High Power Electronics Based on the 2-Dimensional Electron Gas in GaN Heterostructures

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Motivation—GaN-based electronics offer miniaturization potential of radical proportions for microwave power amplifiers. GaN's large bandgap, high breakdown field, high electron velocity, and excellent thermal properties have led to high electron mobility transistors (HEMT) with up to 10x the power density of GaAs and other traditional semiconductors at frequencies up to 20 GHz.

Further contributing to the outstanding performance of GaN-based amplifiers is the highly conducting, 2-dimensional electron gas (2DEG) used for the HEMT channel. Intrinsic polarization and piezoelectric properties of GaN materials can produce a 2DEG at an AlGaN/GaN interface with a sheet carrier concentration of $10^{13}/cm^2$, well in excess of that achievable in any other III-V material system. The physics and material science of the AlGaN/GaN 2DEG are critical to the performance and future development of GaN-based electronics.

Accomplishment—High quality AlGaN/GaN heterostructures have been grown on sapphire substrates using an AlN nucleation layer. Capacitance-voltage and transport measurements confirm that 2DEG sheet densities $>10^{13}/cm^2$ have been achieved at 300 K, Hall mobilities > 1000 cm^2/Vs at the highest densities. A depth profile of the 2DEG is shown in Fig. 1. Experimental results are compared with Schrodinger-Poisson calculations of AlGaN/GaN conduction band-bending and 2DEG concentrations shown in Fig. 2. These bandstructure results are incorporated into a finite element, charge-control HEMT model which includes both saturation velocity and injected space charge effects, in addition to the solid state properties of the AlGaN/GaN interface and 2DEG.

No high quality GaN substrate has been developed to grow GaN HEMT structures. As a consequence GaN is most often grown on substrates with a considerably different lattice constant, most commonly sapphire or SiC. Not surprisingly, GaN material is grown with extremely high levels of threading dislocations and point defects. We have begun to evaluate alternative substrates to sapphire. Initial work has focused on the properties of the 2DEG formed within low-dislocation density regions produced through cantilever-epitaxy or epitaxial-lateral-overgrowth. Overall material quality and properties of the 2DEG are monitored with optical and electrical measurements. Novel optical characterization techniques being explored include electroreflectance spectroscopy of 2DEG energy levels and infrared spectroscopy of defect states near the AlGaN/GaN interface which trap charge, degrading HEMT performance. Unconventional GaN HEMT designs, enabled by novel substrates, are being modeled and evaluated.

Significance—Fundamental studies of GaN growth and the unique 2DEG have led to the demonstration of state-of-the-art solid state microwave amplifiers. We have constructed an AlGaN/GaN HEMT on sapphire, with a power density 3W/mm at 3 GHz. Further improvement in GaN materials and growth promise higher mobilities and novel quantum effects of the 2DEG, leading to the next generation of microwave power devices.

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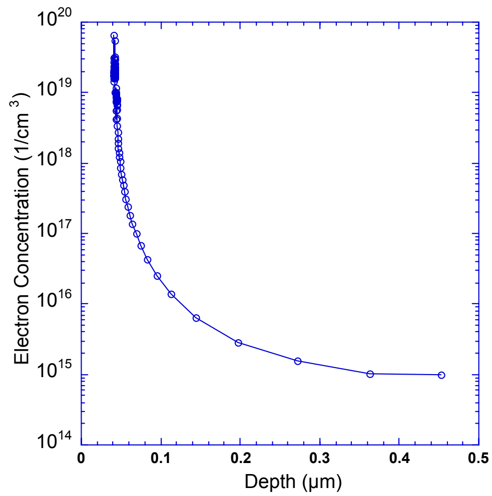

Figure 1. 2DEG concentration at an AlGaN/GaN interface determined by capacitance-voltage measurements.

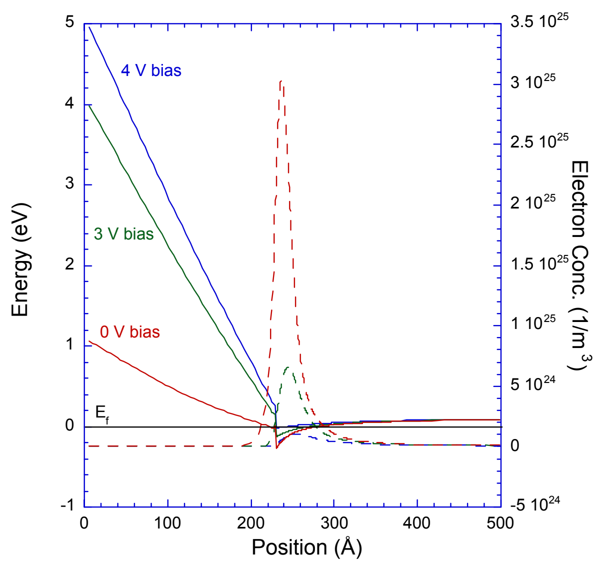

Figure 2. Calculation of conduction band energies (solid) and 2DEG concentration (dotted) at an AlGaN/GaN interface for 0, 3, and 4V bias.