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PEMBE-Growth of Gallium Nitride on (0001) Sapphire: A Comparison to MOCVD-Grown GaN

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Thin films of GaN on *c*-plane sapphire were grown by plasma-enhanced molecular beam epitaxy (PEMBE). The influence of different growth conditions on the quality of the epitaxial layers was studied by x-ray diffraction (XRD), atomic force microscopy (AFM), and Hall measurements. For low deposition temperatures, the growth of a thin buffer layer of AlN results in a decrease of the XRD rocking curve full width at half maximum (FWHM) but also in poorer quality in electronic and optical properties. Samples of 3 μm thickness with 570 arcsec FWHM in the XRD rocking curve, a near bandgap PL-emission FWHM at 5 K of 7 meV, charge carrier densities of $n_e = 2 \times 10^{17}$ cm^{-3}, and Hall mobilities of 270 $cm^2/V\,s$ at 300 K were grown without a buffer layer. A comparison of the morphology and XRD rocking curves with those of GaN films deposited by metalorganic chemical vapor deposition (MOCVD) shows that the two methods have different growth mechanisms.

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Growth of Ga-face and N-face GaN Films Using ZnO Substrates

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We have used plasma molecular beam epitaxy on (0001) and (000$\bar{1}$) ZnO substrates to induce epitaxial growth of GaN of a known polarity. The polarity of the ZnO substrates can be easily and unambiguously determined by measuring the sign of the piezoelectric coefficient. If we assume that N-face GaN grows on O-face ZnO and that Ga-face GaN grows on Zn-face ZnO, then we can study the growth of both Ga- and N-faces. The most striking difference is the doping behavior of the two faces. Growth on the Ga-face is characterized by a higher carrier concentration and a lower threshold for Ga droplet formation.

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Alternative N Precursors and Mg Doped GaN Grown by MOVPE

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In this paper, we address two different aspects relevant to the growth of GaN. The first part concerns alternative nitrogen source whereas in the second part, we report experimental results on Mg doping. Several nitrogen precursors have been used for the growth of GaN in MOVPE. To produce active species from N_2 or NH_3, a remote plasma-enhanced chemical vapor deposition (RPECVD) process has been implemented. In addition, nitrogen organic precursors, triethylamine and t-butylamine were also used. To accurately control the critical parameters of the MOVPE of GaN, we have implemented a laser reflectometry, which allows a real time *in situ* monitoring of the different steps of the growth. $MeCp_2Mg$ was used as Mg precursor for the *p* doping study. The dependence on the partial pressure of Mg precursor of dopant incorporation, electrical activity and growth rate are reported.

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GaN *m-i-n* LED Grown by MOVPE

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Undoped and zinc-doped GaN films have been grown using TMGa, DEZn and ammonia by MOVPE. The GaN blue-green LEDs of *m-i-n* structure have been fabricated. They can be operated at forward bias less than 5 volts. The EL peak wavelength was from 455 nm to 504 nm.

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Microstructure, Growth Mechanisms and Electro-Optical Properties of Heteroepitaxial GaN Layers on Sapphire (0001) Substrates

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We investigate the structure, growth morphology and the related electro-optical properties of gallium nitride (GaN) films deposited on (0001) sapphire substrates by gas source molecular beam epitaxy (GSMBE) and use transmission electron microscopy, atomic force microscopy and scanning tunneling microscopy, photoluminescence (PL) and cathodoluminescence (CL). We find two types of specimens: one type which shows a strong UV luminescence (band-to-band transition at 358 nm/3.46 eV) in CL and PL and only faint yellow luminescence (Gaussian shaped CL/PL peaks at around

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528 nm/2.35 eV), specimen "B," and another type, which shows a strong UV and a comparably strong yellow luminescence, specimen "Y." These two types of specimens have a rough layer surface, specimen "Y" even an islanded one with facetted hexagonal islands with a width of 1-2 μm at a height of 50 nm. A correlation of spectrally resolved CL images to the observed defect structure shows: (i) the yellow luminescence is homogeneously distributed over the complete specimen for "B" and "Y" specimens. Our investigations strongly suggest the yellow luminescence to be related to screw dislocations with $\vec{b} = [0001]$, which are found randomly distributed in "B" and "Y" specimens with a high density of 1.3×10^9 cm^{-2}; (ii) the strong UV luminescence in "Y" specimens is located in the troughs between adjacent surface islands, where dislocations essentially in small angle grain boundaries of edge type, i.e., with $\vec{b} = [\bar{1}2\bar{1}0]$ or $\vec{b} = [\bar{1}\bar{1}23]$ are located; (iii) in the case of the "B" specimens these dislocations are randomly distributed and so is the luminescence.
Order No. NS001-019

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Recent Results in the Crystal Growth of GaN at High N_2 Pressure
I. Grzegory, M. Bockowski, B. Lucznik, S. Krukowski, M. Wroblewski, and S. Porowski
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We present recent results on bulk GaN crystallization. The best quality GaN crystals grown from the solution at high N_2 pressure without an intentional seeding are single crystalline platelets of stable morphology reaching dimensions up to 10 mm. The fastest growth direction for such crystals is $[10\bar{1}0]$, perpendicular to the GaN *c*-axis. The maximum stable growth rate perpendicular to crystal *c*-axis is determined from the experiment and used for an estimate of the effective supersaturation for the $\{10\bar{1}0\}$ face assuming two-dimensional layer growth. The heat of GaN disssolution, determined from experimental solubility data, is used for the estimation of the edge energy of 2-D nuclei on the growing $\{10\bar{1}0\}$ face.

Bulk crystal growth seeded by a single hexagonal needle with well-developed $\{10\bar{1}0\}$ faces is also reported. The crystallization mechanisms and morphological stability in seeded growth of GaN are discussed on the basis of experimental results.

The physical properties of the GaN crystals and homoepitaxial layers grown on them are briefly reviewed.
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Epitaxial Growth of Cubic GaN and AlN on Si(001)
A. Barski, U. Rössner, J. L. Rouvière, and M. Arlery
CEA-Grenoble, DRFMC/ SP2M
Thermal treatment under propane at 1300–1400°C has been used to prepare silicon (001) wafers for subsequent growth of cubic GaN and AlN by electron cyclotron resonance plasma assisted molecular beam epitaxy (ECRMBE). Thermal treatment of silicon wafers under propane, used in this experiment, produced a very thin (40 Å) layer of cubic SiC on the silicon (001) surface. Despite an extremely low thickness of as-produced SiC layer, high-quality cubic GaN has been successfully grown. The cubic form of AlN grown on the SiC(40 Å)/Si(001) surface has also been observed despite a very high density of stacking faults.
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Evidence for Shallow Acceptor Levels in MBE Grown GaN
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We report the results of photoluminescence measurements on a number of GaN thin films grown by MBE on GaAs (111)B substrates. In particular, we draw attention to a new observation of a line at approximately 3.40 eV which is accompanied by complex fine structure and interpret it as due to a donor-acceptor (DA) transition. Assuming a donor energy of 30 meV, we derive an acceptor binding energy of approximately 80 meV which is very much smaller than the accepted value of 250 meV for the well-established Mg acceptor. However, our result is in agreement with a recent estimate of the hydrogenic acceptor energy as being 85 meV.
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Raman Determination of the Phonon Deformation Potentials in α-GaN
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Raman spectroscopy is used to study the effect of the built-in biaxial stress on the E2 and A1 (LO) $q = 0$ phonon modes of wurtzite GaN layers deposited by metalorganic vapor phase epitaxy on (0001) sapphire substrate. By means of phonon frequency shifts, the biaxial pressure coefficients of the mode frequencies are determined and used to calculate the corresponding deformation potentials. Stress calibration has been performed using reflectance data.
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The Growth of InGaN/(Al)GaN Quantum Well Structures in a Multi-Wafer High Speed Rotating Disk Reactor
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In the past year, several organizations have fabricated reliable, high-brightness LEDs from III-nitride materials that emit in the blue and green. Recently, Nichia in Japan have announced lasing action in GaN-based diodes. Quantum well structures are key to all these results, offering higher brightness, narrower EL linewidths, and a wider spectral range. In order for the III-nitride technology to develop, the material growth technique must offer high volume at low cost in addition to the requisite device performance. To date, only MOVPE has demonstrated this capability. We have previously reported the growth of GaN, InGaN, and AlGaN layers by MOVPE in a multi-wafer, high-speed rotating disk reactor. Both *n*- and *p*-doping and high quality optical properties have been achieved. In this paper we extend this earlier work and present results of the performance of InGaN/(Al)GaN quantum well structures. Intense PL spectra were observed in the violet and blue regions. The thinnest wells show evidence from PL and DCXRD measurements of either discontinuous layers (islands) or a diffuse upper interface, with preliminary TEM results showing the latter to be the most likely. We also report excellent uniformity of these quantum well structures, and show electroluminescence from a SQW diode emitting at 473 nm.
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Luminescence and Reflectivity of GaN/Sapphire Grown by MOVPE, GSMBE and HVPE
M. Leroux, B. Beaumont, N. Grandjean, Pierre Gibart, J. Massies, and J.P. Faurie
CRHEA-CNRS
This work presents an optical characterization by luminescence and reflectivity of GaN layers grown on sapphire using MOVPE, HVPE and GSMBE. Well-resolved optical spectra are obtained for each growth technique. The luminescence of Mg doped MOVPE grown GaN is also studied. A Mg acceptor optical depth of ~260 meV is obtained.
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