Polarization Induced Graded AlGaN p-n Junction grown by MBE

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Wide bandgap III-V nitride semiconductors have attracted a large interest in recent years due to their applications in high power and opto-electronic devices. However, the development of nitride based UV optical devices has been limited due to the difficulties in growth and processing of good quality p-type and n-type layers of high Al composition AlGaN, where both acceptor and donor dopants have very high activation energies. High acceptor activation energies of Mg acceptor atoms (~160 meV) combined with low mobilities of holes in nitrides result in very resistive p-type layers, limiting the optical and high frequency performance of any bipolar device. Recently we have demonstrated the ability to produce polarization-induced bulk n-type doping in AlGaN graded slabs[1]. By using the polarization charges found in nitride semiconductors it is possible to controllably induce bulk doping in graded slabs without the introduction of any impurity dopants. By inverting the grading direction during growth the polarization charges will also be inverted, resulting in an induced bulk p-type doping without the need to dope the crystal with Mg atoms.

Graded AlGaN layers were grown by plasma assisted MBE on top of a commercially available n-type Ga-face GaN (0001) substrates to demonstrate the induction of p-type carriers by polarization charges. In the first layer, the Al composition was graded from 0 to 30% across a 100 nm layer to form the polarization induced n-type layers. The Al composition was then graded back down from 30 to 0% across a 100 nm resulting in an induced p-type layer. One sample was also co-doped with Mg atoms across the entire p-type graded AlGaN layer while the other was left un-doped. The samples were capped with a 10 nm GaN:p++ layer for ohmic contacts. A schematic diagram of the sample structure is shown in Figure 1 along with a simulated band diagram and carrier concentrations for the un-doped structure. An impurity doped p-n junction was also grown under the same growth conditions as a control sample. The grading of the Al composition results in the formation of polarization charges which induce the mobile holes and electrons that form the p-n junction. Graded AlGaN layers were pseudomorphically grown on top of the GaN substrates as determined by X-ray diffraction measurements, and evidence of step like growth is found in the surface AFM scans shown in Figure 2. Samples were then processed by etching down mesas to the n-type substrate in a RIE Cl_2 plasma. Al/Au and Ni/Au metal contacts were deposited in an electron beam evaporator on top of the n and p-type layer respectively for ohmic contacts. p-type as deposited metal contacts exhibited ohmic behavior as shown in Figure 3. Large current rectification is observed across the diodes as evidence of the induced p and n-type doping. ON/OFF ratios as high as $2x10^6$ were measured at 5/-5 V, and ideality factors of ~1.7 were extracted from the current-voltage characteristics for the un-doped graded junction (Figure 4). These are larger ON/OFF ratios as compared to the impurity-doped GaN p-n junction control sample. Capacitance-voltage measurements (Figure 4) performed on all samples show small capacitance for the graded layer junction as compared to the impurity doped structures, indicative of a large depletion width. Temperature dependent electroluminescence (EL) measurements were conducted on both the graded junction without doping and the impurity doped junction from 80K to 290K. A luminescence peak around 377nm is observed for the graded junction diodes at 80K under a forward bias of 5V, proof of the injection of both electron and hole mobile carries into the depletion region. Both diodes show a decrease in emission intensity with increasing temperature (Figure 5). Across the same temperature range, the leakage and forward bias current density increased with increasing temperature for both the graded and the impurity doped junction (Figure 5). Hall-effect measurements to these layers have been a challenge due to the difficulty in making good p-type ohmic contacts directly on the AlGaN layers. Therefore, to rule out the possibility that hole injection is a result of the heavily doped p++ cap layer, a ~15nm layer was etched from the top surface to remove the p++ cap from both the un-doped and impurity doped graded junctions. Light emission is still observed across both diodes after etching, but a significant reduction in lateral current is observed across the TLM pads on the top p-type layer for the un-doped junction. No current degradation is observed for the Mg doped graded sample. This could be attributed to carrier depletion due to the Fermi level pinning in the AlGaN layers, which limits the possibility of making good p-type ohmic contacts directly to these layers. Hole injection is observed in our junctions but Hall-effect measurements are still needed in order to confirm the presence of holes due to the polarization charges. For this reason contacts to graded AlGaN layers need to be improved in future work. The technique we demonstrate here is an effective way to produce both p and n-type layers in applications where both types of doping is challenging, such as deep UV optoelectronic devices that require large Al composition AlGaN layers.

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[1] John Simon, Kejia Wang, Huili Xing, Siddharth Rajan and Debdeep Jena. Appl. Phys. Lett. **88**(4), 042109 (2006).

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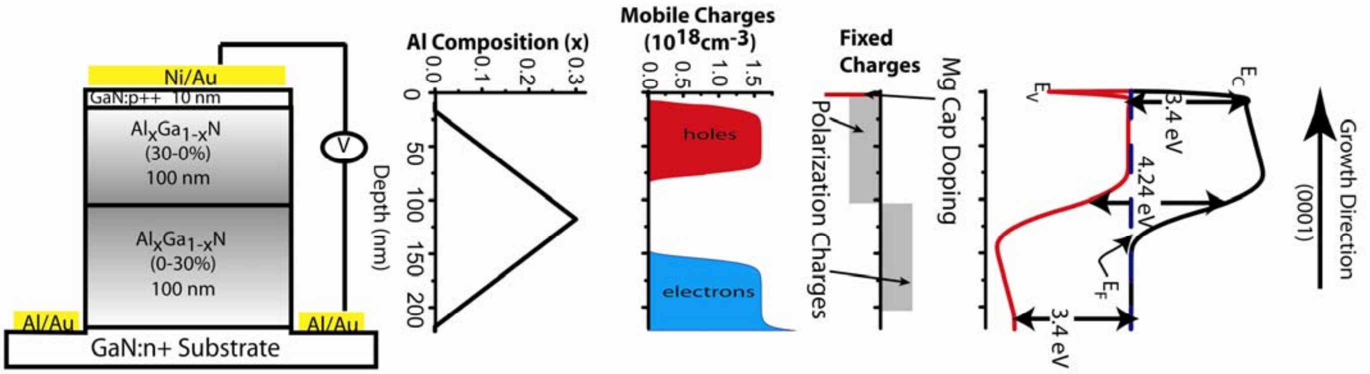


Figure 1: (LEFT) Schematic cross section of the device structure and simulated band diagram (RIGHT) and schematic of fixed and mobile charges present in graded junctions.

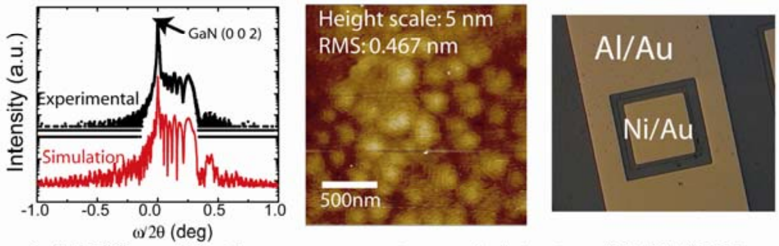


Figure 2: (LEFT) X-ray diffraction measurement on graded structure. (MIDDLE) AFM scan of surface morphology showing atomic steps resulting from layer by layer growth. (RIGHT) Optical microscope image of device after processing.

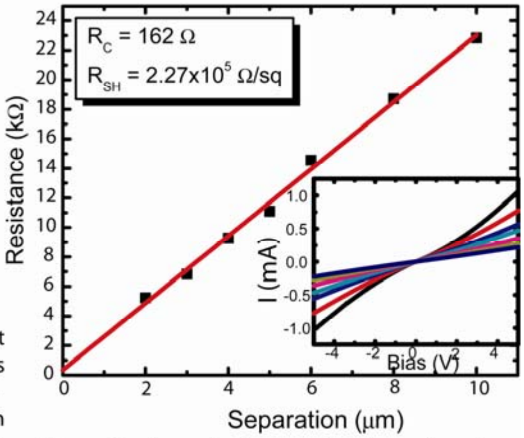


Figure 3: p-type ohmic current-voltage characteristics (insert), and resistance vs separation for ohmic contacts on graded p-type layers.

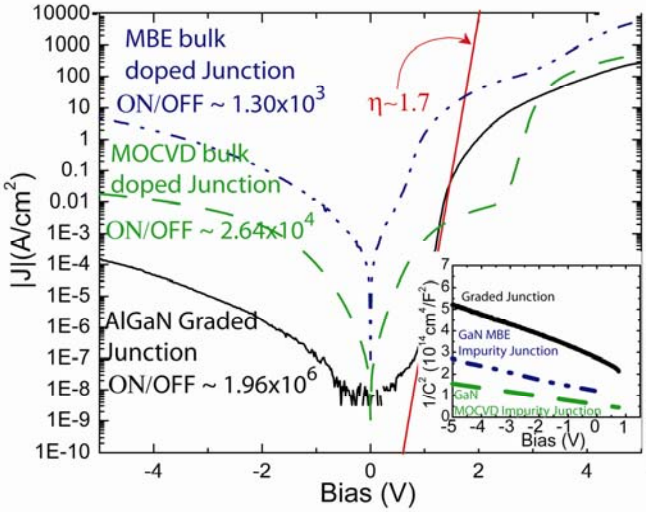
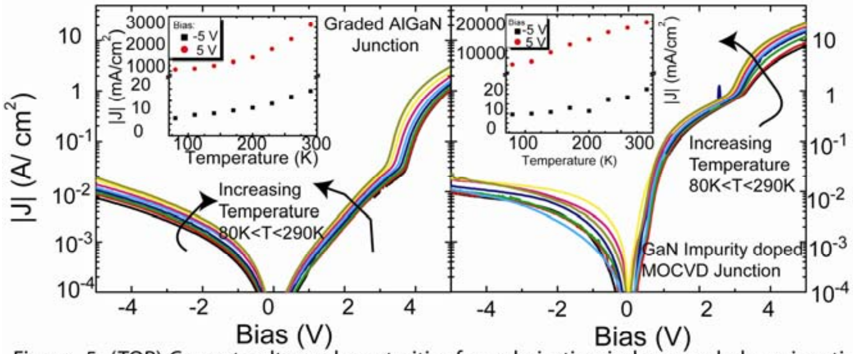


Figure 4: Current voltage characteritics for polarization-induce graded p-n junctions (solid), a normally doped GaN p-n junction grown by MBE (dash-dot), and MOCVD normally doped junction (dash). Insert shows the capacitance voltage measurements performed across graded junctions and impurity doped junctions.



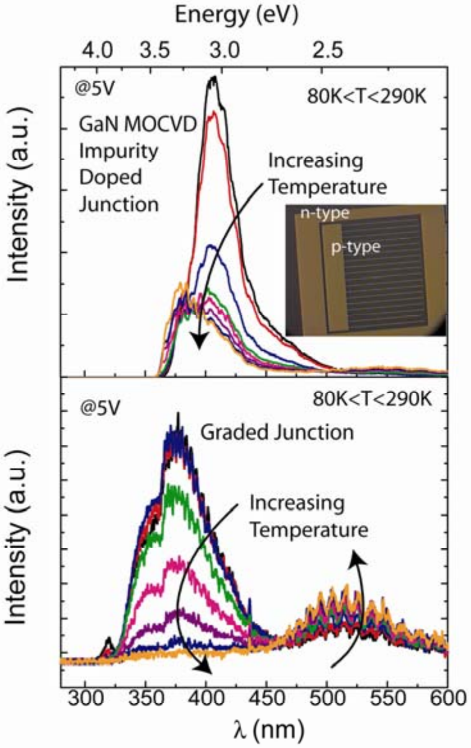


Figure 5 (TOP) Current voltage characteritics for polarization-induce graded p-n junctions (left), and MOCVD normally doped junction (right) as a funtion of temperature. Insert shows the current trend with changing temperature for both reverse (-5V) and foward (5V) bias. (RIGHT) Electroluminescence measurements perfomed across the same diodes as above from 8-0K to 290K.

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