High-voltage polarization-induced vertical heterostructure p-n junction diodes on bulk GaN substrates

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The III-nitride wide bandgap semiconductors show attractive and compelling potential for power electronics due to their high breakdown electric field (E_{br}) as well as high carrier mobilities (μ). Previous efforts have realized GaN high power p-n diodes by traditional acceptor-donor doping.[2-4] The new polarization-induced doping technique using graded AlGaN heterostructures can improve the doping efficiency and simultaneously enable better transport due to lack of impurity scattering. Such polarization-induced AlGaN (Pi-AlGaN) p-n heterojunction diodes have been demonstrated for LEDs.[1] Furthermore, the introduction of AlGaN into the depletion region of the p-n junction can potentially improve the breakdown properties, owing to the higher breakdown field of AlGaN due to the larger bandgap.

In this work, RF plasma-Molecular Beam Epitaxy (MBE) grown polarization-induced AlGaN (Pi-AlGaN) p-n vertical diodes are demonstrated on Ammono single-crystal bulk GaN substrates. A highest breakdown voltage (BV) of 120 V has been achieved on a Pi-AlGaN p-n diode with a 400-nm thick n- drift region, corresponding to an E_{br} of 3.3 MV/cm. The diode structures are sketched in Figure 1. As shown in Figure 1(b), the n-region of Pi-AlGaN p-n diodes consists of a 200-nm-thick n- GaN layer with doping N_D~1.8×10^{16} cm^{-3}, followed by a 200-nm-thick n-type linearly graded AlGaN layer with the Al composition graded up from 2% to 14.5%. The effective polarization-induced doping is this layer is measured to be $N_{D,eff}$~9.1×10^{16} cm^{-3}. Then a 200-nm-thick linear p-type linear graded AlGaN layer with the opposite Al composition gradient from 14.5% to 2% forms the p-region of the p-n junction. As a control sample, an impurity-doped GaN p-n diode is also realized (Fig 1a) with the same thickness of n- region, but using a Si-doped GaN layer with N_D~1.7×10^{17} cm^{-3}. A 100-nm-thick Mg-doped GaN layer forms the p-region. P-regions of both Pi-AlGaN p-n diodes and impurity-doped GaN p-n diodes have the same Mg concentration of N_A~2×10^{19} cm^{-3}. Since the N_A/N_D~100, the depletion region is mainly in the n- side for all junctions. The doping concentrations in the n-region are verified by C-V measurements (not shown). The calculated energy band diagram of Pi-AlGaN p-n diodes at zero bias is shown in Figure 2. X-ray diffraction (not shown) and transmission electron microscopy (TEM, figure 3) verify the successful realization of the layer structures and thicknesses.

The I-V characteristics for Pi-AlGaN p-n diodes with different sizes are shown in Figure 4. Breakdown behavior for the diodes was observed at large reverse bias. A highest breakdown voltage of -120 V is obtained for a 70-μm-diameter diode. The peak electric field is estimated at 3.3 MV/cm at this bias. Larger diodes show lower BV: the TEM in Figure 3 reveals dislocations in the p-type layer potentially due to the low growth temperature. Figure 5 compares the I-V characteristics between the Pi-AlGaN p-n diodes and the impurity-doped GaN p-n diodes. Pi-AlGaN p-n diodes show higher turn-on voltage and on-resistance, owing to the larger bandgap of AlGaN and non-ideal p-type ohmic contacts. The impurity-doped GaN p-n diodes show lower BV of -62 V, and a lower calculated E_{br} of 2.3 MV/cm. The higher breakdown voltage and electric field of Pi-AlGaN p-n diodes indicate that potentially higher power diodes can be realized with thicker drift region, which is currently being investigated. This work is supported by the ARPA-E SWITCHES program.

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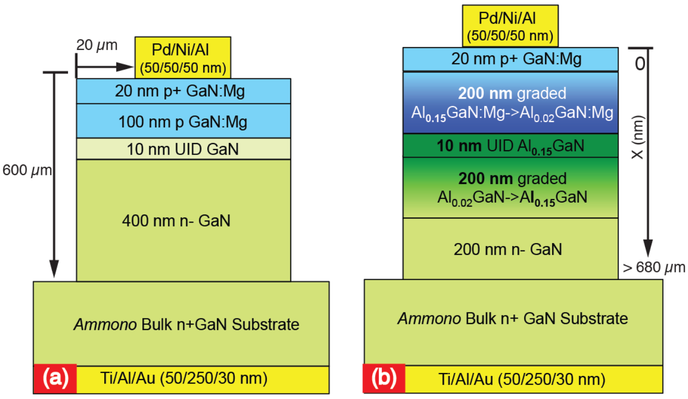

Figure 1. Device layer structure schematic of (a) impurity-doped GaN vertical p-n diode and (b) polarization-induced linearly-graded AlGaN vertical p-n diode, with the same thickness of n-region.

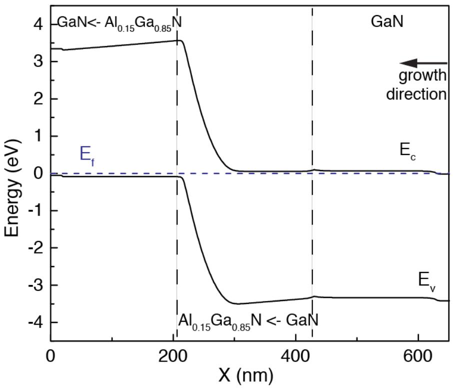

Figure 2. Energy band diagram of polarization-induced (linearly graded) AlGaN vertical p-n diode at zero bias.

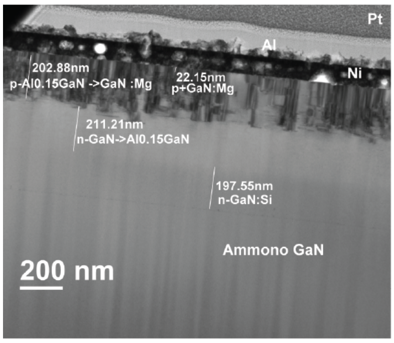

Figure 3. Cross-section TEM of polarization-induced AlGaN p-n diode grown by MBE.

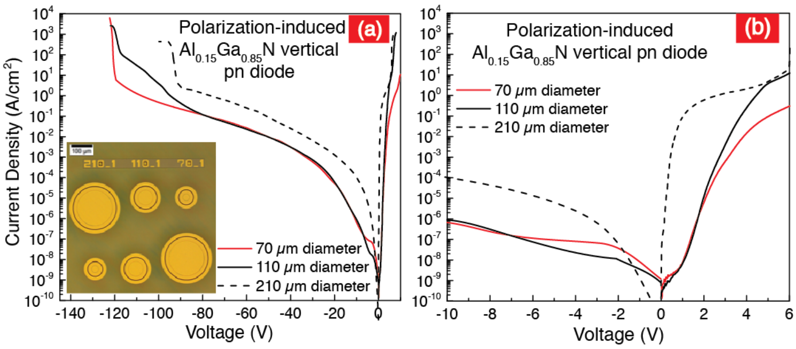

Figure 4. I-V characteristics of the polarization-induced AlGaN p-n diodes of various sizes. Voltage is swept with (a) reverse bias voltages up to -150 V and (b) reverse bias voltages up to -10 V. Inset figure of (a) shows the top view of the diodes.

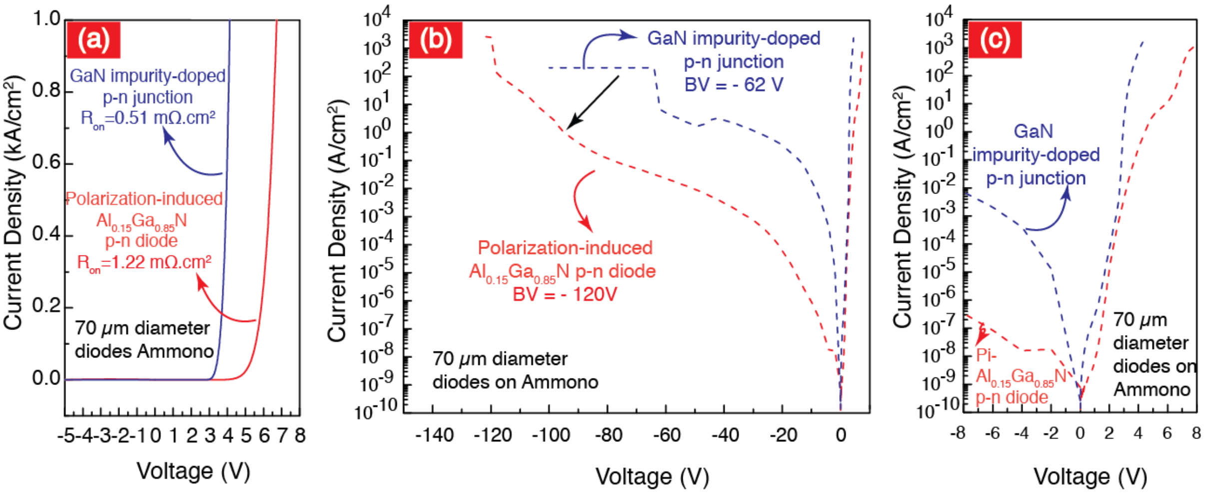

Figure 5. Comparative I-V characteristics between impurity-doped GaN vertical p-n diodes and polarization-induced AlGaN vertical p-n diodes of the same size. (a) Linear plot of I-V (b) Semilog plot of I-V with reverse bias voltages until breakdown. (c) Semilog plot of I-V with small reverse bias voltages.