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Gain Spectroscopy of HVPE-Grown GaN

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We report on photoluminescence and optical gain measurements of highly excited GaN crystals grown by hydride vapor phase epitaxy (HVPE). Inelastic scattering processes of excitons dominate the spontaneous emission spectrum under high excitation up to temperatures of 180 K. Towards room temperature phonon-assisted recombination of excitons and free carriers begins to dominate the spectrum. Similar characteristics are observed in temperature-dependent gain measurements.

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Interfacial Reactions and Electrical Properties of Ti/n-GaN Contacts

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The phase equilibria in the ternary Ti-Ga-N have been investigated. Interfacial reactions in Ti/GaN contacts have been studied by diffusion couple experiments. The ternary phase Ti_2GaN was confirmed by x-ray diffraction in bulk samples as well as in massive Ti/GaN diffusion couples and annealed Ti thin films on GaN. The diffusion path in samples, annealed at 850°C in Ar gas, is GaN/TiN/Ti_2GaN/Ti_3Ga/Ti. A planar TiN layer forms in direct contact to GaN and governs the electrical properties of annealed Ti/GaN contacts. Thin film contacts were fabricated by sputtering Ti on MOVPE grown *n*-GaN (5×10^{17}cm^{-3}) and subsequent rapid thermal annealing in an Argon atmosphere. Initially non-linear current-voltage characteristics become ohmic after annealing and a specific contact resistance of approximately 10^{-2} Wcm^2, measured with the circular transmission line method, was found after annealing at 9000°C for 1 min.

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Temperature-Composition Dependence of the Bandgap and Possible Noncomplanar Structures in GaN-AlN, GaN-InN and InN-AlN Mixed Crystals

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The virtual crystal approximation has been used to determine the temperature-composition dependence of the GaN-AlN, GaN-InN, and InN-AlN bandgap energies. Also, the thermodynamic instability states in the mixed crystals were studied. The expression for the bandgap of mixed A-B crystals has been derived: $E_g^{AB} = (1-x)E_g^A + xE_g^B - bS_{xx}$, where E_g^A and E_g^B are the direct gaps for compounds A and B, respectively, and x is the alloy concentration. The term $S_{xx} \sim T_0/(\partial^2 G/\partial x^2)$ where G is the thermodynamic potential of the mixed crystal, b is a bowing parameter, and T_0 has the meaning of a growth temperature.

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Improved Optical Activation of Ion-Implanted Zn Acceptors in GaN by Annealing Under N_2 Overpressure

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We investigated the properties of ion-implanted GaN:Zn annealed under various conditions using photoluminescence (PL) and high resolution x-ray diffraction (HRXRD). Epitaxial GaN/sapphire of high optical quality was ion-implanted with a 10^{13} cm^{-2} dose of Zn$^+$ ions at 200 keV. The sample was capped with 200 Å of SiN_x and then diced into numerous pieces which were annealed under varied conditions in an attempt to optically activate the Zn. Annealing was performed in a tube furnace under flowing N_2, an atmospheric pressure MOCVD reactor under flowing NH_3 or N_2, and under an N_2 overpressure of 190 atm. The observed improvement in the optical quality of GaN:Zn annealed under N_2 overpressure yields further insights into the trade-off between defect annealing and N loss from the GaN crystal.

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Characteristics of Room Temperature-CW Operated InGaN Multi-Quantum-Well-Structure Laser Diodes

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The continuous-wave (CW) operation of InGaN multi-quantum-well-structure laser diodes (LDs) was demonstrated at room temperature (RT) with a lifetime of 35 hours. The threshold current and the voltage of the LDs were 80 mA and 5.5 V, respectively. The threshold current density

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was 3.6 kA/cm^2. When the temperature of the LDs was varied, large mode hopping of the emission wavelength was observed. The carrier lifetime and the threshold carrier density were estimated to be 2–10 ns and $1-2 \times 10^{20}$/cm^3, respectively. From the measurements of gain spectra and an external differential quantum efficiency dependence on the cavity length, the differential gain coefficient, the transparent carrier density, threshold gain and internal loss were estimated to be 5.8×10^{-17} cm^2, 9.3×10^{19} cm^{-3}, 5200 cm^{-1} and 43 cm^{-1}, respectively.

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The Composition Pulling Effect in MOVPE Grown InGaN on GaN and AlGaN and Its TEM Characterization

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InGaN films have been grown on GaN and AlGaN epitaxial layers by metalorganic vapor phase epitaxy. The "composition pulling effect" during the initial InGaN growth stages has been studied as a function of the lattice mismatch between the InGaN and the underlying epitaxial layer. The crystalline quality of the InGaN is good near the InGaN/GaN interface and the composition is close to that of GaN. However, with increasing InGaN film thickness, the crystal quality deteriorates and the indium mole fraction increases. The composition pulling effect becomes stronger with increasing lattice mismatch. It is suggested that indium atoms are excluded from the InGaN lattice during the early growth stages to reduce the deformation energy from the lattice mismatch. TEM observations of the InGaN/GaN structure reveal that the degradation of the crystalline quality of InGaN films grown on GaN is caused by pit formation which arises from edge dislocations propagating through the InGaN film from the underlying GaN.

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Nonuniform Morphology and Luminescence Properties of a Molecular Beam Epitaxy GaN Film from Atomic Force Microscopy, Scanning Electron Microscopy and Cathodoluminescence

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Complex faceted features of micrometer sizes and with intense luminescence rise 200–300 nm above the surface of a GaN thin film grown by molecular beam epitaxy on (0001) sapphire. Cathodoluminescence measurements at room temperature and at 8 K were used to investigate the luminescence properties of these microfeatures in comparison with those of the background GaN material. The morphology of the micro-features was studied by scanning electron microscopy and by atomic force microscopy.

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Surface Morphology and Structure of GaN$_x$As$_{1-x}$

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University of Göteborg and Chalmers University of Technology

GaN$_x$As$_{1-x}$-layers were grown by solid source molecular beam epitaxy using N$_2$ and excitation by RF-plasma source. The average nitrogen concentration, *x*, determined by secondary ion mass spectrometry, ranges from isovalent nitrogen doping in GaAs up to GaN. X-ray diffraction revealed two peaks, close to the ones for GaAs(002) and the GaN(002) diffraction, respectively. The position of both peaks moved slightly as a function of nitrogen content. Scanning electron microscopy indicated a rough surface structure with improved smoothing for low and high nitrogen compositions. The rough surface is partly due to crystallite formation when mixing arsenic and nitrogen as a result of phase separation between the GaAs and GaN. In ternary films with very high nitrogen composition there were structural features with a different contrast. These were crystallites that arose at the interface and grew up to the surface.

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High Quality Al-Ga-In-N Heterostructures Fabricated by MOVPE Growth in Multiwafer Reactors

D. Schmitz, R. Beccard, O. Schoen, R. Niebuhr, B. Wachtendorf, and Holger Juergensen
AIXTRON GmbH

We present results on the growth of Al-Ga-In-N films in multiwafer reactors with 7 × 2 in. wafer capacity. The design of these reactors allows the combination of high efficiency (TMGa efficiency for GaN around 30%) and excellent uniformity. Results on the growth of all materials from the Al-Ga-In-Nitride family are presented in detail. GaN is grown with an excellent optical quality and very good thickness uniformity below 2% across 2 in. wafers. The material quality is shown by electron mobility of more than 500 cm^2/Vs at an intentional Si-doping of approximately 1×10^{17} cm^{-3}. Controlled acceptor doping with Mg yields carrier concentrations between 5×10^{16} and 10^{18} cm^{-3}. The layer thickness uniformity of the films are better than 2% over a 2 in. wafer area. GaInN is grown with PL emission wavelengths in the visible blue region showing a uniformity better than 1.5 nm standard deviation. The film thickness uniformity represents the same figures as obtained for the binary. The compositional uniformity of AlGaN is in the sub 1% range corresponding to a wavelength variation below 1 nm.

The fabrication of heterostructures from these binary and ternary materials is described as well as results from the characterization of these structures. The results show that reliable and efficient production of Al-Ga-In-Nitride-based optoelectronic devices can be performed in multiwafer reactors.

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Photoluminescence Excitation Spectroscopy of GaN Thin Layers as a Function of Temperature

C. Guénaud[1], E. Deleporte[1], M. Voos[1], C. Delalande[1], B. Beaumont[2], M. Leroux[2], Pierre Gibart[2], and J.P. Faurie[2]
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We report on photoluminescence and photoluminescence excitation experiments performed on hexagonal GaN layers grown on a sapphire substrate. Information about extrinsic and intrinsic optical properties have been obtained. We show that, at low temperature, the fundamental A excitons are preferentially involved in the relaxation towards the neutral donor bound exciton photoluminescence line, while electron-hole pairs rather participate in the relaxation towards D^0-A^0 emission and the yellow band. The relaxation from the A exciton towards the yellow band and D^0-A^0 emission is made easier by temperature. The band structure of the GaN layers has been determined from temperature dependent photoluminescence excitation spectroscopy: A and C excitons and A continuum bandgap have been identified up to 210 K.

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Avalanche Breakdown Luminescence of InGaN/AlGaN/GaN Heterostructures

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Luminescence spectra of InGaN/AlGaN/GaN *p-n*-heterostructures were studied at reverse bias sufficient for impact ionization. There is a high electric field in the active InGaN-layer, and the tunnel component of the current dominates at the low reverse bias. Avalanche breakdown begins at $|V_{th}| > 8 \div 10$ V, i.e. $\approx 3\ E_g/e$. Radiation spectra have a short wavelength edge 3.40 eV, and maxima in the range $2.60 \div 2.80$ eV corresponding to the injection spectra. Mechanisms of the hot plasma recombination in *p-n*-heterojunctions are discussed.

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Characterization and Modeling of Photoconductive GaN Ultraviolet Detectors

E. Monroy[1], J.A. Garrido[1], E. Muñoz[1], I. Izpura[1], F.J. Sánchez[1], M.A. Sánchez-García[1], E. Calleja[1], B. Beaumont[2], and Pierre Gibart[2]
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In this work high gain GaN photoconductive uv detectors have been fabricated and characterized, and a novel gain mechanism, dominant in these detectors, is described. DC responsivities higher than 10^3 A/W have been measured for an incident power of 1 W/m^2 at room temperature. The photoconductive gain depends directly on the bias voltage and scales with incident power as P^k ($k \approx 0.9$) for more than five decades. A decrease of both gain and k parameter with temperature has also been observed. As a consequence of the slow non-exponential transient response, AC gain measurements result in lower values for gain and k parameter, which are frequency dependent. The high responsivity, non-linear behavior and slow non-exponential transient response, are all modeled taking into account a modulation mechanism of the layer conductive volume. Such spatial modulation is due to the photovoltaic response of the potential barriers related to the surface and charged dislocations arrays.

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Studies of Mg-GaN Grown by MBE on GaAs(111)B Substrates

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This paper discusses the growth of Mg-doped GaN samples using a modified Molecular Beam Epitaxy (MBE) method. Our results suggest that the dopant is incorporated from a surface population maintained by the incident Mg flux by a rapid diffusion mechanism. It follows that the chemical concentration will increase with time of growth and that the p-doping level will also increase progressively with film thickness for a given Mg flux. Increasing the Mg flux to the surface results at first in a higher doping density, but this saturates when the Mg surface concentration reaches a finite value.

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GaInN/GaN-Heterostructures and Quantum Wells Grown by Metalorganic Vapor-Phase Epitaxy

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The dependence of the In-incorporation efficiency and the optical properties of MOVPE-grown GaInN/GaN-heterostructures on various growth parameters has been investigated. A significant improvement of the In-incorporation rate could be obtained by increasing the growth rate and reducing the H_2-partial pressure in the MOVPE reactor. However, GaInN layers with a high In-content typically show an additional low energy photoluminescence peak, whose distance to the band-edge increases with increasing In-content. For GaInN/GaN quantum wells with an In-content of approximately 12%, an increase of the well thickness is accompanied by a significant line broadening and a large increase of the Stokes shift between the emission peak and the band edge determined by photothermal deflection spectroscopy. With a further increase of the thickness of the GaInN layer, a second GaInN-correlated emission peak emerges. To elucidate the nature of these optical transitions, power-dependent as well as time-resolved photoluminescence measurements have been performed and compared to the results of scanning transmission electron microscopy.

Order No. NS002-014

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Efficient Optical Activation of Ion-Implanted Zn Acceptors in GaN by Annealing Under 10 kbar N_2 Overpressure

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[3]High Pressure Research Center
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We continue our investigations into the optical activation of Zn-implanted GaN annealed under ever higher N_2 overpressure. The samples studied were epitaxial GaN/sapphire layers of good optical quality which were implanted with a 10^{13} cm^{-2} dose of Zn$^+$ ions at 200 keV, diced into equivalent pieces and annealed under 10 kbar of N_2. The N_2 overpressure permitted annealing at temperatures up to 1250°C for 1 hr without GaN decomposition. The blue Zn-related photoluminescence (PL) signal rises sharply with increasing anneal temperature. The Zn-related PL intensity in the implanted sample annealed at 1250°C exceeded that of the epitaxially doped GaN:Zn standard proving that high temperature annealing of GaN under kbar N_2 overpressure can effectively remove implantation damage and efficiently activate implanted dopants in GaN. We propose a lateral LED device which could be fabricated using ion implanted dopants activated by high temperature annealing at high pressure.

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MOVPE Growth Optimization of High Quality InGaN Films

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[2]Thomas Swan & Co., Ltd.

In this paper growth of high quality InGaN films on (0001) sapphire substrates by atmospheric pressure organometallic vapor phase epitaxy in a vertical rotating disk reactor is investigated. The InGaN layers grown above 800°C are transparent and show no In-droplets on the surface. The In-content varies between 56 and 9 % for growth temperatures between 700 and 850°C. The dc x-ray rocking curve of InGaN typically shows a FWHM between 8 and 15 arcmin. Room temperature PL shows an intense band edge emission with a FWHM between 100 and 200 meV for an In-content of 9 and 56%. The initial efforts on QW growth are discussed.

Order No. NS002-016

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High Frequency AlGaN/GaN MODFETs

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Cornell University

Short-gate MODFETs of AlGaN/GaN on sapphire have been fabricated and characterized with gate lengths in the 0.12 - 0.25 µm range. Values of $f_t = 50$ GHz and $f_{max} = 100$ GHz have been obtained. Analyzing the performance, the average electron transit velocity is shown to be 1.25×10^7 cm/s and in some cases well under that value. This compares with theoretical predictions of ~ 2.0×10^7 cm/s. The electron scattering effects of dislocations, which are charged, are modeled to explain the lower mobility. Ion bombardment or dry etching is used for mesa isolation. Ti/Al/Ti/Au sintered for 100 seconds at 800°C is used to yield ohmic contacts of 0.5 – 1.0 Ω-mm. Pt/Au Schottky gates are used. A high breakdown voltage, exceeding 100 V even for short gate MODFETs, shows that ten times higher load resistance values are possible, compared with GaAs MODFETs. Normalized output power levels well over 10 W/mm are thus projected for GaN MODFETs on SiC substrates, where the thermal conductivity is about 5 W/cm-°C. with future integrated traveling-wave, power-combining circuits, output power > 100 W at 10 GHz is predicted.

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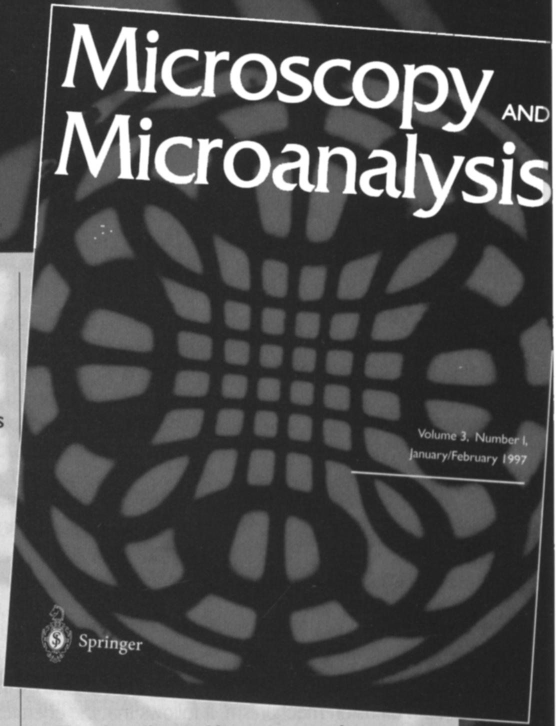

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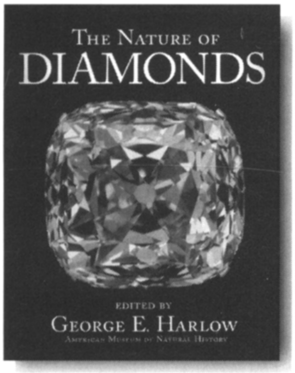

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