Polarization-Induced Zener Tunnel Junctions in Wide-Bandgap Heterostructures

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The large span in direct bandgap covered by the III-V nitride material family makes them extremely suitable for a wide range of optoelectronic devices. This makes it possible to build devices extending from the infrared to deep UV wavelengths in the same material family. The ability to combine multiple emission wavelengths in one device can be made possible by growing devices of different material composition on the same wafer. In order to electrically connect different active regions, whether it is in a Light Emitting Diode (LED) or a solar cell, an efficient tunnel junction is needed.

For wide bandgap semiconductors such as the III-V nitrides (GaN, AlN) and SiC, tunneling is low due to the high barrier heights, and is hampered further by the inability to achieve degenerate n- and p-type impurity doping. However, by utilizing the giant built-in electronic polarization fields present in wurzite III-V nitride semiconductor heterostructures, it is possible to achieve interband tunneling in p-n junction diodes. This principle was recently used for connecting two nitride p-n junctions to demonstrate a multicolor light emitter[1].

In order to investigate this phenomena, GaN-AlN-GaN heterostructures were grown by plasma-assisted Molecular Beam Epitaxy (MBE) on commercially available n-type doped GaN 0001 substrates. The growth was performed at a substrate thermocouple temperature of $600^{o}C$ and a RF plasma power of 275 W, which corresponds to a growth rate of ~ 150 nm/hr. A 100 nm Si-doped GaN layer ($N_D \sim 9 \times 10^{18}/cm^3$) was grown, followed by a Mg doped AlN layer of thickness t_{AlN}, and a 100 nm p-type GaN with Mg doping $N_A \sim 10^{19}/cm^3$. The thickness of the AlN tunnel-barrier was varied over 6 samples (t_{AlN} = 0, 1.4, 2.8, 3.5, 4.3 & 5 nm). The samples were then capped with a heavily p-type doped GaN layer for improved Ohmic contacts. Fig 2 shows the layer structure, and a Transmission Electron Microscope (TEM) image of the GaN/AlN/GaN tunnel junction which was used to confirm the thickness and uniformity of the AlN layer. The TEM image also indicates a sharp heterojunction with high crystalline quality as inferred from lattice imaging.

Following MBE growth, the samples were processed into p-n junctions by etching down to the n-type substrate using Cl_2 plasma in an Inductively Coupled Plasma (ICP) etcher. Ni/Au and Ti/Au Ohmic contacts to the p and n-type layers respectively were deposited in an electron beam evaporator. A schematic of the finished device is shown in Fig 3. Current-voltage characteristics of the junctions were measured at 300 K in a probe station using a semiconductor parameter analyzer. The results are shown in Fig 5. The devices with the AlN interlayer show clear backward-diode behavior, with curvatures as high as $-21\ V^{-1}$ for the sample with 2.8 nm AlN interlayer.

Figure 6 shows the tunnel current densities (circles) at a bias of -0.5 Volt as a function of the AlN layer thickness. This behavior can be explained using a simple model of interband tunneling coupled with the high polarization fields that enable it, and will be presented in this work.

In order to test the capabilities of these nitride backward diodes, compression measurements were performed on a 56x56 μm^2 area device with a 2.8 nm thick AlN interlayer. The sensitivity was measured on-wafer, by using a HP8255A Vector Network Analyzer as the power source. The dc return is measured by a digital multimeter, connected to the device with a bias-T. The power loss due to the cable, the probe, and the transfer function of the bias-T are calibrated. Input power was varied from -35 dBm to 1 dBm, at an RF frequency of 100 MHz. Figure 7 shows the measured detector voltage and unmatched sensitivity versus input power. The detector exhibited square law detection over the tested power range.

By utilizing the polarization fields present in III-V nitride semiconductors it is possible to generate band to band tunneling. This will enable multicolor light emitters/detectors and multijunction solar cells, as well as enable efficient injection of polarized carriers for spintronic devices.

[1] M. Grundmann et. al. phys. stat. sol. (c). 4(**7**), 2830 (2007)

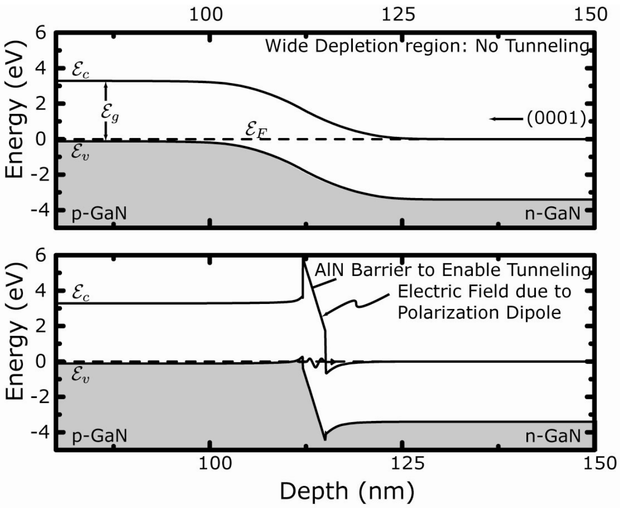

FIG. 1: Simulated band diagrams for GaN p-n junctions with and without an AlN interlayer. The polarization charges generated at the AlN-GaN interface generate large polarization fields that bend the bands to enable tunnelling.

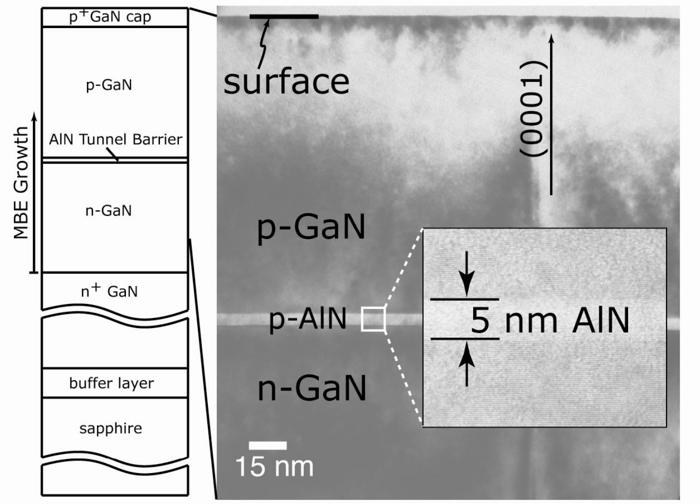

FIG. 2: TEM crosssection of the 5 nm AlN backward diode. Insert shows high resolution image of AlN layer verifying the AlN thickness.

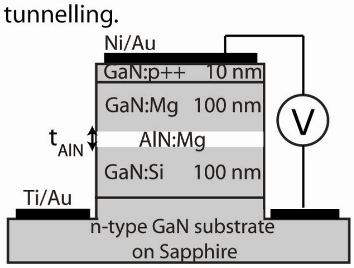

FIG. 3: Sample layer structure for nitride tunnel diodes presented in this work.

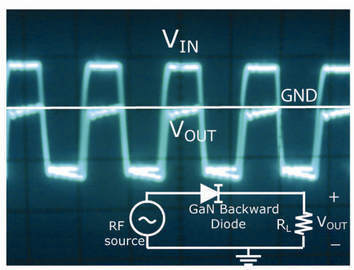

FIG. 4: In put and output signals showing GaN backward diode rectification of 1.5 MHz AC signal at zero bias.

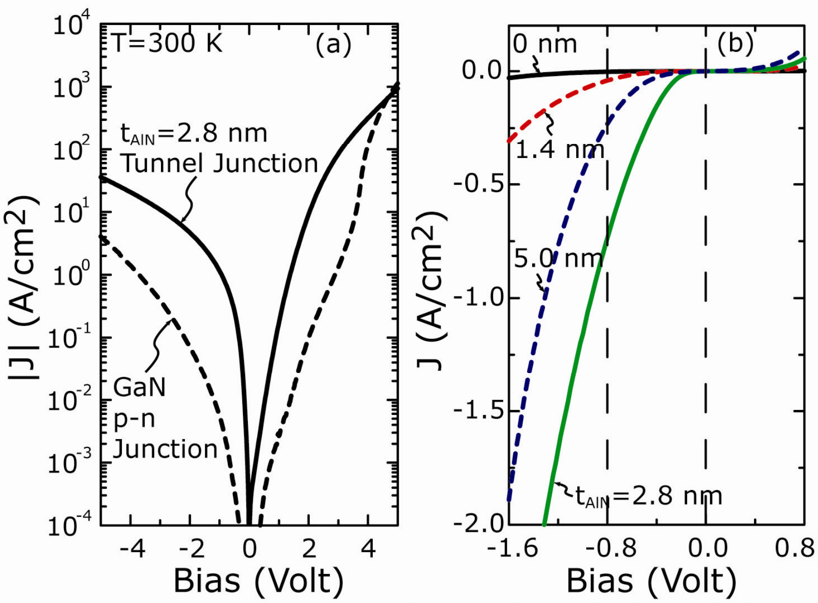

FIG. 5: Current-voltage characteristics for GaN-AlN-GaN backward diodes. (a)Current voltage characteristics for a nitride tunnel junctions and a control p-n junction (tAlN=0 nm). Insertion of AlN barrier results in backward diode characteristics. (b) Expanded current voltage characteristics under small applied biases showing backward diode behavior. The 2.8 nm AlN sample had the best backward diode characteristics under small biases with a zero bias curvature of ~-21 V^{-1}.

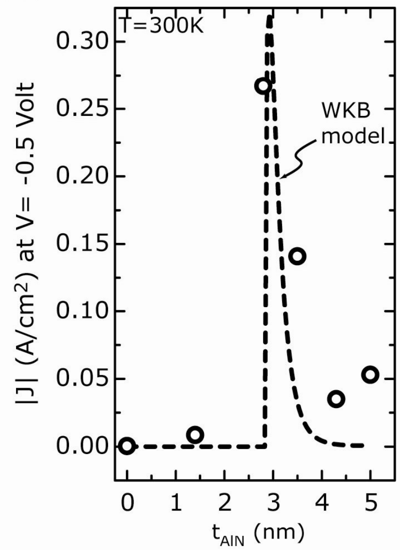

FIG. 6: Dependence of tunneling current on AlN thickness (t_{AlN}) measured at -0.5 V of reverse bias. The experimental results agree with the simulated data by the WKB model.

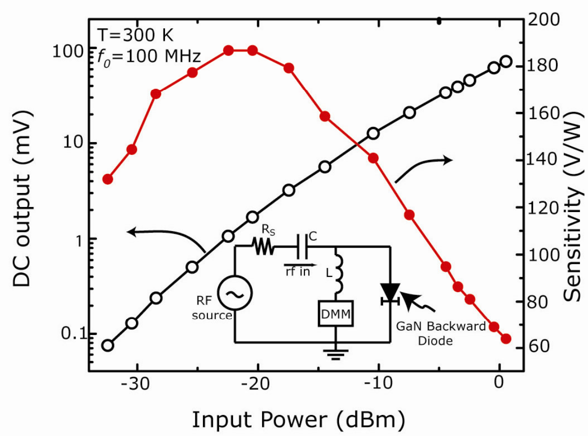

FIG. 7: Measured sensitivity (•) and detector voltage (o) of a 56x56 μm^2 area device against input power at a RF frequency of 100 MHz.