Carbon Doping of <10-11> GaN by Plasma-Assisted Molecular Beam Epitaxy

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Abstract:

Magnesium (Mg) is the most commonly used acceptor dopant in gallium nitride (GaN) devices. Acting as a deep acceptor with an activation energy of ~ 200 meV, Mg can introduce electrical and optical complications. Carbon has been demonstrated to be a possible alternative acceptor dopant atom with a lower activation energy [1]. Carbon-doped GaN (GaN:C) samples were homoepitaxially grown on <10-11> and <10-1-1> planes using plasma-assisted molecular beam epitaxy (PAMBE). A root mean square (RMS) surface roughness of 0.248 nm was achieved as verified by atomic force microscopy (AFM). There was no apparent crystal degradation from carbon doping as demonstrated by full-width half-max calculations of x-ray diffraction (XRD) rocking curves. Hall Effect and current-voltage measurements were used to electrically characterize the samples.

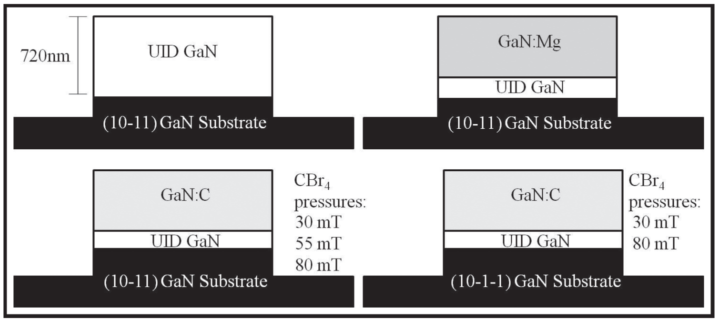

Figure 1: Growth layer(s) on semi-polar GaN substrates. Not to scale.

Introduction:

GaN is a wide band-gap III/V semiconductor material that is used in many short-wavelength emitting devices. Through its alloys, GaN devices are able to function over the entire visible spectrum. GaN has a wurtzite crystal structure lacking inversion symmetry; therefore, polar, non-polar, and semi-polar planes are available for growth. Much research has dealt with growth on the polar <0001> plane. This project examined growth on the semi-polar <10-11> plane.

To obtain electrically-conducting, extrinsic semiconductor material, impurities are placed into the semiconductor. When an acceptor atom takes an electron from a valence band shell, holes are produced. When holes are the majority carrier, the material is said to be p-type. Magnesium is commonly used as the acceptor dopant in GaN material. Because magnesium is a deep acceptor with a relatively high activation energy of ~ 200 meV, only ~ 1% of the impurities are ionized. An increase in doping is necessary to obtain desirable hole concentrations; this increase leads to additional imperfections. Carbon has been predicted to be an alternative to magnesium [2]. Green, et al. [3], showed that, while being the primary dopant, carbon will incorporate and self-compensate on the <0001> plane [3]. It was also demonstrated that CBr$_4$ is an effective carbon source that has no significant impact on growth rate and crystal quality of GaN material grown by RF-plasma-assisted MBE.

Hikosaka, et al. [1], demonstrated p-type conduction in GaN:C grown on the <1-101> plane by metal-organic vapor phase epitaxy. The hole density within the GaN was controllable by varying the carbon precursor flow rates. To further investigate the physical and electrical properties of carbon-doped material, GaN:C was grown on the <10-11> plane using PAMBE in this study.

Experimental Procedure:

PAMBE was used to grow UID GaN, GaN:Mg, and GaN:C with CBr$_4$ foreline pressures of 30, 55, and 80 mT on bulk semi-polar <10-11> GaN as well as GaN:C with CBr$_4$ foreline pressures of 30 and 80 mT on bulk <10-1-1> GaN. Sample schematics are shown in Figure 1.

All GaN samples were grown using a Varian GenII system with a substrate temperature of 710°C. "Active" nitrogen was provided by a Veeco Uni-bulb nitrogen plasma source using RF-plasma power of 300 W and a nitrogen flow rate of 0.4 sccm. Elemental gallium was introduced via a standard SUMO effusion cell. These conditions correspond to a growth rate of ~ 8 nm/min.

AFM images were taken using a Veeco Dimension 3000/3100 scanning probe microscope to measure surface morphology and roughness. XRD measurements were taken using a PANalytical X'Pert PRO MRD high-resolution x-ray diffractometer to observe crystal quality. Hall effect measurements were taken on mesa-isolated photolithographically-defined metal contacts on a Van der Pauw pattern as shown in Figure 2. Al/Au contacts were deposited on UID GaN samples while Pd/Au contacts were deposited on all other samples.

Results and Conclusions:

Visible step-edges in the AFM images of all samples indicate good step-flow growth, as seen in Figure 3. As CBr_4 foreline pressure increased, surface roughness decreased. The average RMS surface roughness of GaN:C samples was calculated to be 0.248 nm, indicating atomically smooth surfaces. Samples grown on <10-1-1> were 47% smoother than those grown on <10-11>. Full-width half-max (FWHM) calculations of the XRD rocking curves were all within one standard deviation of the average FWHM except one, suggesting no significant crystal degradation due to carbon incorporation, as shown in Figure 4.

The single outlier was the sample grown on <10-1-1> with the highest CBr_4 foreline pressure of 80 mT with a FWHM of more than one standard deviation smaller than the average. This result suggests that with increasing CBr_4, there is improvement of crystal quality on <10-1-1>.

Hall effect measurements were inconclusive due to Schottky behavior of the metal contacts; however, current-voltage measurements taken from contacts on top of the mesa to the substrate at the base of the mesa suggest rectifying p-n diode type behavior. As the substrate is n-type material, the growth layer is subsequently suggested to have p-type behavior.

Future Work:

The growth layer should be better isolated from the substrate to avoid carrier leakage and help generate conclusive Hall effect measurements. Better electrical characterization will confirm that the <10-11> and <10-1-1> planes generates higher carrier ionization via carbon doping.

Acknowledgements:

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References:

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[2] Seager, et al., J. Appl. Phys. 92, No. 11, 6553 (2002).

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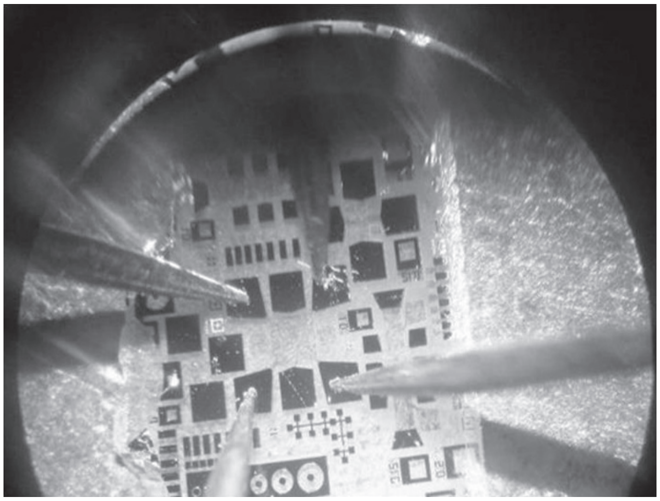

Figure 2: Four Hall probes on Van der Pauw patterned mesa-isolated photolithographically-defined contacts.

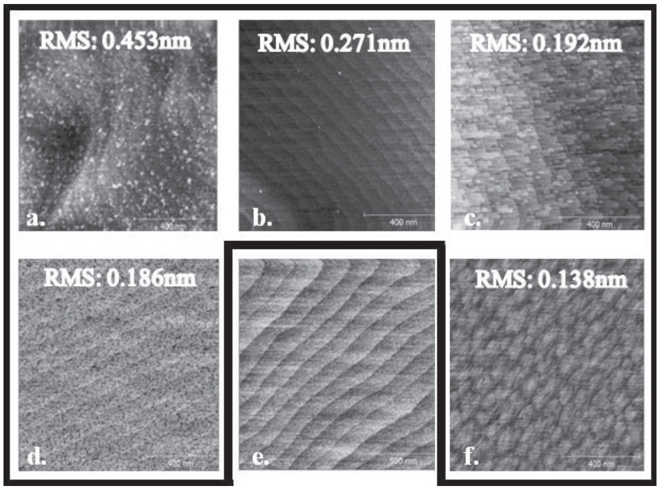

Figure 3: Approximately one micron AFM images. a,b,c. <10-11> GaN:C. d,f. <10-1-1> GaN:C. e. Evident step-flow growth of GaN:Mg. a,d / b / c,f. CBr_4 foreline pressure of 30, 55, 80 mT, respectively.

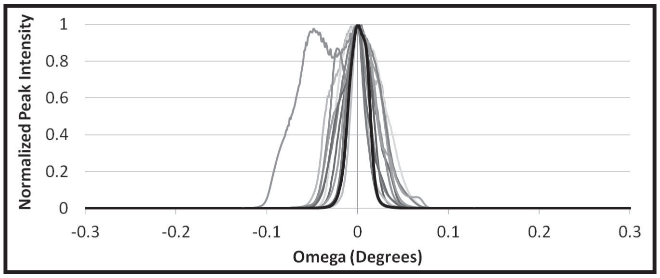

Figure 4: Normalized Omega-2 Theta x-ray diffraction rocking curves. Pre-grown <10-11> GaN represented in bold. Second peak seen in <10-11> GaN:C 80 mT samples.