Optical Measurements and Theory Test AlGaN/GaN High Electron Mobility Transistor (HEMT) Models

by ***Steven R. Kurtz***

Motivation—GaN-based electronics offer radical miniaturization of microwave power amplifier and radar circuitry. GaN's large bandgap, high breakdown field, high electron velocity, and excellent thermal properties have led to high electron mobility transistors (HEMTs) with up to ten times 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—To further reduce dislocation densities, we are evaluating alternative substrates to sapphire. Focusing on the properties of AlGaN/GaN devices grown on SiC substrates, we found that overall material quality and transport properties of the 2DEG were much improved over structures grown on sapphire. Hall mobility versus electron density measurements revealed that 2DEG mobility was limited by scattering in the AlGaN barrier, not dislocations, in devices grown on SiC.

Electronic properties of AlGaN/GaN heterostructures and HEMTs on SiC were determined using a contacted electroreflectance technique. This optical probe augments conventional electrical characterization of GaN-based field-effect transistors. By studying variations in the electroreflectance with applied electric field, spectral features associated with the AlGaN barrier, the 2DEG at the interface, and bulk GaN are clearly identified. The 2DEG produced a broad, first-derivative-like electroreflectance feature. Changing bias voltage, the 2DEG electroreflectance narrowed and converged with the GaN band-edge. A first-principle, Golden Rule calculation of the dielectric function was developed which described the variation of 2DEG electroreflectance with voltage (see Fig. 1). The AlGaN barrier displayed Franz-Keldysh oscillations (FKO), and the period of the FKO varied with bias voltage. Airy function lineshape fits provided accurate determinations of AlGaN barrier composition and polarization electric field. Comparing measured AlGaN electric fields with values predicted by a standard model of the AlGaN/GaN heterostructure conduction band, we found < 10% discrepancy between the measured polarization field and that predicted by a standard model for devices grown on SiC (see Fig. 2). However, AlGaN electric field measurements for devices grown on sapphire produced anomalous results, indicating the presence of trapped space charge.

Significance—An optical probe of AlGaN/GaN heterostructures and transistors augments conventional electrical characterization tools. The electroreflectance technique and supporting calculations provide the first optical measurements of AlGaN barrier electric field and composition and 2DEG Fermi energy and electron density. This new information allows us to test and refine basic models of AlGaN/GaN heterostructures and transistors.

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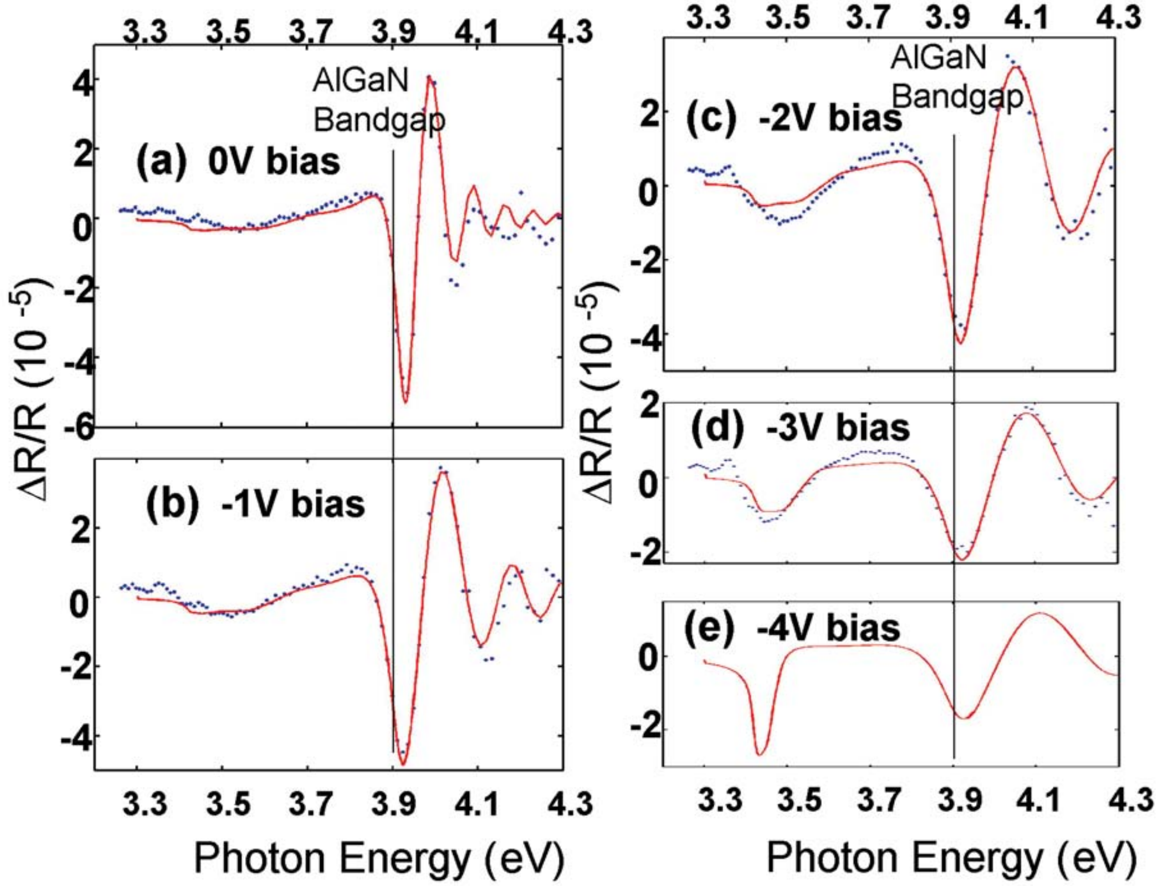

Figure 1. Electroreflectance spectra (300 K) for the $Al_{0.19}Ga_{0.81}N$ (320Å)/GaN heterostructure at 0V (a), −1V (b), −2V (c), and −3V (d) gate bias. (same scale) Solid lines are the AlGaN FKO lineshape fit plus the contribution from the 2DEG dielectric model. Based on the models, the −4Vspectrum (e) was simulated.

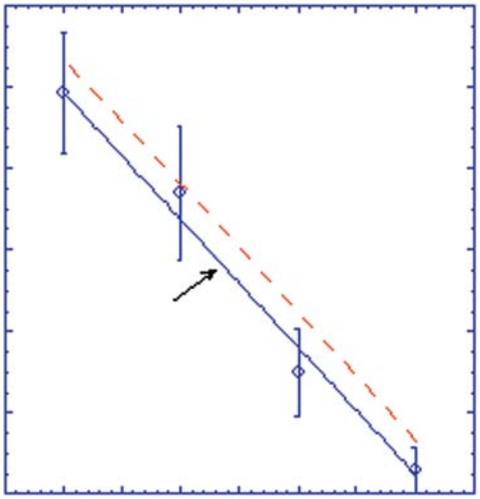

Figure 2. Electric field versus gate bias obtained from the electroreflectance spectra in 1(a)-(d). The electric field predicted by the "standard model" for an $Al_{0.19}Ga_{0.81}N$ (320Å)/GaN heterostructure is indicated by the dotted line.