN, indicating this level acts as a limiting factor for achieving controllably low doping. The device blocking voltage should increase if compensating defects reduce the free carrier concentration of the n drift region. Understanding the incorporation of as-grown and native defects in thick n-GaN is essential for enabling large VBD in the next-generation wide-bandgap power

The study of the contribution of the surface and bulk traps to the dynamic Rdson in AlGaN/GaN HEMT by light illumination
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semiconductor devices. Thus, controlling the as-grown defects induced by epitaxial growth conditions is critical to achieve blocking voltage capability above 5 kV.

Impact of diamond seeding on the microstructural properties and thermal stability of GaN-on-diamond wafers for high-power electronic devices

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Scripta Materialia
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The impact of seeding of the diamond growth on the microstructural properties of GaN-on-diamond wafers was studied using in situ focused ion beam cross-sectioning and scanning electron microscopy imaging. Microstructural studies revealed that the seeding conditions are a critical parameter to obtain an optimal material, allowing the manufacture of GaN-on-diamond wafers with no microscopic defects and with structural stability under thermal annealing at 825 °C. The use of the right seeding conditions also results in homogeneous thermal properties across four inch GaN-on-diamond wafers, which is of critical importance for their use for ultra-high power microwave electronic devices.

Temperature-dependent electrical transport characteristics of a NiO/GaN heterojunction diode

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Surfaces and Interfaces
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We explored the temperature-dependent behavior of a NiO/GaN heterojunction diode in this work. The cubic crystalline structured NiO film exhibited p-type semiconducting behavior with a resistivity of approximately 6.3 Ω cm. The heterojunction diode showed an excellent stability over the temperature range of 25–175 °C. The turn-on voltage of the devices decreased from 2.2 to 1.5 V with increasing temperature. The device characteristics in forward bias were dominated by three types of current transport mechanisms and were found to be dependent on the applied bias voltages and temperature.

Comparing electrical performance of GaN trench-gate MOSFETs with a-plane (11-20) and m-plane (1-100) sidewall channels

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Applied Physics Express
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GaN trench-gate MOSFETs with m- and a-plane-oriented sidewall channels were fabricated and characterized. The trench-gate MOSFET performance depended strongly on the sidewall-MOS-channel plane orientation. The m-plane-oriented MOS channel devices demonstrated higher channel mobility, higher current density, lower sub-threshold slope, and lower hysteresis with similar threshold voltage and on–off ratio compared to a-plane MOS channel devices. These results indicate that orienting trench-gate MOSFET toward the m-plane would allow for better on-state characteristics while maintaining similar off-state characteristics.

NiO gate GaN-based enhancement-mode heterojunction field-effect transistor with extremely low on-resistance using metal organic chemical vapor deposition regrown Ge-doped layer

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Japanese Journal of Applied Physics,
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In this paper, we present a normally-off GaN-based transistor with an extremely low on-
resistance (R on) fabricated by using a Ge-doped n++-GaN layer for ohmic contacts. We developed a novel GaN regrowth technique using Ge as a dopant, which achieved an extremely high doping concentration of 1 × 1020 cm−3, and thereby the lowest specific contact resistance of 1.5 × 10−6 Ω·cm2. The NiO gate fabricated using an atomic layer deposition technique reduced the spacing between the source and drain electrodes. The fabricated device showed the record-breaking R on of 0.95 Ω·mm with the maximum drain current and transconductance of 1.1 A/mm and 490 mS/mm, respectively. Note that the obtained threshold voltage was 0.55 V. This extremely low R on characteristic indicates the great potential of NiO-gate GaN-based heterojunction field-effect transistors.

**Novel fully vertical GaN p–n diode on Si substrate grown by metalorganic chemical vapor deposition**

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We report novel GaN fully vertical p–n diode on Si grown by metalorganic chemical vapor deposition. The thick strained layer superlattice is effective in controlling a doping level of 1016 cm−3 in an n−-GaN drift layer. The GaN p–n diode exhibits a differential on-resistance R on of 7.4 mΩ cm2, a turn-on voltage of 3.4 V, and a breakdown voltage V B of 288 V. The corresponding Baliga's figure of merit (FOM) $V_B^2/R_{on}$ is 11.2 MW/cm2. A good FOM value for the GaN-on-Si vertical p–n diode is realized for a drift layer thickness of 1.5 µm without using substrate removal technology.

**DC characteristics of ALD-grown AlGaN/GaN MIS-HEMTs and HEMTs at 600 °C in air**

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Semiconductor Science and Technology
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To the best of our knowledge, the 600 °C device characteristics detailed here reflect the highest operation temperature reported for AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs) in air which supports the realization of electronics for high-temperature applications (e.g., space exploration, combustion and downhole). The high-temperature response of AlGaN/GaN MIS-HEMTs with Al2O3 deposited by plasma-enhanced atomic layer deposition (ALD) as the gate dielectric and passivation layers was examined here. More specifically, the DC current–voltage response and the threshold voltage characteristics of the MIS-HEMTs were evaluated to temperatures up to 600 °C in air. For comparison, the response of AlGaN/GaN HEMTs without the ALD Al2O3 layer was also measured. It was observed that the HEMTs failed above 300 °C accompanied by a ~500 times increase in leakage current and observation of bubbles formed in active region of gate. On the contrary, the MIS-HEMTs continued to operate normally up to 600 °C. However, within the 30 min period exposed to 600 °C the MIS-HEMT degraded permanently. This was observed at 20 °C after return from operation at 600 °C as a change in threshold voltage and saturation drain current. The failure of the HEMTs is suggested to be due to the diffusion of gate metals (Ni and Au) into the active regions of the AlGaN/GaN heterostructure, which creates additional leakage current pathways. The impact of strain relaxation and interfacial trapped charges on threshold voltage as a function of temperature was studied using an energy band-gap model. The ALD Al2O3 gate dielectric layer acts as a diffusion barrier to the Ni and Au gate metals, thus enabling short-term operation of MIS-HEMTs to 600 °C, the highest operation temperature reported for this device architecture to date.
Reduced performance in Gallium Nitride (GaN)-based high electron mobility transistors (HEMTs) as a result of self-heating has been well-documented. To mitigate this effect, the incorporation of high thermal conductivity diamond heat spreading films or substrates has been proposed. A mid-process integration scheme, termed “gate-after-diamond,” is shown to improve the thermal budget for NCD deposition and enables scalable, large-area diamond coating without degrading the Schottky gate metal. The optimization of this process step is presented in this work. Nanocrystalline (NCD)-capped devices had a 20% lower channel temperature at equivalent power dissipation. Improved electrical characteristics were also observed, notably improved on-resistance and breakdown voltage, and reduced gate leakage.

Deep Trap Levels Responsible for Current Collapse in AlGaN/GaN MISHFET
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We investigated the current collapse in AlGaN/GaN MISHFETs after negative gate bias by observing the spectral photo-responsive drain current. The photons of 2.25 eV were the most effective photon energy to excite the electrons trapped by the deep levels, and the energy was attributed to the current collapse induced by the negative gate bias. This trap deep energy might be related to the Ga vacancy in GaN bulk layer. The current collapse in AlGaN/GaN MISHFET was more significant for the wider gate-drain spacing.
200 K. The change was most prominent for temperatures from 290 K to ∼330 K and occurred due to deep traps capturing electrons in the AlGaN barrier and near the AlGaN/GaN interface. C-V measurements at low temperature showed that the traps in the AlGaN barrier are located near Ec−2 eV and have a density of ∼1012 cm−2, while the traps at the interface have an optical ionization threshold near 1.7 eV and the density of ∼4 × 1012 cm−2. Capacitance deep level transient spectroscopy (DLTS) and current DLTS (CDLTS) revealed electron traps with levels near Ec−0.56 eV and hole traps with levels near Ev+0.9 eV and Ev+0.5 eV. The Ec−0.56 eV traps are known to be located near the AlGaN/GaN interface in the GaN buffer. The Ev+0.9 eV hole traps are located in the buffer.
Saturation of photoresponse to intense THz radiation in AlGaN/GaN HEMT detector

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We report on the photoresponse of AlGaN/GaN high electron mobility transistors to the THz radiation of low (15 mW/cm²) and high (up to 40 kW/cm²) intensities. We show that the response can be described by the Dyakonov-Shur theory in the whole range of radiation intensity. At low intensities, the photoresponse is linear in radiation intensity. Under intense laser radiation, we observe a saturation at intensities >20 kW/cm². We explain our results by the change of the channel conductivity under the influence of strong THz field. This mechanism of photoresponse saturation, which is due to the mobility decrease in high ac electric field, should exist for any type of field effect transistor detectors.

Peculiarities of tunneling current in w-AlN/GaN(0001) two-barrier structures induced by deep-level defects

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The influence of deep-level defects localized in spacer layers on the tunneling current in a w-AlN/GaN (0001) double-barrier structure is studied. It is shown that the current value essentially depends on the nature and spatial distribution of defects. New effects (screening of built-in fields, negative feedback, fixing of current peaks at high temperature) and a new mechanism of formation of resonances and tunneling current hysteresis caused by deep centers are established. The results of calculation agree with a number of experimental data on the position and temperature dependence of the current peak. It is noted that the current bistability can be caused by multicharged deep centers localized near the heteroboundaries of a double-barrier structure. Due to the defects, electric field in the barriers can reach values, at which the Poole-Frenkel effect should be taken into account.

Electric field dependence of optical phonon frequencies in wurtzite GaN observed in GaN high electron mobility transistors

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Due to the high dissipated power densities in gallium nitride (GaN) high electron mobility transistors (HEMTs), temperature measurement techniques with high spatial resolution, such as micro-Raman thermography, are critical for ensuring device reliability. However, accurately determining the temperature rise in the ON state of a transistor from shifts in the Raman peak positions requires careful decoupling of the simultaneous effects of temperature, stress, strain, and electric field on the optical phonon frequencies. Although it is well-known that the vertical electric field in the GaN epilayers can shift the Raman peak positions through the strain and/or stress induced by the inverse piezoelectric (IPE) effect, previous studies have not shown quantitative agreement between the strain and/or stress components derived from micro-Raman measurements and those predicted by electro-mechanical models. We attribute this
discrepancy to the fact that previous studies have not considered the impact of the electric field on the optical phonon frequencies of wurtzite GaN apart from the IPE effect, which results from changes in the atomic coordinates within the crystal basis and in the electronic configuration. Using density functional theory, we calculated the zone center E2 (high), A1 (LO), and E2 (low) modes to shift by −1.39 cm−1/(MV/cm), 2.16 cm−1/(MV/cm), and −0.36 cm−1/(MV/cm), respectively, due to an electric field component along the cc-axis, which are an order of magnitude larger than the shifts associated with the IPE effect. Then, we measured changes in the E2 (high) and A1 (LO) Raman peak positions with ≈1 μm spatial resolution in GaN HEMTs biased in the pinched OFF state and showed good agreement between the strain, stress, and electric field components derived from the measurements and our 3D electro-mechanical model. This study helps to explain the reason the pinched OFF state is a suitable reference for removing the contributions of the electric field and the IPE-induced stress from the temperature rise in the ON state and suggests that the IPE-induced stress in the GaN buffer is an order of magnitude smaller than previously believed. Our analysis and experimental results support previous theoretical studies discussing the electric field dependence of optical phonon frequencies apart from the IPE effect and suggest that this is a general phenomenon occurring in all wurtzite and zincblende crystals. The total electric field dependence of the optical phonon frequencies in piezoelectric crystals is a critical consideration in accurately characterizing the stress, strain, electric field, and temperature distributions in microelectronic devices via micro-Raman spectroscopy.

Graphene integration with nitride semiconductors for high power and high frequency electronics
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Group III nitride semiconductors (III-N), including GaN, AlN, InN, and their alloys, are currently the materials of choice for many applications in optoelectronics (light-emitting diodes, laser diodes), and high-power and high-frequency transistors. Due to its attractive electrical, optical, mechanical, and thermal properties, graphene (Gr) integration with III-N technology has been considered in the last few years, in order to address some of the major issues which still limit the performances of GaN-based devices. To date, most of the studies have been focused on the use of Gr as transparent conductive electrode (TCE) to improve current spreading from top electrodes and light extraction in GaN-LEDs. This paper will review recent works evaluating the benefits of Gr integration with III-N for high power and high frequency electronics. From the materials side, recent progresses in the growth of high quality GaN layers on Gr templates and in the deposition of Gr on III-N substrates and templates will be presented. From the applications side, strategies to use Gr for thermal management in high-power AlGaN/GaN transistors will be discussed. Finally, recent proposals of implementing new ultra-high-frequency (THz) transistors, such as the Gr base hot electron transistor (GBHET), by Gr integration with III-N will be highlighted.

High current density 2D/3D MoS2/GaN Esaki tunnel diodes
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http://dx.doi.org/10.1063/1.4966283

The integration of two-dimensional materials such as transition metal dichalcogenides with bulk semiconductors offer interesting opportunities for 2D/3D heterojunction-based device structures without any constraints of lattice matching. By exploiting the favorable band alignment at the GaN/MoS2 heterojunction, an Esaki interband tunnel diode is demonstrated by transferring large area Nb-doped, p-type MoS2 onto heavily n-doped GaN. A peak current density of 446 A/cm2 with repeatable room temperature negative differential resistance, peak to valley current ratio of 1.2, and minimal hysteresis was measured in...
the MoS2/GaN non-epitaxial tunnel diode. A high current density of 1 kA/cm² was measured in the Zener mode (reverse bias) at −1 V bias. The GaN/MoS2 tunnel junction was also modeled by treating MoS2 as a bulk semiconductor, and the electrostatics at the 2D/3D interface was found to be crucial in explaining the experimentally observed device characteristics.

**High frequency N-polar GaN planar MIS-HEMTs on sapphire with high breakdown and low dispersion**
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Lester Eastman Conference (LEC), 2016
http://dx.doi.org/10.1109/LEC.2016.7578930

N-polar planar GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) grown by metal-organic chemical vapor deposition on sapphire substrate with a high combination of power cutoff frequency (fmax) and three-terminal breakdown voltage (BVDS) as well as a decent DC-to-RF dispersion control are demonstrated. Compared to previously reported N-polar planar HEMTs, devices presented in this letter not only maintain comparable fmax/BVDS of 221 GHz/116 V, but also exhibit a mitigation of drain current collapse and ON-resistance dispersion. In addition, a higher output power of 5.43 W/mm at the same VDS,Q = 25 V and a reduction of efficiency drop with increasing VDS,Q were achieved by load-pull measurements at 10 GHz.
GROUP 5 – MEMS and Sensors
Group leader: Marc Faucher (IEMN)
Information selected by Knowmade

Compositional inhomogeneities in AlGaN thin films grown by molecular beam epitaxy: Effect on MSM UV photodetectors
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J. Appl. Phys.
http://dx.doi.org/10.1063/1.4964420

Ultraviolet (UV) MSM photodetectors (PD) based on AlGaN alloys find many applications, including flame sensing. In this work we investigate the dependence of AlGaN based photodetectors grown by MBE on the kinetics of growth. MSM photodetectors were fabricated in the interdigitated configuration with Ni/Au contacts having 400 μm finger length and 10 μm finger spacing. Bulk Al 0.4Ga0.6N films were grown on to sapphire substrates using an AlN buffer layer. A series of PDs were developed using the Al 0.4Ga0.6N films grown under different group III/V flux ratios ranging from stoichiometric conditions to much higher than unity. Upon testing, it was observed that the otherwise identical photodetectors show significant decrease in dark current as AlGaN deposition conditions change from stoichiometric to excess group III, due to reduction of unintentional incorporation of oxygen-related point defects. In addition, the intensity and spectral dependence of the photocurrent also change, showing an extended low energy tail for the former and a sharp and prominent excitonic peak for the latter. The optical transmission measurements indicate a variation in Urbach energy with deposition conditions of the AlGaN films, although they have the same absorption edge. While all samples show a single red-shifted photoluminescence peak at room temperature, upon cooling, multiple higher energy peaks appear in the photoluminescence (PL) spectra, indicating that the alloys contain complex compositional inhomogeneities. Two types of alloy fluctuations, determined by the growth conditions, have been identified that modulate the optoelectronic properties of AlGaN by changing the spatial localization of excitons, thereby altering their stability. We identified that growth under stoichiometric conditions leads to compositional inhomogeneities that play a detrimental role in the operation of MSM photodetectors, which reduces the sharpness of the sensitivity edge, while growth under excess metal conditions enhances it.

The effect of transparent conductive nanocrystalline oxide thin layer on performance of UV detectors fabricated on Fe-doped GaN
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Materials Science in Semiconductor Processing
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Two kinds of metal-semiconductor-metal (MSM) Schottky UV detectors with and without an insertion layer of transparent conductive nanocrystalline oxide were fabricated on Fe-doped semi-insulating GaN epilayers. It is found that the optical responsivity of the detectors can be significantly improved by two orders of magnitude by inserting a thin layer of Ga-doped nanocrystalline ZnO (GZO) between metal electrode and Fe-doped GaN. Such improvement is suggested to be associated with the valence-band discontinuities and efficient suppression recombination of traps induced by Fe impurities in GaN due to the insertion of a thin layer of GZO.

Mercury(II) selective sensors based on AlGaN/GaN transistors
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This work presents the first polymer approach to detect metal ions using AlGaN/GaN transistor-based sensor. The sensor utilised an AlGaN/GaN high electron mobility transistor-type structure by functionalising the gate area with a polyvinyl chloride (PVC) based ion selective membrane. Sensors based on this technology are portable, robust and typically highly sensitive to the target analyte; in this case Hg2+. This sensor showed a rapid and stable response when it was introduced to solutions of varying Hg2+ concentrations. At pH 2.8 in a 10−2 M KNO3 ion buffer, a detection limit below 10−8 M and a linear response range between 10−8 M-10−4 M were achieved. This detection limit is an order of magnitude lower than the reported detection limit of 10−7 M for thioglycolic acid monolayer functionalised AlGaN/GaN HEMT devices. Detection limits of approximately 10−7 M and 10−6 M in 10−2 M Cd(NO3)2 and 10−2 M Pb(NO3)2 ion buffers were also achieved, respectively. Furthermore, we show that the apparent gate response was near-Nernstian under various conditions. X-ray photoelectron spectroscopy (XPS) experiments confirmed that the sensing membrane is reversible after being exposed to Hg2+ solution and rinsed with deionised water. The success of this study precedes the development of this technology in selectively sensing multiple ions in water with use of the appropriate polymer based membranes on arrays of devices.

Simple fabricate ZnO individual microwall UV detector grown along the cracks of GaN/Si by the aqueous method
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Optics Communications
http://dx.doi.org/10.1016/j.optcom.2016.09.012

Ultraviolet (UV) photodetector(PD) based on ZnO microwall (MW) structure was fabricated in this paper. The MW structure was directed by the crack of GaN substrate, which was formed by self-assembly growth ZnO nanorods. Meanwhile, simple UV PD was fabricated by directly contacting with Ag paste. The UV PD based on MW shows ultra-fast photoresponses and reliable UV sensitivity. It can be attribute to the large surface-to-volume ratio of the ZnO MW and the hexagonal cross-section which can strongly confine the light inside and enhance the interaction between the light and the ZnO material. It suggests that ZnO MW is superior materials for UV detection.

Gas Sensing of Nitrogen Oxide Utilizing Spectrally Pure Deep UV LEDs
Institut für Festkörperphysik, Technische Universität Berlin, Berlin, Germany

IEEE Journal of Selected Topics in Quantum Electronics
http://dx.doi.org/10.1109/JSTQE.2016.2597541

In this paper, we will present the development of a compact LED-based optical gas sensing system in the ultraviolet-C spectral region. This includes the design of the LED heterostructure emitting near 226 nm, the development of an LED chip, and the implementation into a gas sensing system capable of detecting nitrogen oxide concentrations in the ppm range.

Low-temperature-dependent property in an avalanche photodiode based on GaN/AlN periodically-stacked structure
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Scientific Reports
http://dx.doi.org/10.1038/srep35978

In ultra-high sensitive APDs, a vibrate of temperature might bring a fatal decline of the multiplication performance. Conventional method to realize a temperature-stable APD focuses on the optimization of device structure, which has
limited effects. While in this paper, a solution by reducing the carrier scattering rate based on a GaN/AlN periodically-stacked structure (PSS) APD is brought out to improve temperature stability essentially. Transport property is systematically investigated. Compared with conventional GaN homojunction (HJ) APDs, electron suffers much less phonon scatterings before it achieves ionization threshold energy and more electrons occupy high energy states in PSS APD. The temperature dependence of ionization coefficient and energy distribution is greatly reduced. As a result, temperature stability on gain is significantly improved when the ionization happens with high efficiency. The change of gain for GaN (10 nm)/AlN (10 nm) PSS APD from 300 K to 310 K is about 20% lower than that for HJ APD. Additionally, thicker period length is found favorable to ionization coefficient ratio but a bit harmful to temperature stability, while increasing the proportion of AlN at each period in a specific range is found favorable to both ionization coefficient ratio and temperature stability.
Improving InGaN heterojunction solar cells efficiency using a semibulk absorber

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We demonstrate enhanced short circuit current density and power conversion efficiency in InGaN heterojunction solar cells using a semibulk absorber (multi-layered InGaN/GaN structure), with 8% indium concentration. The semibulk absorber shows peak external quantum efficiency of 85% and short current density of 0.57 mA/cm² under AM 1.5 G, i.e. almost four times higher than the typical InGaN solar cells based on single thick InGaN absorber. The power conversion efficiency is around 0.39% under AM 1.5 G, almost three times higher than state of the art for 8% indium incorporation. The improvement in power conversion efficiency is attributed to the enhancement in structural quality of the InGaN absorber. Simulations and experimental results are presented for an in depth investigation of the parameters limiting the power conversion efficiency of the solar cell. The semibulk absorber is an elegant solution for the realization of highly efficient InGaN-based PIN heterojunction solar cells.

Efficiency optimization of the structure pin-InGaN/GaN and quantum well-InGaN for solar cells

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International Journal of Hydrogen Energy
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In this aim, we were interested in the optimization and simulation of pin-In1−xGaxN structure and InGaN multi quantum well structures for photovoltaic applications. This ternary alloy which is an III-V semiconductor presents important characteristics especially its gap energy, thus, the increase of the photons absorption of wavelengths. It has been shown that the increase in indium concentration increases the current density Jsc and the maximum output power. In return, the Voc decreases consequently. For In0.50Ga0.50N structure we observed that the current density and the maximum power are respectively around 19.50 mA/cm² and 27.50 mW/cm² with a ratio of 21.65 mA/cm². Also it is shown that the incorporation of the quantum well in the active region results in an increase of Jsc and Pmax but Voc remains unchanged. The incorporation of 50 quantum well structure in the In0.50Ga0.50N gives 22 mA/cm² of the current density and 32 mW/cm² of the maximum output power. The use of the structure based on In0.50Ga0.50N (MQW) induces an efficiency of 32%. We deduced that the relative efficiency is improved by 10.9%.

Direct observation of the carrier transport process in InGaN quantum wells with a pn-junction

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Chinese Physics B
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A new mechanism of light-to-electricity conversion that uses InGaN/GaN QWs with a p–n junction is reported. According to the well established light-to-electricity conversion theory, quantum wells (QWs) cannot be used in solar cells
and photodetectors because the photogenerated carriers in QWs usually relax to ground energy levels, owing to quantum confinement, and cannot form a photocurrent. We observe directly that more than 95% of the photoexcited carriers escape from InGaN/GaN QWs to generate a photocurrent, indicating that the thermionic emission and tunneling processes proposed previously cannot explain carriers escaping from QWs. We show that photoexcited carriers can escape directly from the QWs when the device is under working conditions. Our finding challenges the current theory and demonstrates a new prospect for developing highly efficient solar cells and photodetectors.

**Photoelectrochemical Property Differences between NiO Dots and Layer on n-Type GaN for Water Splitting**

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The n-type GaN photoelectrode is suitable for hydrogen generation from water because it can split water without bias. However, the n-type GaN photoelectrode has the anodic corrosion problem caused by the etching of the GaN. This problem can be resolved by NiO loading on GaN. The reported method of NiO loading on GaN surface was carried out by coating the surface by diluted metal organic decomposition (MOD) and high-temperature annealing. Since no NiO loading methods using Ni(OH)2 dispersed solution and low-temperature annealing have been reported, in this study, we attempted NiO loading Ni(OH)2 dispersed solution. Experimental results confirmed that the method can be easily performed and effective. In addition, we also compared the photoelectrochemical properties of the n-type GaN samples obtain by Ni(OH)2 loaded using four different Ni(OH)2 synthetic methods, loading by NiO-MOD, and no-NiO loading. The photocurrent densities of all samples loaded using Ni(OH)2 dispersed solution increased compared to samples without NiO and with NiO-MOD. The photocurrent densities and stabilities were affected by the NiO shape and density which were found to be related with the method of synthesizing the Ni(OH)2 dispersed solutions. The effects of NiO shape and density on the photocurrent density and stability are also discussed.

**GaInN/GaN solar cells made without p-type material using oxidized Ni/Au Schottky electrodes**

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GaInN/GaN solar cells made without p-type material are demonstrated using an oxidized Ni/Au Schottky barrier design to collect photogenerated carriers. The best devices exhibit a short-circuit current density of 0.065 mA/cm2 with an open-circuit voltage of 0.4 V under AM0 (1-Sun) illumination. Preliminary computer simulations are in reasonable agreement with experimental results, giving a pathway to improve device performance via iterative redesign and testing.
Fabrication of normally-off GaN nanowire gate-all-around FET with top-down approach
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Lateral GaN nanowire gate-all-around transistor has been fabricated with top-down process and characterized. A triangle-shaped GaN nanowire with 56 nm width was implemented on the GaN-on-insulator (GaNOI) wafer by utilizing (i) buried oxide as sacrificial layer and (ii) anisotropic lateral wet etching of GaN in tetramethylammonium hydroxide solution. During subsequent GaN and AlGaN epitaxy of source/drain planar regions, no growth occurred on the nanowire, due to self-limiting growth property. Transmission electron microscopy and energy-dispersive X-ray spectroscopy elemental mapping reveal that the GaN nanowire consists of only Ga and N atoms. The transistor exhibits normally-off operation with the threshold voltage of 3.5 V and promising performance: the maximum drain current of 0.11 mA, the maximum transconductance of 0.04 mS, the record off-state leakage current of ~10−13 A/mm, and a very high Ion/Ioff ratio of 108. The proposed top-down device concept using the GaNOI wafer enables the fabrication of multiple parallel nanowires with positive threshold voltage and is advantageous compared with the bottom-up approach.

Selective area growth of high-density GaN nanowire arrays on Si(111) using thin AlN seeding layers
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Selective area growth (SAG) of high-density (2.5×109 cm−2) GaN nanowires (NWs) on Si(111) substrate by plasma-assisted molecular beam epitaxy is presented. The effects of morphology and thickness of the AlN seeding layer on the quality of SAG GaN NWs are investigated. A thin AlN seeding layer of 30 nm thick with a surface roughness of less than 0.5 nm is suitable for high quality SAG GaN NWs growth. High-density AlN nanopedestal arrays used as seeds for SAG GaN NWs are fabricated from thin AlN seeding layers using soft nanoimprint lithography. By adjusting the growth temperature and Ga/N flux ratio, hexagonal shaped SAG GaN NWs are realized. The quality of SAG GaN NWs is evaluated by low temperature photoluminescence (PL) measurements. Three major groups of PL peaks at 3.47, 3.45, and 3.41 eV are identified. The peak at 3.471 eV is related to the neutral donor-bound exciton emission, and the 3.41 eV broadband emission is attributed to stacking faults or structural defects. The 3.45 eV peak is identified as the emission due to exciton recombination at polar inversion domain boundaries of NWs.

Electron beam induced current microscopy investigation of GaN nanowire arrays grown on Si substrates
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Materials Science in Semiconductor Processing  http://dx.doi.org/10.1016/j.mssp.2016.03.002

We report on the electron beam induced current (EBIC) investigation of GaN nanowires grown on n-
doped Si (111) substrates. The objective of this study is to acquire information about the modifications of the substrate properties induced by the wire growth. We show that the growth procedure using deposition of an ultra-thin AlN layer prior to the nanowire growth step leads to the formation of a p-n junction in the Si substrate with a high surface conductivity. The induced p-n junction exhibits a photoresponse over the spectral range from 360 nm to 1100 nm. The properties of the induced p-n junction are investigated on the cross section and in a top view configuration with EBIC microscopy. For a localized contact of the GaN nanowires, the collection range in Si extends over a few millimeters. The treatment of the surface using reactive ion etching with a CHF3 plasma leads to the inhibition of the surface conductivity and to the appearance of an S-shape in the current-voltage characteristics under illumination. The conversion efficiency of the plasma-treated sample under AM1.5G solar spectrum is estimated to be in the 2.1–2.7% range.

**Chemical composition fluctuations and strain relaxation in InGaN nanowires: The role of the metal/nitrogen flux ratio**

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The chemical composition fluctuations of InGaN nanowires are studied by a combination of Energy Dispersive X-ray spectroscopy and photoluminescence spectroscopy. It is demonstrated that these fluctuations are linked to the elastic strain relaxation mechanism affecting InGaN sections grown on GaN nanowires. It is further shown that the elastic strain relaxation mechanism depends itself on the growth conditions, in particular on the effective metal/active nitrogen flux ratio. As a consequence of the presence of chemical composition fluctuations, wide photoluminescence spectra are observed, associated with a marked carrier localization.

**Analysis of incubation times for the self-induced formation of GaN nanowires: influence of the substrate on the nucleation mechanism**

M. Sobanska et al.

Crystal Growth Design
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Surprisingly long incubation times for the self-induced formation of GaN nanowires on different substrates can reach hundreds of minutes and remain a mystery in GaN crystal growth. Herein, we examine the incubation times of GaN islands that subsequently give rise to nanowires on amorphous AlxOy/Si and SiNx/Si substrates versus the temperature and gallium flux. Experimental data are obtained by in-situ monitoring of the surface morphology by reflection high energy electron diffraction during plasma-assisted molecular beam epitaxy. We develop a model that confirms an inverse power-law dependence of the incubation time on the gallium flux and the Arrhenius-type temperature dependence. The power exponent and the activation energy are related to the nucleation mechanism and the island growth regime. We find the values, = 6.0 eV for AlxOy and, = 10.6 eV for SiNx buffer. The dominant nucleation mechanism on amorphous AlxOy should be heterogeneous. Homogeneous nucleation dominates on SiNx, while the diffusion growth regime of GaN islands occurs in both cases. Overall, the long incubation times are attributed to extremely low effective diffusion lengths of gallium adatoms such that the squared diffusion length times the gallium bonding rate ranges from 10-4 to 1 nm2 in typical cases.

**Synthesis of hybrid nanowires comprising uniaxial and coaxial InGaN/GaN MQWs with a nano-cap**

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We propose a novel hybrid nanostructure which comprises both uniaxial and coaxial multi-
quantum wells (MQWs) on nanowires topped with an InGaN nano-cap. The growth process included both top-down and bottom-up approaches followed by the intentional growth of an InGaN nano-cap to offer larger active area. The In composition was optimized to absorb light at green and blue wavelengths by the uniaxial and coaxial quantum wells respectively. Extensive structural and optical characterizations were carried out. Field emission scanning electron microscopy (FE-SEM) revealed a high density of nanowires. High resolution transmission electron microscopy (HR-TEM) images displayed 5 pairs of uniaxial multi-quantum wells, 6 pairs of coaxial multi-quantum wells and the existence of the intended nano-caps. A photoluminescence (PL) spectrum was recorded for the grown structure at room temperature. The resultant emission spectrum comprised two distinct peaks resulting from each of the multi-quantum well assemblies and emission from the nano-cap. Cathodoluminescence (CL) mapping data revealed discrete bright field images of the InGaN nano-caps and uniaxial multi-quantum well structures. Emission peaks for the nano-caps and both of the multi-quantum well structures were observed in the CL point spectrum which in turn corroborated the PL measurement. During an energy-dispersive X-ray (EDX) study, a high composition of In was found in the nano-cap area along with the distinct presence of both types of multi-quantum wells. In addition, to investigate the opto-electronic device applicability of the grown MQW structure, the photocurrent was measured at various light intensities. The photocurrent density was observed to increase linearly with the increasing light power density. Also the photocurrent density was found to be higher for the hybrid structure than a single uniaxial or coaxial assembly.

Metalorganic chemical vapor deposition of GaN nanowires: From catalyst-assisted to catalyst-free growth, and from self-assembled to selective-area growth
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Materials Science in Semiconductor Processing
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With the increasing attention dedicated to GaN nanowires for the realization of advanced optoelectronic devices, important efforts have been devoted to the nanowire growth optimization. This review covers the developments achieved so far in the growth of GaN nanowires by Metal Organic Chemical Vapor Deposition. Different approaches are discussed, including growth with and without catalyst, self-assembled growth as well as selective-area growth; their respective advantages and limits are detailed.

NON/SEMI POLAR
Information selected by
Philippe De Mierry (CRHEA-CNRS)

Radiative recombination mechanisms in polar and non-polar InGaN/GaN quantum well LED structures
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We study the photoluminescence internal quantum efficiency (IQE) and recombination dynamics in a pair of polar and non-polar InGaN/GaN quantum well (QW) light-emitting diode (LED) structures as a function of excess carrier density and temperature. In the polar LED at 293 K, the variation of radiative and non-radiative lifetimes is well described by a modified ABC type model which accounts for the background carrier concentration in the QWs due to unintentional doping. As the temperature is reduced, the sensitivity of the radiative lifetime to excess carrier density becomes progressively weaker. We attribute this behaviour to the reduced mobility of the localised electrons and holes at low temperatures, resulting in a more monomolecular like radiative process. Thus we propose that in polar QWs, the degree of carrier localisation determines the sensitivity of the radiative lifetime to the excess carrier density. In the non-polar LED, the radiative lifetime is independent of excitation density at room temperature, consistent with a wholly excitonic recombination mechanism. These findings have
significance for the interpretation of LED efficiency data within the context of the ABC recombination model.

**Role of substrate quality on the performance of semipolar (112̅2)(112̅2) InGaN light-emitting diodes**

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We compare the optical properties and device performance of unpackaged InGaN/GaN multiple-quantum-well light-emitting diodes (LEDs) emitting at ~430 nm grown simultaneously on a high-cost small-size bulk semipolar (112̅2112̅2) GaN substrate (Bulk-GaN) and a low-cost large-size (112̅2112̅2) GaN template created on patterned (101̅2101̅2) r-plane sapphire substrate (PSS-GaN). The Bulk-GaN substrate has the threading dislocation density (TDD) of ~105 cm−2–10^6 cm−2 and basal-plane stacking fault (BSF) density of 0 cm−1, while the PSS-GaN substrate has the TDD of ~2 × 10^8 cm−2 and BSF density of ~1 × 10^3 cm−1. Despite an enhanced light extraction efficiency, the LED grown on PSS-GaN has two-times lower internal quantum efficiency than the LED grown on Bulk-GaN as determined by photoluminescence measurements. The LED grown on PSS-GaN substrate also has about two-times lower output power compared to the LED grown on Bulk-GaN substrate. This lower output power was attributed to the higher TDD and BSF density.

**Control of GaN facet structures through Eu doping toward achieving semipolar {11̅01}{11̅01} and {22̅01}{22̅01} InGaN/GaN quantum wells**

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We have grown Eu-doped GaN on striped GaN facet structures with {11̅01}{11̅01} faces using a selective-area-growth technique. It was found that the orientation of the Eu-doped GaN facets depends on the Eu doping conditions. Semipolar {nn̅01}{nn̅01} (n = 2, 3) facets, which are difficult to form using conventional undoped GaN, can be obtained by changing the growth temperature and the amount of the supplied Eu precursor. InGaN/GaN multiple quantum wells (MQWs) were also fabricated on the Eu-doped semipolar facets, and their structural and luminescence properties were investigated. The MQWs fabricated on the Eu-doped semipolar {22̅01}{22̅01} facets have a photoluminescence decay time of 112–314 ps, which is 10 times shorter than those of conventional (0001) QWs. These results show that the Eu doping of GaN is a promising means of obtaining various semipolar facets, which can contribute to improve the radiative recombination probability.

**Effect of SiO2 hexagonal pattern on the crystal and optical properties of epitaxial lateral overgrown semipolar (11-22) GaN film**

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We studied the optical and crystal properties of semipolar (11-22) hexagonal epitaxial lateral overgrown (HELO) GaN films with different SiO2 hexagonal pattern widths (6–15 μm). With increasing SiO2 hexagonal pattern width, it was difficult to achieve coalescence and planarization of the semipolar HELO-GaN film. Furthermore, the surface root mean square roughness of the semipolar (11-22) HELO-GaN film increased with the increasing SiO2 hexagonal pattern width. The increasing SiO2 hexagonal pattern width, the full width at half maximum (FWHM) of the X-ray rocking curve (XRC) toward [1-100] decreased from 1474 to 721 arcsec, but the FWHM of XRCs toward [11-2-3] decreased to 9 μm, and then, increased with the SiO2 pattern width (> 12 μm). However, the PL intensity of the semipolar HELO-GaN film increased with the SiO2 hexagonal pattern width.
pattern width. From the findings of this study, we believe that the optical and crystal properties of the semipolar (11-22) HELO-GaN film would be significantly affected by the SiO2 hexagonal pattern width because of the friction between the GaN and SiO2 pattern during the coalescence and planarization step.

**Improved crystal quality of semipolar (10-13) GaN on Si(001) substrates using AlN/GaN superlattice interlayer**

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Journal of Crystal Growth

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The planar epitaxial growth of semipolar (10View the MathML source3) GaN on a Si(001) substrate was performed on a directionally sputtered AlN buffer layer. Three types of interlayers, i.e., single AlN, double AlN, and a stack of AlN/GaN layers were grown by metalorganic chemical vapor deposition (MOCVD) to achieve high quality GaN films. The results for the stack of AlN/GaN layers provide highest crystal quality and optical properties for GaN. Comparing the top (Ga face) and bottom (N face) surfaces of grown semipolar (10View the MathML source3) GaN confirms the defect density reduction that is due to the application of interlayers. Moreover, reduced inversion domain density on the bottom surface is attributed with the insertion of interlayers. Improving the quality of semipolar GaN on Si(001) substrates is expected to be useful for GaN/Si(001) integrated optoelectronics.

**Defect blocking via laterally induced growth of semipolar (1 0 -1 1) GaN on patterned substrates**

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Journal of Physics D: Applied Physics

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Semipolar (1 0 -1 1) GaN thin films with state-of-the-art optical and structural quality have been obtained on silicon substrates by metal organic chemical vapor deposition using a novel defect reduction method. We initially apply a classical patterning approach on Si (0 0 1) 7° off substrates to reveal the Si (1 1 1) facets over which the subsequent inclined epitaxy will be carried out. After the growth of AlN, the sample is etched with SF6 before the GaN growth is done on the same structure. The process has shown to induce the spontaneous formation of a defect blocking layer that substantially reduces the presence of threading dislocations and basal stacking faults. This is confirmed by correlated optical and structural characterizations. Further, a simple model explaining the origin and working-principle of the blocking layer will be discussed.

**An atomistic mechanism study of GaN step-flow growth in vicinal m-plane orientations**

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Elucidation of homoepitaxial growth mechanisms on vicinal non-polar surfaces of GaN is highly important for gaining an understanding of and control thin film surface morphology and properties. Using first-principles calculations, we study the step-flow growth in m-plane GaN based on atomic row nucleation and kink propagation kinetics. Ga–N dimer adsorption onto the m-plane is energetically more favorable than that of Ga and N isolated adatoms. Therefore, we have treated the dimers as the dominant growth species attached to the step edges. By calculating the free energies of sequentially attached Ga–N dimers, we have elucidated that the a-step edge kink growth proceeds by parallel attachment rather than by across the step edge approach. We found a series of favorable configurations of kink propagation and calculated the free energy and nucleation barriers for kink evolution on five types of step edges (a, +c, −c, +a + c, and −a − c). By changing the chemical potential μGa and the
excess chemical potential $\Delta \mu$, the growth velocities at the five types of edges are controlled by the corresponding kink pair nucleation barrier $E^*$ in their free energy profiles. To explore the kink-flow growth instability observed at different Ga/N flux ratios, calculations of kink pairs on the incompact $-c$ and $+c$-step edges are further performed to study their formation energies. Variations of these step edge morphologies with a tuned chemical environment are consistent with previous experimental observations, including stable diagonal $\pm a \pm c$-direction steps. Our work provides a first-principles approach to explore step growth and surface morphology of the vicinal m-plane GaN, which is applicable to analyze and control the step-flow growth of other binary thin films.

**First-principles identification of defect levels in Er-doped GaN**

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Physica status solidi (RRL) - Rapid Research Letters http://dx.doi.org/10.1002/pssr.201600273

Erbium (Er) doped GaN has been studied extensively for optoelectronic applications, yet its defect physics is still not well understood. In this work, we report a first-principles hybrid density functional study of the structure, energetics, and thermodynamic transition levels of Er-related defect complexes in GaN. We discover for the first time that ErGa–C–VN, a defect complex of Er, a C impurity, and an N vacancy, and ErGa–O–VN, a complex of Er, an O impurity, and an N vacancy, form defect levels at 0.18 eV and 0.46 eV below the conduction band, respectively. Together with ErGa–VN, a complex of Er and an N vacancy which has recently been found to produce a donor level at 0.61 eV, these defect complexes provide explanation for the Er-related defect levels observed in experiments. The role of these defects in optical excitation of the luminescent Er center is also discussed.

**Electric field dependence of optical phonon frequencies in wurtzite GaN observed in GaN high electron mobility transistors**

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Due to the high dissipated power densities in gallium nitride (GaN) high electron mobility transistors (HEMTs), temperature measurement techniques with high spatial resolution, such as micro-Raman thermography, are critical for ensuring device reliability. However, accurately determining the temperature rise in the ON state of a transistor from shifts in the Raman peak positions requires careful decoupling of the simultaneous effects of temperature, stress, strain, and electric field on the optical phonon frequencies. Although it is well-known that the vertical electric field in the GaN epilayers can shift the Raman peak positions through the strain and/or stress induced by the inverse piezoelectric (IPE) effect, previous studies have not shown quantitative agreement between the strain and/or stress components derived from micro-Raman measurements and those predicted by electro-mechanical models. We attribute this discrepancy to the fact that previous studies have not considered the impact of the electric field on the optical phonon frequencies of wurtzite GaN apart from the IPE effect, which results from changes in the crystal coordinates within the crystal basis and in the electronic configuration. Using density functional theory, we calculated the zone center $E_2$ (high), $A_1$ (LO), and $E_2$ (low) modes to shift by $-1.39\, \text{cm}^{-1}/(\text{MV/cm})$, $2.16\, \text{cm}^{-1}/(\text{MV/cm})$, and $-0.36\, \text{cm}^{-1}/(\text{MV/cm})$, respectively, due to an electric field component along the $cc$-axis, which are an order of magnitude larger than the shifts associated with the IPE effect. Then, we measured changes in the $E_2$ (high) and $A_1$ (LO) Raman peak positions with
≈1 μm spatial resolution in GaN HEMTs biased in the pinched OFF state and showed good agreement between the strain, stress, and electric field components derived from the measurements and our 3D electro-mechanical model. This study helps to explain the reason the pinched OFF state is a suitable reference for removing the contributions of the electric field and the IPE-induced stress from the temperature rise in the ON state and suggests that the IPE-induced stress in the GaN buffer is an order of magnitude smaller than previously believed. Our analysis and experimental results support previous theoretical studies discussing the electric field dependence of optical phonon frequencies apart from the IPE effect and suggest that this is a general phenomenon occurring in all wurtzite and zincblende crystals. The total electric field dependence of the optical phonon frequencies in piezoelectric crystals is a critical consideration in accurately characterizing the stress, strain, electric field, and temperature distributions in microelectronic devices via micro-Raman spectroscopy.

Surface photovoltage studies of p-type AlGaN layers after reactive-ion etching
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The surface photovoltage (SPV) technique was used to study the surface and electrical properties of Mg-doped, p-type AlxGa1–xN (0.06 < x < 0.17) layers. SPV measurements reveal significant deviation from previous SPV studies on p-GaN:Mg thin films and from the predictions of a thermionic model for the SPV behavior. In particular, the SPV of the p-AlGa:N:Mg layers exhibited slower-than-expected transients under ultraviolet illumination and delayed restoration to the initial dark value. The slow transients and delayed restorations can be attributed to a defective surface region which interferes with normal thermionic processes. The top 45 nm of the p-AlGa:N:Mg layer was etched using a reactive-ion etch which caused the SPV behavior to be substantially different. From this study, it can be concluded that a defective, near-surface region is inhibiting the change in positive surface charge by allowing tunneling or hopping conductivity of holes from the bulk to the surface, or by the trapping of electrons traveling to the surface by a high concentration of defects in the near-surface region. Etching removes the defective layer and reveals a region of presumably higher quality, as evidenced by substantial changes in the SPV behavior.

Photocapacitance spectroscopy of InAIN nearly lattice-matched to GaN
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http://dx.doi.org/10.1063/1.4964466

We study the deep levels in InAIN nearly lattice-matched to GaN by photocapacitance spectroscopy. This technique allows the study of very deep levels having too slow thermal emission rates to be detected by other deep level spectroscopy techniques. We will identify a broad band of deep levels centered 1.7 eV below the InAIN conduction band edge. The deep level band is characterized by a negligible Franck-Condon shift and by a broadening parameter ΔE = 0.38 eV. Furthermore, we will show evidences for a second class of deep levels with optical ionization energy >2 eV, which will be attributed to previously reported oxygen-related DX centers.

Thermal resistance optimization of GaN/substrate stacks considering thermal boundary resistance and temperature-dependent thermal conductivity
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Here, we investigate the effects of thermal boundary resistance (TBR) and temperature-dependent thermal conductivity on the thermal resistance of GaN/substrate stacks. A combination of parameters such as substrates (diamond,
silicon carbide, silicon, and sapphire), thermal boundary resistance (10–60 m2K/GW), heat source lengths (10 nm–20 μm), and power dissipation levels (1–8 W) are studied by using technology computer-aided design (TCAD) software Synopsys. Among diamond, silicon carbide, silicon, and sapphire substrates, the diamond provides the lowest thermal resistance due to its superior thermal conductivity. We report that due to non-zero thermal boundary resistance and localized heating in GaN-based high electron mobility transistors, an optimum separation between the heat source and substrate exists. For high power (i.e., 8 W) heat dissipation on high thermal conductive substrates (i.e., diamond), the optimum separation between the heat source and substrate becomes submicron thick (i.e., 500 nm), which reduces the hotspot temperature as much as 50 °C compared to conventional multi-micron thick case (i.e., 4 μm). This is attributed to the thermal conductivity drop in GaN near the heat source. Improving the TBR between GaN and diamond increases temperature reduction by our further approach. Overall, we provide thermal management design guidelines for GaN-based devices.

A combined growth process for state-of-the-art GaN on silicon
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Physica status solidi (a)
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This study aims to simplify the heteroepitaxy of GaN on Si while keeping state-of-the-art III-nitride materials. The originality of this work is to combine the advantages of both NH3-MBE and metal organic chemical vapor deposition (MOCVD) growth techniques. First, the structural quality of AlN is assessed by AFM, XRD measurements, and TEM. Terraces and atomic step edges are observed by AFM showing a good structural quality of the AlN epilayer. TEM investigation reveals a sharp and well-controlled AlN/Si using NH3-MBE. Then, a 2-μm thick smooth GaN layers are obtained by MOCVD on top of these AlN templates with the use of a SiNx treatment allowing a 3D growth mode able to induce an efficient dislocation filtering to be obtained. GaN structural properties, measured by XRD, AFM, and SEM, are discussed and compared to GaN-on sapphire (Al2O3). In addition, the stress in the GaN layers grown on these AlN templates with or without a SiNx treatment is assessed. GaN epilayers with a dislocation density in the range of few 108 dislocations per cm2 have been achieved using a single AlN buffer layer (no interlayer) and only 2 μm of GaN.

Origin of unintentional gallium incorporation into AlN spacer layer grown by metalorganic vapor phase epitaxy
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Physica status solidi (b)
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This article presents the origin of unintentional gallium (Ga) incorporation into AlN spacer layers grown by metalorganic vapor phase epitaxy (MOVPE). We systematically investigated the impacts on the growth layer caused by the reactor inner walls condition, under-layer compositions and growth temperature. The Ga incorporation is not influenced by the GaN deposits on the inner walls of the reactor, but is strongly affected by the underlying GaN layer. We found that the AlN spacer layer incorporates Ga atoms that originate from the underlying GaN layer, and the amount of Ga incorporation decreases with decreasing growth temperature. We conclude that the dominant source of unintentional Ga incorporation into an AlN spacer layer is the underlying GaN layer. Furthermore, we successfully achieved a Ga composition below 0.05, almost without unintentional Ga incorporation, by growing the AlN layers at a low temperature of 805 °C.

Carbon nanotube assisted Lift off of GaN layers on sapphire
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State Key Laboratory for Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China
Laser lift off (LLO) was one of the most essential processes in fabrication of vertical GaN-based LEDs. However, traditional laser lift off of GaN on sapphire substrates needed high laser energy threshold, which deteriorated the GaN crystal. In this paper, it was found that inserting carbon nanotube between GaN and sapphire could effectively reduce the laser energy threshold in GaN LLO, from 1.5 J/cm² of conventional GaN/sapphire to 1.3 J/cm² of CNT inserted GaN/sapphire. The temperature distributions at the GaN/sapphire interfaces with and without CNTs were simulated by the finite elements calculation under laser irradiation. It was found that, due to the higher laser absorption coefficient of CNT, the CNT played as a powerful heating wire, sending out the thermal outside to elevate the GaN's temperature, and thus reduce the laser threshold for LLO. Raman and photoluminescence measurements indicated that residual stress of GaN membranes was as small as 0.3 GPa by the carbon nanotube assisted LLO. This work not only opens new application of CNTs, but also demonstrates the potential of high performance blue and green LEDs.

Germanium doping of GaN by metalorganic chemical vapor deposition for polarization screening applications
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Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA
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We demonstrate n-type doping of GaN with Ge by MOCVD at high concentrations that are necessary to fully screen the polarization fields in c-plane InGaN/GaN quantum wells. Hall measurements show linear Ge incorporation with dopant flow rate and carrier concentrations exceeding 1×10²⁰ cm⁻³. GaN:Ge layers exhibit excellent electron mobility, high conductivity, and contact resistivity comparable to the best unannealed contacts to Si-doped GaN. However, the surface morphology begins to degrade with Ge concentrations above 1×10¹⁹ cm⁻³, resulting in severe step bunching and a network of plateaus and trenches, even in layers as thin as 10 nm.

HVPE homoepitaxial growth of high quality bulk GaN using acid wet etching method and its mechanism analysis
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Sino Nitride Semiconductor CO., LTD, Dongguan 523500, PR China

In this paper, crack-free 2-inch bulk GaN wafer with the thickness up to 3 mm was obtained by HVPE homoepitaxy. A new method of acid wet etching was used to pre-treat GaN substrate before re-growth. The formation of the mesh-like subsurface crack and interface layer were found to be suppressed between the re-growth layer and as-grown GaN substrate. EDS and time varied contact angle measurement proved that chemical etching would decrease the oxygen related surface adsorption and increase atoms diffusion length during HVPE homoepitaxial growth. Moreover, Morphology, Low temperature photoluminescence measurements indicated a reduction in stress of wet etching treated as-grown GaN substrate due to etching effect on its N face. High quality bulk GaN with the dislocation density of 1×10⁶ cm⁻² was achieved by using wet etching and HVPE multiple re-growth. It would offer a simple method to obtain bulk GaN with thicker layer and high quality.
High indium content homogenous InAlN layers grown by plasma-assisted molecular beam epitaxy
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Journal of Crystal Growth
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InAlN grown by plasma-assisted molecular beam epitaxy often contains a honeycomb microstructure. The honeycomb microstructure consists of 5–10 nm diameter aluminum-rich regions which are surrounded by indium-rich regions. Layers without this microstructure were previously developed for nominally lattice-matched InAlN and have been developed here for higher indium content InAlN. In this study, InAlN was grown in a nitrogen-rich environment with high indium to aluminum flux ratios at low growth temperatures. Samples were characterized by high-resolution x-ray diffraction, atomic force microscopy, high-angle annular dark-field scanning transmission electron microscopy, and atom probe tomography. Atomic force microscopy showed InAlN layers grown at temperatures below 450 °C under nitrogen-rich conditions were free of droplets. InAlN films with indium contents up to 81% were grown at temperatures between 410 and 440 °C. High-angle annular dark-field scanning transmission electron microscopy and atom probe tomography showed no evidence of honeycomb microstructure for samples with indium contents of 34% and 62%. These layers are homogeneous and follow a random alloy distribution. A growth diagram for InAlN of all indium contents is reported.

Control of Crystal Morphologies and Interface Structures of AlN Grown on Sapphire by Elementary Source Vapor Phase Epitaxy
Department of Electronic Science and Engineering, Kyoto University, Kyoto 615-8510, Japan

Crystal Growth Design
http://dx.doi.org/10.1021/acs.cgd.6b00979

Elementary source vapor phase epitaxy is an environmentally friendly method for producing AlN from Al metal and N2 gas. Here, we demonstrate that crystalline whiskers and films can be grown by adjusting the growth conditions. Appropriately designing the growth procedure can realize self-separation of AlN films from sapphire and spontaneous, nanometer-scale lateral overgrowth for quality improvement.

Interface phonon modes in the [AIN/GaN]20 and [Al0.35Ga0.65N/Al0.55Ga0.45N]20 2D multi-quantum well structures
Nanomaterials and Sensors Section, Surface and Nanoscience Division, Indira Gandhi Centre for Atomic Research, Homi Bhabha National Institute, Kalpakkam–603102, India

http://dx.doi.org/10.1039/C6CP05520F

The observation of interface (IF) phonon modes in the recorded Raman spectra of c-plane oriented [AIN/GaN]20 and [Al0.35Ga0.65N/Al0.55Ga0.45N]20 multi-quantum well (MQW) structures grown via plasma assisted molecular beam epitaxy is reported. The nominal shift in the IF phonon mode of E1 symmetry for [Al0.35Ga0.65N/Al0.55Ga0.45N]20 compared to that of the [AIN/GaN]20 MQW structure is understood on the basis of change in dielectric constants (εm) of the surrounding medium. The presence of buffer layers in [Al0.35Ga0.65N/Al0.55Ga0.45N]20 MQW over a sapphire substrate is also understood by characterizing the IF phonon mode of A1 symmetry. The observed IF phonon modes in the spectra are attributed to the relaxation of Raman selection rules away from the Brillouin zone centre because of the breakdown of the translational symmetry of surface potential due to the presence of the periodic interfaces and surface modulations in the superlattice structures of MQWs. The corresponding required edge lengths (L) of 2D plates, for the observation of the breakdown of the surface potential, are computed from the simulated dispersion relation curve of IF modes. The integral multiples of uniformly distributed platelets, originated due to the horizontal uneven irregularities on the surface of superlattices, are matched with the calculated L values.
Stretching magnetism with an electric field in a nitride semiconductor
Institute of Physics, Polish Academy of Sciences, aleja Lotników 32/46, PL 02-668 Warszawa, Poland

Nature Communications
http://dx.doi.org/10.1038/ncomms13232

The significant inversion symmetry breaking specific to wurtzite semiconductors, and the associated spontaneous electrical polarization, lead to outstanding features such as high density of carriers at the GaN/(Al,Ga)N interface—exploited in high-power/high-frequency electronics—and piezoelectric capabilities serving for nanodrives, sensors and energy harvesting devices. Here we show that the multifunctionality of nitride semiconductors encompasses also a magnetoelectric effect allowing to control the magnetization by an electric field. We first demonstrate that doping of GaN by Mn results in a semi-insulating material apt to sustain electric fields as high as 5 MV cm$^{-1}$. Having such a material we find experimentally that the inverse piezoelectric effect controls the magnitude of the single-ion magnetic anisotropy specific to Mn$^{3+}$ ions in GaN. The corresponding changes in the magnetization can be quantitatively described by a theory developed here.

Large-roll growth of 25-inch hexagonal BN monolayer film for self-release buffer layer of free-standing GaN wafer
Fujian Key Laboratory of Semiconductor Materials and Applications, CI center for OSED, College of Physical Science and Technology, Xiamen University, Xiamen 361005, China

Scientific Reports
http://dx.doi.org/10.1038/srep34766
Hexagonal boron nitride (h-BN) is known as promising 2D material with a wide band-gap (~6 eV). However, the growth size of h-BN film is strongly limited by the size of reaction chamber. Here, we demonstrate the large-roll synthesis of monolayer and controllable sub-monolayer h-BN film on wound Cu foil by low pressure chemical vapor deposition (LPCVD) method. By winding the Cu foil substrate into mainspring shape supported by a multi-prong quartz fork, the reactor size limit could be overcome by extending the substrate area to a continuous 2D curl of plane inward. An extremely large-size monolayer h-BN film has been achieved over 25 inches in a 1.2” tube. The optical band gap of h-BN monolayer was determined to be 6.0 eV. The h-BN film was uniformly transferred onto 2” GaN or 4” Si wafer surfaces as a release buffer layer. By HVPE method, overgrowth of thick GaN wafer over 200 μm has been achieved free of residual strain, which could provide high quality homo-epitaxial substrate.
**PRESS RELEASE**

*Technical and economic information selected by Knowmade*

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## OPTOELECTRONICS

**COB LED market for lighting applications to grow at 4% CAGR from $580m in 2016 to over $700m in 2021**

*Semiconductor Today*

The global market for chip-on-board (COB) LEDs used in lighting applications – including COB products belonging to ceramic and EMC packages - will rise at a compound annual growth rate (CAGR) of about 4% from $580m in 2016 to more than $700m in 2021, according to the '2016-2021 Global LED Industry Demand and Supply Database Report' by LEDinside (a division of TrendForce).

[Read more](#)

**Epistar to quadruple CSP LED chip capacity in early 2017**

*Semiconductor Today*

In view of fast-growing demand for chip-scale package (CSP) LED chips used in TV backlighting, Epistar Corp of Hsinchu Science-based Industrial Park, Taiwan (the world's largest manufacturer of LED epiwafers and chips) will expand production capacity four-fold in early 2017, according to Taiwan's Digitimes.

While CSP LED chips were adopted for direct-type LED-backlit LCD TVs, the adoption in edge-type backlit LCD TVs came much later due to technological problems, Epistar says. These problems have been solved, and demand for CSP LED chips has taken off, the firm adds. Monthly shipments of CSP LED chips have increased from 5 million units in early 2016 to 230 million units, and Epistar claims to have a global market share of 30%.

In addition, Epistar has been developing quantum dot (QD)-on-chip technology through combing CSP LED chips with QD technology. Epistar expects QD-on-chip technology to be adopted for backlighting in 60-70” LCD TVs beginning 2017.

[Read more](#)

**DOE announces 2017 solid-state lighting R&D funding opportunity**

*Semiconductor Today*

The US Department of Energy (DOE) has announced the funding opportunity DE-FOA-0001613, 'Solid-State Lighting Advanced Technology R&D—2017'), in which a total of up to $10m is directed toward all three existing DOE SSL R&D program areas:

- **Core Technology Research** — applied research aiming to demonstrate scientific principles, technical application, and application benefits, and encompassing scientific efforts that focus on new knowledge or understanding of the subject under study, with specific application to SSL;
- **Product Development** — the development of commercially viable, state-of-the-art SSL materials, devices, or luminaires using concepts from basic and applied research;
- **US Manufacturing** — research to develop advanced manufacturing approaches to reduce the cost of SSL sources and luminaires and improve product consistency and quality, with the additional benefit of supporting the development of US-based manufacturing.

The DOE will select up to 10 projects. Concept papers are due by 14 November, and full applications are due by 10 January 2017.

The National Energy Technology Laboratory will hold an informational webinar on the FOA on 25 October (1pm Eastern Time).

[Read more](#)
Advanced UV for Life exhibits custom-tailored UV LED developments at micro photonics fair

Semiconductor Today

In hall 7.2 c, booth 207, at the micro photonics 2016 International Congress & Expo in Berlin, Germany (11–13 October), the consortium Advanced UV for Life is presenting a selection of current developments.

In the interdisciplinary consortium, 37 scientific institutions and industrial companies with expertise along the entire value chain of ultraviolet light-emitting diode (UV LED) technology - from development to applications - have partnered to promote the technological development, availability and use of UV LEDs. Funded by Germany's Federal Ministry of Education and Science (BMBF) the program 'Twenty20 - Partnership for Innovation', Advanced UV for Life is managed by the Ferdinand-Braun-Institut (FBH) and addresses customized solutions in application fields including medicine, environment & life sciences, water treatment, and production.

Read more

FBH introduces diode lasers & UV LED developments at micro photonics expo

Semiconductor Today

In hall 7.2C, booth 207, at the micro photonics 2016 International Congress & Expo in Berlin, Germany (11-13 October), Berlin-based Ferdinand-Braun-Institut (FBH) is presenting novel developments of its diode lasers and UV light-emitting diodes (LEDs). Also, in the conference, Martin Maiwald is presenting the capability of mobile SERDS technology using FBH's compact handheld probe with implemented dual-wavelength laser.

FBH develops diode lasers and LEDs from the chip through to the final module, and increasingly advances these devices up to the operational system. Customers and partners can hence test their developments in the respective application. FBH's customized diode lasers open up a variety of applications, from material analytics, sensors, and display technology to materials processing. Similarly, UV LEDs (focusing on the UV-B and UV-C spectral range) can be adjusted flexibly to the requirements. Applications cover medical diagnostics and fluorescence spectroscopy as well as surface treatment and disinfection.

Read more

Plessey launches beam-forming LED module using Stellar optical technology

Semiconductor Today

UK-based LED maker Plessey has announced the first standard LED module based on its Stellar beam-forming technology. The new standard module is said to open up opportunities for creativity in industrial and architectural lighting design.

Plessey's Orion PLWS3000 series is an LED array module delivering more than 3000 lumens, integrating LED and optics into a module just 5.6mm thick and 82mm in diameter. Alternative solutions typically require optics that are usually 100mm deep and 111mm in diameter for a comparable light output and beam. Plessey says that it has achieved this size and performance by combining its Stellar beam-forming optics and gallium nitride on silicon (GaN-on-Si) LED technology. Plessey expects applications of the module to be in the design of track, retail, architectural, high-intensity, spot and directional lighting, and especially architectural applications.

Plessey's new Orion series of LED modules include optics is just 5.6mm thick, allowing control of light for greater design freedom.

Read more

Epistar licenses LED filament patents to Super Trend

Semiconductor Today

Epistar Corp of Hsinchu Science-based Industrial Park, Taiwan (the world's largest manufacturer of LED epiwafers and chips) has signed a license
agreement for its filament patents to be used in the products of Super Trend Lighting (Group) Ltd.

Epistar holds key intellectual property regarding the LED filament technology used in making LED filament bulbs. The patents relate to, among other things, LED filament structures, and light-emitting products using LED filaments. The patent portfolio covers Taiwan, China, USA, Europe and other territories.

Super Trend is the existing licensee with the right to manufacture products covered by Epistar’s LED filament patents. Epistar says that it will continue to update its licensee list. Read more

BluGlass announces institutional placement and shareholder share purchase plan
BluGlass Ltd of Silverwater, Australia – which was spun off from the III-nitride department of Macquarie University in 2005 to develop a low-temperature process using remote plasma chemical vapor deposition (RPCVD) to grow materials including gallium nitride (GaN) and indium gallium nitride (InGaN) on glass substrates – has received commitments from both existing investors and new institutional investors for a placement of new fully paid ordinary shares to raise AUS$5m.

BluGlass proposes to issue 15.625 million shares at AUS$0.32 per share when the placement is settled, which is expected to occur within the next five business days. The issue price of AUS$0.32 per share represents a discount of 18.36% to the 5 day VWAP (volume weighted average price) share price to 27 October of AUS$0.392 per share. Read more

Nichia files white LED patent infringement lawsuit against HTC Nippon and its distributor Kanematsu
On 18 October, Nichia Corp of Tokushima, Japan filed a patent infringement lawsuit with the Tokyo District Court against Taiwan-based smartphone vendor HTC’s Japanese subsidiary HTC Nippon Corp and its distributor Kanematsu Communications Ltd alleging that the white LEDs in the HTC Desire 626 smartphone sold in Japan incorporate white LED that infringe on Nichia’s patents JP5177317 and JP5610056.

Nichia is seeking an injunction to indemnify the patent infringement as well as compensation for damages. Neither HTC nor HTC Nippon has yet responded to the accusation. Read more

BluGlass and Lumileds move to Phase II of evaluation agreement after completing Phase I
BluGlass Ltd of Silverwater, Australia – which was spun off from the III-nitride department of Macquarie University in 2005 to develop a low-temperature process using remote plasma chemical vapor deposition (RPCVD) to grow materials including gallium nitride (GaN) and indium gallium nitride (InGaN) on glass substrates – has completed the technology demonstration outlined in Phase I of the exclusive evaluation agreement (announced in March) with LED maker Lumileds of San Jose, CA, USA.

The Phase I demonstration of BluGlass’ unique low-temperature RPCVD technology involved delivering technical milestones previously unachieved by RPCVD. “The successful demonstration of these milestones has broken exciting new ground for the RPCVD technology development,” says chief technology officer Dr Ian Mann. “These initial demonstrations indicate that the novel implementation of RPCVD we are working on with Lumileds has certain advantages over the standard MOCVD process.”

BluGlass is commercializing RPCVD for the LED and power electronics industries. The firm has developed patented hardware and processes targeting the production of more efficient semiconductor devices at lower cost. BluGlass entered into its Phase I Evaluation with industry leader, Lumileds this year. Read more
Plessey launches single-chip high-power 7070 LEDs
Semiconductor Today

UK-based lighting and sensing product and component maker Plessey has launched its 7070 high-power LED range (PLW7070GA.).

The PLW7070 products take advantage of Plessey’s MaGIC (Manufactured on GaN-on-Si I/C) technology and provide a high-power LED component in an industry standard package footprint, complementing Plessey’s existing family of i2LED high-power products. Using its proprietary gallium nitride on silicon (GaN-on-Si) high-voltage technology, Plessey says that it has been able to use a single LED die to improve thermal performance, improve far-field imaging and dramatically reduce cost over incumbent solutions.

Read more

Electronics

EPC giving IEEE Power Electronics Society webinar on ‘Getting the Most from GaN Transistor and IC Chip-scale Packaging’
Semiconductor Today

Sponsored by the IEEE Power Electronics Society (PELS), on 3 November (11am to 12pm EDT) experts on the design and use of gallium nitride transistors at Efficient Power Conversion Corp (EPC) of El Segundo, CA, USA – which makes enhancement-mode gallium nitride on silicon (eGaN) power field-effect transistors (FETs) for power management applications – will conduct a one-hour webinar ‘Getting the Most from GaN Transistor and IC Chip-scale Packaging’.

Since GaN transistors and integrated circuits are significantly faster and smaller than silicon predecessors, this has enabled many new applications such as envelope tracking, LiDAR, wireless energy transfer, and enhanced medical imaging. The webinar will discuss the design and PCB manufacturing methods users need to maximize the speed and size advantages required for embracing the chip-scale package.

GaN power devices industry: fast and furious
Yole Développement

Driven by emerging applications including power supplies for data-centers and telecoms – AC fast charger – Lidar – ET – and wireless power, the GaN power device market is rising at a compound annual growth rate (CAGR) of 86% to $280m in 2021, according to the report ‘Power GaN 2016: Epitaxy and Devices, Applications and Technology Trends’ Yole Développement.

The presenters CEO & co-founder Alex Lidow and VP of applications engineering Michael de Rooij are both widely published, including being co-authors of ‘GaN Transistors for Efficient Power Conversion’, the first textbook on the design and applications of gallium nitride transistors.

Read more

Advantech Wireless receives new orders for GaN-based 250W Ku-band SSPAs
Semiconductor Today

Advantech Wireless Inc of Montreal, Canada (which manufactures satellite, RF equipment and microwave systems) has received new orders in excess of US$1m for its second-generation gallium nitride (GaN)-based 250W Ku-band solid-state power amplifier (SSPA).

Designed specifically for size- and weight-limited applications, with very low energy consumption and high reliability, the new generation of GaN-based SSPAs is suitable for the broadcast industry, as well as emergency response government services.

Read more
“Numerous powerful developments and key collaborations have been announced during this period and confirmed a promising and fast-growing industry,” comments Dr Hong Lin, technology & market analyst at Yole.

Integrated Device Technology (IDT) and Efficient Power Conversion (EPC) – Infineon Technologies and Panasonic – Exagan and XFab – TSMC and GaN Systems for volume production and much more... all collaborations took place within only 2 years, between 2015 and 2016. In parallel, Texas Instruments announced a 80V power stage in 2015 and a 600V power stage in 2016. Also, VisIC announced its first GaN product in 2015. Since then, 2015-2016 have been exciting years for the GaN power business: after many ups and downs, 600V GaN is now commercially available.

**GaN Systems presenting GaN HEMT workshop at China Power Supply Society Conference**

At the 24th China Power Supply Society Conference (CPSSC) in Shanghai, China, in a three-hour seminar on 31 October, GaN Systems Inc of Ottawa, Ontario, Canada - a fabless developer of gallium nitride (GaN)-based power switching semiconductors for power conversion and control applications - is presenting the advanced technology session 'GaN E-HEMT Devices, Principles and Applications' as part of a program that introduces the most current power semiconductor devices.

Global applications engineering manager Di Chen will present the seminar to an audience consisting of several hundred researchers and engineers. Topics covered include new wide-bandgap semiconductor technology, and an in-depth analysis of the structure, characteristic parameters, device selection and protection of high-frequency switching devices used for efficient power application problems. The agenda for Chen's workshop is as follows:

- A basic introduction to GaN E-HEMT power transistors;
  - GaN E-HEMT principles and package design;
  - GaN E-HEMT technology and reliability;
- Driver & component selection;
- PCB layout and thermal considerations;
- GaN E-HEMT applications.

GaN Systems says that it continues to invest heavily in supporting its Asian customers by providing in-country staff, technical support and resources. This is extended by providing practical technology workshops. The firm says that it is bringing design knowledge to power system engineers, enabling them to rapidly develop the most efficient and competitive products that leverage the performance benefits of GaN.

“More and more customers in China are developing leading-edge power electronics,” notes Charles Baillie, director of GaN Systems' Asian operations. “Using GaN, they have been gaining a competitive edge across the industrial, consumer, transportation, and data-center server markets,” he adds. “This workshop gives engineers the tools to understand and use GaN transistors so they can meet their customers’ power saving demands.”

**Oxford Instruments develops SiC via etch for GaN-on-SiC RF device manufacture**

UK-based process equipment maker Oxford Instruments has announced the development and launch of a silicon carbide (SiC) via plasma etch process using its PlasmaPro100 Polaris etch system.

**Picture: SEM showing smooth via etch through SiC.**
SiC is becoming an increasingly important material, particularly for gallium nitride (GaN) RF devices using SiC as a substrate. A smooth via etch through the SiC is essential to enable these devices. Oxford Instruments says that it has developed a solution for etching high-quality SiC vias efficiently. Combined with a low-damage GaN etch within the same hardware, the PlasmaPro100 Polaris offers what is claimed to be a unique capability for GaN-based RF device plasma etch processing requirements.

Read more

Mentor Graphics joins Wide Band Gap integration power electronics consortium in Japan

Electronic hardware and software design and manufacturing solutions provider Mentor Graphics Corp of Wilsonville, OR, USA has joined the Wide Band Gap integration (WBGi) power electronics consortium to participate in thermal management and power cycling initiatives.

Established in 2013 by professors Katsuaki Suganuma and Tsuyoshi Fuaki of Osaka University in Japan, the WBGi Consortium assembles academics and industrialists worldwide to leverage the possibilities of wide-bandgap semiconductors materials such as silicon carbide (SiC) and gallium arsenide (GaN) - which enable devices to operate at much higher voltages, frequencies and temperatures than conventional silicon materials - and the associated challenges.

Read more

Qorvo launches compact GaN L- and S-band power amplifiers for advanced radar systems

Qorvo Inc of Greensboro, NC and Hillsboro, OR, USA (which provides core technologies and RF solutions for mobile, infrastructure and defense applications) has launched two new power amplifiers (PAs) including what is claimed to be the first 500W, L-band PA internally matched to 50 ohms. The high-power devices are optimized for use in defense and civilian radar systems, with features designed to shorten and simplify system implementation.

Built on Qorvo's gallium nitride (GaN) technology, the new QPD1003 meets the performance needs of high-power phased arrays such as active electronic scanned array (AESA) radars, which operate in the 1.2-1.4GHz frequency range. These systems require PAs that operate at maximum efficiency, resulting in low heat generation in demanding environmental conditions. The QPD1003 addresses these requirements through the use of highly efficient GaN on silicon carbide (SiC) technology.

Read more

Qorvo launches new family of 0.15μm GaN-on-SiC die transistors

Qorvo Inc, a provider of core technologies and RF solutions for mobile, infrastructure and aerospace/defense applications, has launched a family of gallium nitride (GaN) die transistors with the higher-frequency performance and low noise essential for advanced applications in communications, radar and defense RF systems.

The family includes six new GaN transistors manufactured using Qorvo’s QGaN15 0.15μm GaN on silicon carbide (SiC) process and its associated models. The QGaN15 process enables these transistors to offer high-frequency operation of up to 25GHz, supporting die-level designs that deliver higher-frequency, cost-effective discrete technology up through K-band applications.

Read more

Raytheon wins MDA contract modification to transition AN/TPY-2 radar production from GaAs to GaN

The US Missile Defense Agency has awarded Raytheon Company of Waltham, MA, USA a contract modification to develop a transition to production process to incorporate gallium nitride (GaN) components into existing and future AN/TPY-2 radars. This initial effort will support the transition from gallium arsenide (GaAs) to GaN technology, which would further modernize the ballistic missile defense radar and drive down system obsolescence.
As demonstrated in other Raytheon-developed military radar applications, GaN has the capability to enhance range, increase detection and discrimination performance and lower production costs.

Currently fielded AN/TPY-2 radars use GaAs-based transmit/receive modules to emit high-power radiation. Raytheon and the MDA are pursuing a retrofit approach to leverage GaN elements.

Read more

GaN Systems co-founder & CTO to deliver WiPDA 2016 keynote address showcasing GaN's value to automotive market

GaN Systems Inc of Ottawa, Ontario, Canada, a fabless developer of gallium nitride (GaN)-based power switching semiconductors for power conversion and control applications, says that co-founder & chief technology officer John Roberts will deliver the keynote address at the 4th IEEE Power Electronics Society Workshop on Wide Bandgap Power Devices and Applications (WiPDA 2016) at The Chancellor Hotel in Fayetteville, AR, USA (7-9 November).

The presentation 'GaN Power Transistors – Powering Up' (to an audience of device scientists, circuit designers, and application engineers) will focus on the existing state of high-current GaN power transistors and will discuss how GaN Systems’ 100V and 650V GaN transistors are positioned to meet automotive power systems requirements.

Roberts has been a champion of gallium nitride technology for over a decade. Over that period, he has spearheaded the research, development, manufacturing and large-scale production of GaN devices that are now being designed into power systems across the consumer, data-center, industrial, transportation and energy markets. Roberts will share his perspective on where power design engineers are using GaN transistors to solve power management challenges. He will also present examples where GaN transistors have been used to make systems more efficient, smaller, lighter and less costly.

Read more

JIIPlus and EPC partner on GaN-based wireless charging designs

To address the Taiwan wireless power standards organization's announcement of adopting AirFuel Alliance's resonant wireless charging standard, Taiwan-based JIIPlus Corp (which designs and manufactures industrial-grade and high-power WiFi solutions) and Efficient Power Conversion Corp (EPC) of El Segundo, CA, USA – which makes enhancement-mode gallium nitride on silicon (eGaN) power field-effect transistors (FETs) for power management applications – are collaborating to design and implement GaN-based wireless power solutions. In addition to the Taiwan initiative, the designs will have application for wireless charging systems worldwide.

The AirFuel Alliance, a global consortium focused on enabling and accelerating the adoption of wireless power technology, recently signed a Letter of Intent with the Taiwan Association of Information and Communication Standards (TAICS) to establish a wireless charging ecosystem in Taiwan through the introduction of AirFuel's resonant technology standard.

Read more

Tektronix launches Keithley S540 power semiconductor test system targeting SiC and GaN devices up to 3kV

Test, measurement and monitoring equipment supplier Tektronix Inc of Beaverton, OR, USA has introduced the Keithley S540 Power Semiconductor Test System, a fully automated, 48-pin parametric test system for wafer-level testing of power semiconductor devices and structures up to 3kV. Optimized for use with compound power semiconductor materials including silicon carbide (SiC) and gallium nitride (GaN), the fully integrated S540 can perform all high-voltage, low-voltage, and capacitance tests in a single probe touch-down.

As demand for power semiconductor devices continues to increase and as SiC and GaN become more commercialized, manufacturers are adopting wafer-level testing in their production processes to optimize yields and improve
profitability, says Tektronix. For these applications, the S540 lowers cost of ownership by minimizing test time, test set-up time and floor space while achieving lab-grade high-voltage measurement performance, it adds.

Read more

AFRL and OSD award Raytheon $14.9m Title III contract to enhance GaN process technology
Semiconductor Today
The US Air Force Research Laboratory (AFRL) and the Office of the Secretary of Defense (OSD) have awarded Raytheon Company of Waltham, MA, USA a $14.9m Title III contract to further enhance its process for producing gallium nitride (GaN)-based semiconductors. The new agreement follows a previous GaN Title III contract, completed in 2013, and aims to increase the performance, yield and reliability of Raytheon GaN-based, wideband, monolithic microwave integrated circuits (MMICs) and circulator components.

As GaN can efficiently amplify high-power radio frequency signals at microwave frequencies (enhancing a system’s range and raid handling, while reducing size, weight, power and cost), it is used in a broad spectrum of military radars and defense systems, including the US Navy’s Air and Missile Defense Radar (AMDR) and Next Generation Jammer (NGJ).

Read more

EPC presenting user-friendly GaN-based multi-mode wireless charging solution at Wireless Power Summit
Semiconductor Today
Efficient Power Conversion Corp (EPC) of El Segundo, CA, USA – which makes enhancement-mode gallium nitride on silicon (eGaN) power field-effect transistors (FETs) for power management applications – says that, on 10 November at the Wireless Power Summit 2016 in Seattle, WA, USA, its vice president of applications engineering Dr Michael de Rooij is presenting a multi-mode wireless power charging solution that works with either of the two wireless charging standards – Qi or Airfuel.

“The 8th annual Wireless Power Summit will focus on business strategies and technology developments in this rapidly changing field, with a focus on how wireless power has evolved to higher-power applications including laptops, tools and vehicles,” say the conference organizers. Also giving presentations are leaders from major companies engaged in the development of wireless power products, such as Dell, Hewlett-Packard, Bosch and Witricity.

Read more

Navitas' CEO presenting AllGaN power ICs at WiPDA 2016
Semiconductor Today
At the IEEE Power Electronics Society 4th IEEE Workshop on Wide Bandgap Power Devices and Applications (WiPDA) at The Chancellor Hotel, Fayetteville, AR, USA (7–9 November), Navitas Semiconductor Inc of El Segundo, CA, USA says that, in a keynote 'Speed Drives Performance' (at 9am on 9 November), its CEO Gene Sheridan is presenting the advantages of what it claims are the first gallium nitride (GaN) power ICs, which use the firm's proprietary 'AllGaN' technology. A technical paper '650V AllGaN Power IC for Power Supply Applications' (1068) is being presented later the same day by VP of IC design Marco Giandalia.

WiPDA provides a forum for device scientists, circuit designers and application engineers from the Power Electronics and Electron Devices Societies to share technology updates, research findings, development experience and potential applications.

Read more

US District Court grants MACOM preliminary injunction against Infineon on GaN-on-Si rights
Semiconductor Today
MACOM Technology Solutions Holdings Inc of Lowell, MA, USA (which makes semiconductors, components and subassemblies for analog RF, microwave, millimeter-wave and photonic applications) says that the US District Court for the Central District of California in Los Angeles has granted its request for a preliminary injunction in its lawsuit against Infineon Technologies Americas
Corporation (MACOM) over gallium nitride on silicon (GaN-on-Si) technology rights.

The court's decision on 31 October (i) confirmed MACOM's continuing exclusive rights in certain GaN-on-Si RF fields under a 2010 license agreement between Nitronex LLC of Durham, NC, USA (acquired by MACOM for $26m in February 2014) and International Rectifier (acquired by Infineon in 2015); (ii) ruled that MACOM is likely to succeed in its claim that Infineon's purported termination of that agreement was improper and without effect; and (iii) granted MACOM's motion for a preliminary injunction prohibiting Infineon from engaging in activities inconsistent with the 2010 license agreement pending the court's final decision in the case.

When MACOM initiated the legal action in April, it alleged that Infineon had attempted to interfere with and usurp MACOM's rights under certain agreements between Nitronex and International Rectifier. “Nitronex and IR, and later, MACOM and IR, successfully collaborated for many years. Problems developed only after Infineon acquired IR and began to try to 'renegotiate' the Nitronex-IR agreements to reduce MACOM's rights,” said MACOM's president & CEO John Croteau. “When MACOM declined to accede to Infineon's demands, Infineon concocted claims to interfere with our rights under the agreements,” he alleged. “Infineon's behavior is clear validation that MACOM's GaN technology – the product of 15 years and over $100m in investment – is at the tipping point of market adoption, threatening large incumbents like Infineon,” continued Croteau. “This has caused Infineon to engage in strong-arm tactics designed to retard, rather than accelerate, innovation,” he concluded.

MACOM's suit against Infineon includes claims for breach of contract, breach of the covenant of good faith and fair dealing, declaratory judgment of contractual rights, and intentional interference with contract. Among other relief, MACOM asked the court to grant it declaratory and injunctive relief confirming its rights under the Nitronex-IR agreements and ordering Infineon to assign to MACOM several Nitronex GaN patents.

“We were forced to file this lawsuit to stand up to Infineon's bullying and anticompetitive behavior,” states Croteau now. “We are gratified by the court's preliminary decision confirming that the GaN-on-Si rights granted to us under the 2010 license agreement remain in full force and effect and that Infineon acted improperly in trying to operate in our exclusive field of use,” he adds. “We are firmly committed to vigorously litigating this case to its rightful conclusion. We continue on the path to providing GaN-on-Si technology that promises to improve network data service and cell coverage of 4G/LTE and 5G base-stations.”

Read more

Galium demand to grow at 6% annually to 420t in 2020

Semiconductor Today

The market for gallium in semiconductor/semi-insulating applications is set to rise at 6% annually to about 420 tons in 2020 as general illumination shifts away from incandescent-filament and fluorescent lamps to light-emitting diodes, according to the report ‘Galium: Global Market Trends and Prospects’ from Merchant Research & Consulting Ltd.

In particular, the usage of gallium in LEDs for general lighting is set to grow at 16% per year. Meanwhile, the usage of gallium in integrated circuits is projected to remain most prominent, but to drop to 43% of the total. Consumption in LEDs for backlighting applications is unlikely to see robust growth due to the increased technical effectiveness of LEDs.

Despite the overall growth, the gallium market sees continuing oversupply. Between 2010 and 2013 Chinese capacity for production of primary gallium increased threefold in anticipation of surging demand for gallium nitride (GaN) LEDs for backlighting of liquid-crystal display (LCD) panels used in tablets, cell phones and TVs. The worldwide transition to LED general lighting over the next five years is poised to restore some
balance to the gallium marketplace, but supply will likely remain more than adequate.

Japan is poised to take the lead in gallium consumption, although its market share will fall from 47% in 2014 to just over 40% in 2020, forecasts the report. Meanwhile, due largely to the increased usage in lighting, China’s share is likely to surge to 35%.

**Read more**

**Picosun providing production-scale AlN batch process, targeting power electronics applications**

*Semiconductor Today*

Atomic layer deposition (ALD) thin-film technology firm Picosun Oy of Espoo, Finland says that it is now providing customers with production-scale aluminum nitride (AlN) batch process with what is claimed to be superior film thickness uniformity (within-wafer 1σ non-uniformity of 0.9 %) and high speed (throughput for 10nm of 1300 wafers per day).

Compatibility with III-V semiconductors makes AlN an excellent material for power electronics, says Picosun, and in mobile communications technology it is used in the production of several key components such as RF filters and microphones.

**Read more**

**Veeeco’s MOCVD sales double as display backlighting demand stabilizes and LED industry recovers**

*Semiconductor Today*

For third-quarter 2016, epitaxial deposition and process equipment maker Veeeco Instruments Inc of Plainview, NY, USA has reported revenue of $85.5m, down 39% on $140.7m a year ago but up 13% on $75.3m last quarter and slightly above the $70-85m guidance.

By region, the Americas comprised 22% of total revenue and Europe, Middle East & Africa (EMEA) 23%, while China fell from 44% last quarter to 25% as the rest of the world (including Southeast Asia and Japan) rose to 30%, driven by strong sales of metal-organic chemical vapor deposition (MOCVD) systems.

The Lighting, Display & Power Electronics segment – primarily MOCVD – has rebounded further, from 33% of total revenue last quarter to 58%, with revenue doubling quarter-on-quarter. “We are seeing a clear improvement in LED industry conditions and solid demand for our MOCVD products,” says chairman & CEO John R. Peeler. “We continue to win LED lighting and display opportunities with our TurboDisc EPIK700 MOCVD system and expand our positions in red, orange and yellow LEDs with our TurboDisc K475i arsenic phosphide (As/P) system,” he adds. “We were able to support customers’ accelerated shipment requests for a couple of MOCVD systems by effectively utilizing existing inventory,” says chief financial officer Sam Maheshwari.

The Advanced Packaging, MEMS & RF segment comprised 14% of revenue, falling further from 23% last quarter. However, although sales in Advanced Packaging are down on last quarter, year-to-date sales have already exceeded those of full-year 2015. “We have broadened our PSP [Precision Surface Processing] customer engagements in Advanced Packaging, and are now working with multiple OSATs [outsourced semiconductor assembly & test providers] and IDMs [integrated device manufacturers] to further penetrate this market,” notes Maheshwari.

Veeeco’s Foundational Businesses fell from $34m (44% of revenue) last quarter to $24m (28% of revenue), with the Scientific & Industrial segment falling from 26% last quarter to 16% and the Data Storage segment falling from 18% to 12%.

**Read more**
More than 160 new patented inventions were published between 2016-10-02 and 2016-11-01.

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<thead>
<tr>
<th>Patent Applicants</th>
<th>Number of new patent applications</th>
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<tbody>
<tr>
<td>Xiamen Changelight</td>
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<td>China Bright Photoelectricity</td>
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Distribution of new patent applications by country of publication (October 2016)

![Chart showing the distribution of new patent applications by country of publication. China has the highest number of applications with 88, followed by the USA with 44, and other countries with varying numbers.](image-url)
New patent applications selected by Knowmade

**Method for manufacturing flexible GaN LED**
Publication Number: KR20160122340
Patent Applicant: ULSAN National Institute of Science and Technology (Korea)

Following this invention nitrification gallium light-emitting diode manufacturing method (a) [hyeng] nitrification gallium lamella and nitrification gallium lamella to sapphire layer as for under evaporation phase. To form the lower part electrode to (b) nitrification gallium lamella, to the lower part electrode the copper petal as for under plating phase. From (c) sapphire layer Laser lift - through off public law pn junction nitrification gallium thin film as for under separating phase; (d) to the pn junction nitrification gallium thin film which separates photoresist and the trench etching mask about under using trench etching pattern as for under producing phase. As (e) trench etching patterns the phase which does the trench etching to the pn junction nitrification gallium thin film which separates; (f) to the pn junction nitrification gallium thin film which separates photoresist and photolithography process about under using the upper electrode and upper electrode pattern as for under attachment forming phase. And (g) from the nitrification gallium light-emitting diode which is produced with the pn junction nitrification gallium thin film which separates photoresist as for under removing phase. About under including, following strain the output electric current and electronic radiation efficient rise are possible, and following bending the energy band uses the actual condition bending with the electronic will be able to rise the reunion rate of frontal attack there is an effect.

**Read more**

**Method of integrating inorganic light emitting diode with oxide thin film transistor for display applications**
Publication Number: US2016293586
Patent Applicant: eMagin (USA)

A method of fabricating an active matrix display is disclosed in which one or more oxide thin film transistors is monolithically integrated with an inorganic light emitting diode structure. The method comprises forming an array of inorganic light emitting diodes over a substrate defining a plurality of sub-pixels, depositing an insulating layer over the inorganic LED array, forming conductive vias through the insulating layer, one via for each LED in the LED array, and forming a metal oxide thin film transistor backplane, including an array of pixel driver circuits, over the dielectric layer and conductive vias, wherein one driver circuit electrically controls each sub-pixel through the dielectric layer.

**Read more**
UV light emitting device and lighting system
Publication Number: KR20160120085
Patent Applicant: LG Innotek (Korea)

Following conduct example as for the ultraviolet luminous element first defiant style second semiconductor layer (the second defiant style fourth semiconductor layer which to under 112); minute description first defiant style second semiconductor layer (112) is arranged (the active layer which to between 116); minute description first defiant style second semiconductor layer (112) and second defiant style fourth semiconductor layer (116) is arranged (of 114); minute description second defiant style fourth semiconductor layer (116) from the bottom with minute description second defiant style fourth semiconductor layer (116) about under penetrating the minute description active layer (114) part of minute description first defiant style second semiconductor layer (112) as for under exposing the hall of multiple (H). From the bottom of minute description second defiant style fourth semiconductor layer (116) through the hall (H) of minute description multiple the first contact electrode which to minute description first defiant style second semiconductor layer (112) is connected electrically (with 160); minute description first contact electrode (160) the insulation layer which to between the hall (H) of minute description multiple is arranged (with 140); minute description first contact electrode (160) the first defiant style 3rd semiconductor layer which to between minute description first defiant style second semiconductor layer (112) is arranged (will be able to include 113).

Nano vacuum gap device with a gate-all-around cathode
Publication Number: US2016307722, WO2016168376
Patent Applicant: HRL Laboratories (USA)

A semiconductor power handling device, includes a cathode pillar, a gate surrounding the cathode pillar, and an anode spaced from the cathode by a nano-vacuum gap. An array of semiconductor power handling devices, each comprises a cathode pillar, a gate surrounding the cathode pillar, and an anode spaced from the cathode pillar by a nano-vacuum gap. The semiconductor power handling devices can be arranged as rows and columns and can be interconnected to meet the requirements of various applications. The array of power handling devices can be fabricated on a single substrate.

Method for fabricating suspended mems structures
Publication Number: US2016304340, WO2016167853, WO2016167848
Patent Applicant: US Navy (USA)

A process for fabricating a suspended microelectromechanical system (MEMS) structure comprising epitaxial semiconductor
functional layers that are partially or completely suspended over a substrate. A sacrificial release layer and a functional device layer are formed on a substrate. The functional device layer is etched to form windows in the functional device layer defining an outline of a suspended MEMS device to be formed from the functional device layer. The sacrificial release layer is then etched with a selective release etchant to remove the sacrificial release layer underneath the functional layer in the area defined by the windows to form the suspended MEMS structure. Read more

**Semiconductor structure and etch technique**

for monolithic integration of III-N transistors

Publication Number: US2016300835

Patent Applicant: Cambridge Electronics (USA)

Semiconductor structures are disclosed for monolithically integrating multiple III-N transistors with different threshold voltages on a common substrate. A semiconductor structure includes a cap layer comprising a plurality of selectively etchable sublayers, wherein each sublayer is selectively etchable with respect to the sublayer immediately below, wherein each sublayer comprises a material AlxInyGazN (0 ≤ x, y, z ≤ 1), and wherein at least one selectively etchable sublayer has a non-zero Ga content (0<z≤1). A gate recess is disposed in a number of adjacent sublayers of the cap layer to achieve a desired threshold voltage for a transistor. Also described are methods for fabricating such semiconductor structures, where gate recesses and/or ohmic recesses are formed by selectively removing adjacent sublayers of the cap layer. The performance of the resulting integrated circuits is improved, while providing design flexibility to reduce production cost and circuit footprint. Read more

**Integrated semiconductor device**

Publication Number: US2016293597, DE102016106314, CN106057800

Patent Applicant: Infineon Technologies (Austria)

A semiconductor device includes a first semiconductor device, a second semiconductor device, and a third semiconductor device. The first semiconductor device and the second semiconductor device are integrated to form a half-bridge. The third semiconductor device is a normally-off semiconductor device that is arranged in series with the half-bridge. Read more

**Compound semiconductor device including a multilevel carrier**

Publication Number: US2016293543, DE102015104995, CN106024773

Patent Applicant: Infineon Technologies (Austria)
A device includes a carrier having a first carrier section on a first level and a second carrier section on a second level different from the first level. The device further includes a compound semiconductor chip arranged over the first carrier section and a control semiconductor chip arranged over the second carrier section. The control semiconductor chip is configured to control the compound semiconductor chip. An encapsulation material covers the compound semiconductor chip and the control semiconductor chip.

Read more