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Quantitative mobility spectrum analysis of AlGaN/GaN heterostructures using variable-field hall measurements

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Carrier transport properties of AlGaN/GaN heterostructures have been analyzed with the quantitative mobility spectrum analysis (QMSA) technique. The nominally undoped $Al_{0.08}Ga_{0.92}N$/GaN sample was grown by plasma-assisted molecular beam epitaxy on a GaN/sapphire template prepared with hydride vapor phase epitaxy. Variable-magnetic-field Hall measurements were carried out in the temperature range of 5–300 K and magnetic field range of 0.01–7 T. QMSA was applied to the experimental variable-field data to extract the concentrations and mobilities associated with the high-mobility two-dimensional electron gas and the relatively low-mobility bulk electrons for the temperature range investigated. The mobilities at $T=80$ K are found to be 7100 and 880 cm^2/V s, respectively, while the corresponding carrier densities are 7.0×10^{11} and 8×10^{14} cm^{-3}. Any conclusions drawn from conventional Hall measurements at a single magnetic field would have been highly misleading.
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The wide band gap compound semiconductor GaN and its alloys $Al_xGa_{1-x}N$ and $In_xGa_{1-x}N$ have attractive material properties for high-temperature, high-power, and high-frequency microelectronic devices, such as modulation doped field-effect transistors (MODFETs), light emitters, and detectors.[1–3] High-performance AlGaN/GaN-based MODFETs have been demonstrated by several research groups.[4–7] Since the electron mobility and two-dimensional electron gas (2DEG) carrier density are among the key parameters that influence the performance of these heterostructure devices, precise evaluation of the electronic transport properties is of critical importance. Conventional Hall measurements at a single magnetic field provide only a weighted average of the electron mobility and carrier density, whereas in practice the doped bulk GaN and AlGaN layers can also contribute to the measurements in addition to the 2DEG. To characterize the multicarrier properties of such multilayered heterostructure devices, alternative measurement and analysis techniques are required.

The quantitative mobility spectrum analysis (QMSA) is an effective technique for treating mixed conduction by multiple carrier species in a semiconductor, since it simultaneously extracts the densities and mobilities for each class of electron and hole.[8,9] The experimental inputs to this analysis are variable-magnetic-field measurements of the Hall coefficient and resistivity. The QMSA method has been applied successfully to a number of material systems, including AlGaAs, InP/InAlGaAs,[8] and HgCdTe (Ref. 9) heterostructures, as well as bulk InN (Ref. 10) and GaN epilayers.[11] Saxler *et al.* previously reported variable-field Hall results for AlGaN/GaN 2DEG structures grown by molecular beam epitaxy on GaN/sapphire templates generated by organometallic vapor phase epitaxy.[12] More recently, Elhamri *et al.* obtained variable-field Hall data and performed a "reduced conductivity" analysis on AlGaN/GaN samples grown by metal organic chemical vapor deposition on Si (111) substrates.[13]

In the present study, we have carried out variable-field Hall and resistivity measurements on AlGaN/GaN heterostructures grown on GaN/sapphire templates prepared by hydride vapor phase epitaxy. We apply QMSA to the data for nominally undoped AlGaN/GaN heterostructures, in which a 2DEG is induced by polarization. With the aid of QMSA, temperature-dependent mobilities and carrier densities are extracted for both the bulk GaN buffer layer and the 2DEG.

The investigated sample was grown by plasma-assisted radio frequency molecular beam epitaxy (RF-MBE) on an 8-μm-thick GaN layer prepared by hydride vapor phase epitaxy (HVPE) on a *c*-plane sapphire substrate. The MBE deposition consisted of a 0.8 μm overgrown GaN layer, followed by a 30 nm $Al_{0.08}Ga_{0.92}N$ layer, and capped by 2 nm of GaN, all nominally undoped. Surface band bending considerations,[14] coupled with a low nominal electron concentration in the AlGaN layer, lead to the expectation that transport contributions from the AlGaN and top GaN (too thin) layers should be negligible, as is borne out by the analysis discussed below. The entire structure was grown under Ga-rich conditions at 700 °C. The sample for Hall measurements was cleaved from the area near the Ga droplet region.

A six-contact Hall-bar sample was fabricated using standard photolithography and electron-beam-evaporated Ti/Al/Ti/Au Ohmic contacts. After ultrasonic lift-off and cleaning, the sample was annealed at 800 °C for 1 min in a rapid thermal annealing furnace. The sample was then placed in a package and electrical contacts were made using gold wires and In soldering. Variable-field Hall measurements were carried out using a superconducting cryogenic physical parameter measurement system (PPMS). With the PPMS,

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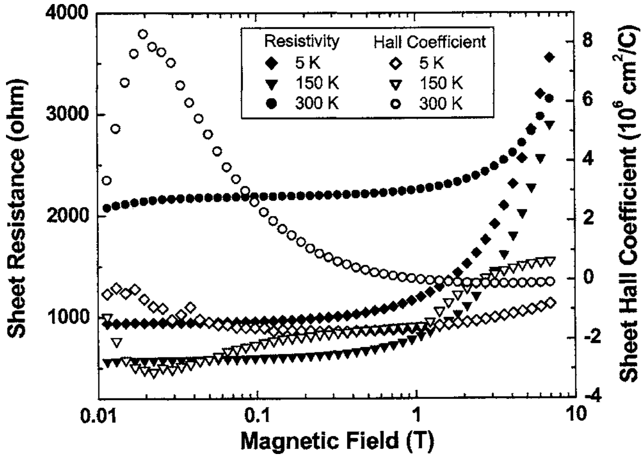

FIG. 1. Measured sheet resistivity and sheet Hall coefficient of the $Al_{0.08}Ga_{0.92}N/GaN$ heterostructure sample investigated.

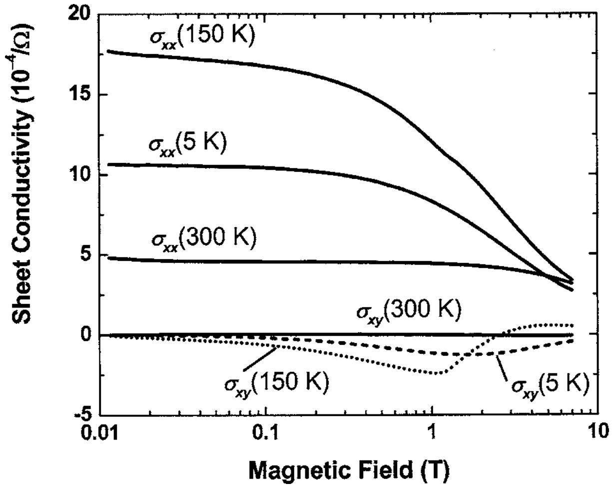

FIG. 2. Calculated conductivity tensor elements σ_{xx} and σ_{xy} vs the magnetic field strength normal to the surface.

measurements were performed under a constant current of 0.1 mA and varying magnetic field (0.01–7.0 T) applied perpendicular to the sample surface. Measurements were performed at a series of temperatures spanning the range of 5–300 K. Results were compared with the density and mobility implied by a conventional single-field Hall measurement at $B=0.48$ T.

Hall coefficient and resistivity values obtained from the variable-field measurements were used to determine the corresponding conductivity tensor elements $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$.[15] Then QMSA was employed to derive the mobility spectrum and extract the densities and mobilities of carriers in the $Al_{0.08}Ga_{0.92}N/GaN$ heterostructure.

Figure 1 shows the measured sheet resistivity and Hall coefficient data obtained at 5, 150, and 300 K. The sample resistance is seen to increase with increasing magnetic field, and display a minimum in its dependence on temperature at around 150 K (the minimum actually occurs between 100 and 150 K). At 5 K, the Hall coefficient is negative at all B. At 150 K it becomes positive at high B, whereas at $T=300$ K it is positive at most B before finally changing sign near the highest field. These Hall results immediately confirm that both electrons and holes are present in the structure, and that the ratio of their mobilities shifts as a function of temperature. From the raw Hall and conductivity data, we calculate the conductivity tensor elements $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ shown in Fig. 2. As expected, the longitudinal conductivity (σ_{xx}) displays a maximum at $T\approx 150$ K. While the observed upturn of the transverse conductivity (σ_{xy}) at high magnetic field is probably unphysical, it does not substantially influence the mixed-conduction analysis discussed below. The upturn is apparent to some extent at all temperatures between 60 and 250 K, being most pronounced in the 150–200 K range.

Application of QMSA to the variable-field data showed that one high-mobility electron and one lower-mobility electron contribute to the transport. Surprisingly, a moderate-mobility hole was also observed in the spectra, which is consistent with the observation mentioned above that the Hall coefficient (and σ_{xy}) becomes positive for a portion of the magnetic field range at some temperatures. Figure 3 shows the multicarrier quantitative mobility spectrum for the $Al_{0.08}Ga_{0.92}N/GaN$ sample at 80 K. The high-mobility carrier (peaked at 7100 cm^2/V s) corresponds to the 2DEG electrons within the channel at the $Al_{0.08}Ga_{0.92}N/GaN$ interface. It should be reiterated that the sample was not intentionally doped and the 2DEG formed due to polarization. The low-mobility electron (peaked at 900 cm^2/V s) may be associated with bulk electrons within the HVPE-grown GaN template. The hole mobility is too high for any known carrier in the GaN/AlGaN material system. Therefore this unphysical carrier is named as "ghost hole." Such ghost holes are an artifact of a type that is seen quite frequently in mobility spectrum analyses, and even in multicarrier fits. Several research groups have reported ghost carriers in their mobility spectrum analysis of different material systems and heterostructures which emphasizes how pervasive such ghost carriers are.[8,16,17] To our knowledge, no satisfying explicit explanation for the actual mechanism(s) of ghost carriers is reported yet. The possible origins of the ghost carriers may include nonideality of measurements and the assumptions made in the analysis (laterally uniform carrier densities, magnetic-field-independent mobility and carrier density, and absence of quantum oscillations).

The temperature-dependent mobilities and carrier concentrations extracted from the quantitative mobility spectra

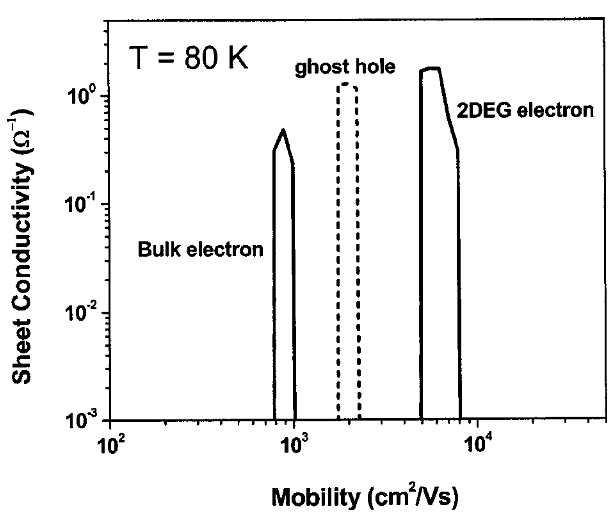

FIG. 3. Quantitative mobility spectrum for the $Al_{0.08}Ga_{0.92}N/GaN$ sample delineating the 2DEG and bulk electron mobilities at 80 K. The dashed peak corresponds to the ghost hole carrier.

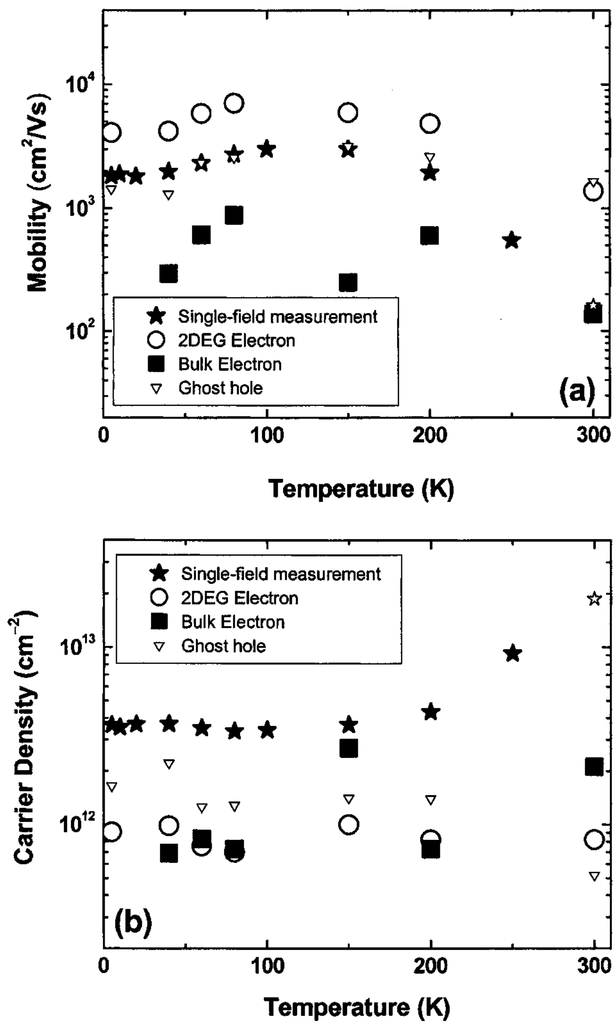

FIG. 4. Comparison of the extracted variable-field and measured single-field mobility and density data. (a) Temperature-dependent mobility and (b) temperature-dependent carrier density curves.

are shown in Figs. 4(a) and 4(b), respectively. The mobility for the 2DEG electron (filled circles) is seen to decrease at higher temperatures, an expected consequence of the increased dominance of polar optical phonon scattering. At lower temperatures, the 2DEG carrier mobility and density are fairly constant. The nominal mobilities and densities for the low-mobility (bulk) electron (filled boxes) do not show strong variations in any temperature range, although the values fluctuate somewhat because the analysis is inevitably less sensitive to lower-mobility carrier species.

For comparison, carrier densities derived in the conventional way from the Hall coefficient at a single field (0.48 T) are shown as stars in Fig. 4(b), while corresponding mobilities obtained by combining this density with the zero-field resistivity are given by the same symbol in Fig. 4(a). Whereas the single-field data imply n-type conduction at $T \leq 250$ K (filled stars), a low-mobility hole (i.e., the Hall coefficient is positive) is implied at 300 K (open stars). At this temperature the electron and hole contributions to the Hall coefficient nearly cancel out, leaving a small value which implies a large (but unphysical) nominal carrier density. Clearly, this behavior and the other properties implied by the raw data at a single field do not realistically approximate those of any of the actual carriers known from QMSA to be present in the heterostructure. This further illustrates the importance of performing a mixed-conduction analysis when multiple carrier species contribute.[15]

From Fig. 4(b), we find that at 80 K the sheet carrier concentrations of the 2DEG and bulk electrons are $n_s^{2DEG} \sim 7.0 \times 10^{11}$ cm^{-2} and $n_s^{GaN} \sim 7 \times 10^{11}$ cm^{-2}. Accounting for the total GaN thickness of 8.8 μm, the latter result corresponds to a bulk density of $\sim 8 \times 10^{14}$ cm^{-3}, which is quite consistent with the previously determined carrier density of $\sim 1 \times 10^{15}$ cm^{-3} for the HVPE-grown GaN template at this temperature.

In summary, we have demonstrated that the QMSA technique can indeed be applied to the AlGaN/GaN heterostructure system, in conjunction with measurements of the Hall coefficient and resistivity as a function of magnetic field. QMSA successfully separated the 2DEG and bulk carriers within the investigated heterostructure, which had a substantial contribution from the 8-μm-thick bulklike HVPE buffer layer. The analysis led to 2DEG and bulk electron mobility values of $\sim$7100 and 880 cm^2/V s at 80 K, respectively.

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