Abstracts of

MRS Internet Journal of Nitride Semiconductor Research

An electronic, peer-reviewed journal published by the Materials Research Society.

http://nsr.mij.mrs.org/ Volume 1, Articles 39–46 MIJ-NSR Abstracts

Editors-in-Chief: S. Strite, Cammy R. Abernathy • Journalmaster: E.S. Hellman
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High-Power High-Temperature Heterobipolar Transistor with Gallium Nitride Emitter

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A new heterobipolar transistor was made with the wide bandgap semiconductors gallium nitride (GaN) and silicon carbide (SiC). The heterojunction allows high injection efficiency, even at elevated temperatures. A record current gain of ten million was obtained at room temperature, decreasing to 100 at 535°C. An Arrhenius plot of current gain vs $1/T$ yields an activation energy of 0.43 eV that corresponds to the valence band barrier blocking the escape of holes from the base to the emitter. This activation energy is approximately equal to the difference of energy gaps between emitter and base. This transistor can operate at high power without cooling. A power density of 30 kw/cm^2 was sustained.

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Determination of the Dislocation Densities in GaN on *c*-Oriented Sapphire

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We report on a comprehensive study of the defect structure in GaN grown on *c*-oriented sapphire by gas source molecular beam epitaxy and metal organic vapor phase epitaxy. Transmission electron microscopy is used to investigate the defect structures which are dominated by threading dislocations perpendicular to the sapphire surface and stacking faults. Additionally, dislocation densities are determined. For determination of dislocation densities by x-ray diffraction we employ a model that uses the linewidth of x-ray rocking curves for this purpose. Finally, Rutherford backscattering spectrometry is performed to complement the structural investigation.

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Metal Contacts on a-GaN

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The Schottky barrier heights of silver and lead contacts on *n*-type GaN (0001) epilayers were determined from current-voltage characteristics. The zero-bias barrier heights and the ideality factors were found to be linearly correlated. Similar observations were previously reported for metal contacts on Si (111) and GaAs (110) surfaces. The barrier heights of ideal Schottky contacts are characterized by image force lowering of the barrier only. This gives an ideality factor of 1.01. From our data we obtain barrier heights of 0.82 eV and 0.73 eV for ideal Ag and Pb contacts on GaN, respectively. The metal-induced gap states (MIGS) model predicts the barrier heights of ideal Schottky contacts on a given semiconductor to be linearly correlated with the electronegativities of the metals. The two important parameters of this MIGS-and-electronegativity model are the charge neutrality level (CNL) of the MIGS and a slope parameter. The CNL may be calculated from the dielectric bandgap and using the empirical tight-binding method. The slope parameters are given by the optical dielectric constant of the respective semiconductor. The predictions of the MIGS model for metal/GaN contacts are confirmed by the results presented here and by barrier heights previously reported by others for Au, Ti, Pt, and Pd contacts on GaN.

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Initial Growth Prismatic Domains in Cyclotron-Assisted MBE of GaN/SiC

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In N-rich growth conditions, prismatic domains were formed in the initial stage of a cyclotron assisted MBE [molecular beam epitaxy] of GaN over 6H-SiC (0001). They exhibit $\{10\bar{1}0\}$ facets and are either voids or amorphous phase. Their density is of a few 10^9 cm^{-2} and they are located in a 50 nm layer closest to the substrate surface.

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https://doi.org/10.1557/S0883769400034047 Published online by Cambridge University Press

http://nsr.mij.mrs.org/1/43/

Growth and Properties of InGaN and AlInGaN Thin Films on (0001) Sapphire

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High quality InGaN films have led to the development of LEDs [light-emitting diodes] and blue lasers. The quaternary AlInGaN, however, represents a more versatile material since the bandgap and lattice constant can be independently varied. We report on such films grown on (0001) sapphire substrates in an atmospheric pressure MOCVD [metalorganic chemical vapor deposition] reactor at 750–800°C. The ternary films have a composition of up to 40% InN and the quaternary films were grown in the composition range of 0 to 20% AlN and 0 to 20% InN. The quaternary compositions studied by EDS [energy dispersive spectroscopy] and the lattice constants from double crystal XRD [x-ray diffraction] followed Vegard's law indicating solid solubility for the range studied. Room temperature PL is dominated by band edge emission for InGaN and AlInGaN, at low AlN%. Higher AlN alloys of AlInGaN had PL dominated by deep levels. AlInGaN/InGaN and AlGaN/InGaN heterostructures were grown with abrupt interfaces. We emphasize the most important growth parameters for the growth of high-quality ternary and quaternary thin films. The structural, electrical, and optical properties of these In-based ternary and quaternary films and their lattice matched and strained heterostructures will also be presented.

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Identification of a Cubic Phase in Epitaxial Layers of Predominantly Hexagonal GaN

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Epitaxial layers of GaN on *c*-plane sapphire are analyzed by continuous-wave and time-resolved photoluminescence at 4 K and by x-ray diffraction. Besides the well-known emissions from hexagonal GaN we observe luminescence bands at 3.279 and 3.15 to 3.21 eV which are identified as the transition of the donor bound exciton and the donor-acceptor pair recombination in cubic GaN, respectively. Measurements of the luminescence decay times are essential for the clarification of the emission processes. Due to the probing depth of about 200 nm in PL we find that the fraction of cubic phase typically decreases with layer thickness. In our best samples, however, we do not detect the cubic phase at all.

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GaN Layers Grown by HVPE on *p*-Type 6H-SiC Substrates

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Gallium nitride films were successfully grown by HVPE technique on *p*-type 6H-SiC substrate. The layers exhibit high crystal quality as was determined by x-ray diffraction. Photoluminescence (PL) of these films was measured. The PL spectra were dominated by band edge emission. Concentration N_d-N_a in undoped epitaxial layers ranged from 2×10^{17} to 1×10^{19} cm^{-3}. Mesa structures formed by reactive ion etching showed good rectifying current-voltage characteristics for GaN/SiC *pn* heterojunctions.

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The Rate of Radiative Recombination in the Nitride Semiconductors and Alloys

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The radiative recombination rates have been calculated for the first time in the wide bandgap wurtzite semiconductors GaN, InN, and AlN and their solid solutions $Ga_xAl_{1-x}N$ and $In_xAl_{1-x}N$ on the base of existing data on the energy band structure and optical absorption in these materials. We calculated the interband matrix elements for the direct optical transitions between the conductivity band and the valence one using the experimental photon energy dependence of the absorption coefficient near the band edge. In our calculations we assumed that the material parameters of the solid solutions (the interband matrix element, carrier effective masses, and so on) could be obtained by a linear interpolation between their values in the alloy components. The temperature dependence of the energy gap was taken in the form proposed by Varshni. The calculations of the radiative recombination rates were performed in the wide range of temperature and alloy compositions.

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