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Quantitative Mobility Spectrum Analysis of AlGaN/GaN Heterostructures Using Variable-Field Hall Measurements

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Abstract. Carrier transport properties of AlGaN/GaN heterostructures have been analyzed with the quantitative mobility spectrum analysis (QMSA) technique. The nominally-undoped $Al_{0.15}Ga_{0.85}N$/GaN sample was grown by metal-organic vapor phase epitaxy. Variable-magnetic-field Hall measurements were carried out in the temperature range of 4–160 K and magnetic field range of 0–6.6 T. QMSA was applied to the experimental variable-field data to extract the concentrations and mobilities associated with the high-mobility 2DEG and the relatively low-mobility bulk electrons for the temperature range investigated. For temperatures below 100 K the calculated mobility and carrier density values were close to the experimental results. No bulk conduction was observed in this temperature range. At 160 K, QMSA results show that parallel conduction in 3 μm thick GaN layer started to affect the average electron mobility.

Introduction

The wide bandgap 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]. High-performance AlGaN/GaN-based MODFETs have been demonstrated by several research groups [2, 3]. Since the electron mobility and 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 multi-carrier properties of such multi-layered 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 [4]. 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, and HgCdTe heterostructures, as well as bulk InN and GaN epilayers. 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 [5]. More recently, Elhamri *et al.* obtained variable-field Hall data and performed a "reduced conductivity" analysis, on AlGaN/GaN samples grown by metalorganic chemical vapor deposition on Si (111) substrates [6].

In the present study, we have carried out variable-field Hall and resistivity measurements on AlGaN/GaN heterostructures grown on sapphire substrates prepared by metal-organic vapor phase epitaxy (MOVPE). We apply QMSA to the data for nominally-undoped AlGaN/GaN heterostructures, in which a 2 dimensional electron gas (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.

Experimental

The investigated sample was grown in a rotating-disk MOVPE chamber on a c-plane sapphire substrate. The MOVPE deposition consisted of a 3 μm GaN layer, followed by a 25 nm $Al_{0.15}Ga_{0.85}N$ layer, and capped by 3 nm of GaN, all nominally undoped. Surface band bending considerations, 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. A four-contact Van der Pauw 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 900 °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 7 T magneto-cryostat and low-noise ac lock-in technique. The measurements were performed under ac current of 1 μA and varying magnetic field (0–6.6 T) applied perpendicular to the sample surface. Measurements were performed at temperatures of 4 K, 40 K, 90 K, and 160 K.

Longitudinal resistivity (ρ_{xx}) and Hall resistivity (ρ_{xy}) values obtained from the variable-field measurements were used to determine the corresponding conductivity tensor elements $\sigma_{xx}(B)$ and $\sigma_{xy}(B)$ [7]. Then QMSA was employed to derive the mobility spectrum and extract the densities and mobilities of carriers in the $Al_{0.15}Ga_{0.85}N$/GaN heterostructure.

Results and Discussion

Figure 1 shows the measured magnetoresistivity curves as a function of sample temperature. The ρ_{xx} data recorded at 4 K in Figure 1(a) displays clear Shubnikov de-Haas (SdH) oscillations starting around 3.5 T, confirming the existence of a high-mobility 2DEG at the hetero-interface. At 4 K, the measured mobility and carrier density were determined as 16980 cm^2/Vs and 4.4×10^{12} cm^{-2} respectively. Temperature dependence of ρ_{xx} and ρ_{xy} curves are plotted in Figure 1(b) and 1(c). SdH oscillations disappear for temperatures higher than ~10 K. ρ_{xx} increases at elevated temperatures which indicates that the mobility decreases with temperature. The mobility at 160 K decreases to 4940 cm^2/Vs. Since the slope of Hall resistivity, ρ_{xy} is inversely proportional to the carrier concentration, the carrier density is increasing at higher temperatures. At 160 K, the carrier density becomes 6.1×10^{12} cm^{-2}.

Application of QMSA to the variable-field data showed that only one high-mobility electron contribute to the transport at temperatures up to at least 90 K. Figure 2(a) shows the calculated mobility spectrum for the $Al_{0.15}Ga_{0.85}N$/GaN sample at 40 K. The single peak at 12600 cm^2/Vs corresponds to the high-mobility 2DEG electrons within the channel at the $Al_{0.15}Ga_{0.85}N$/GaN interface. It should be reiterated that the sample was not intentionally doped and the 2DEG formed due to polarization. No sign of low-mobility parallel conduction was observed till 90 K. QMSA data shown in Figure 2(b) demonstrates that bulk conduction becomes active in the heterostructure: Besides the 2DEG carrier, a low-mobility electron is recorded which may be associated with the bulk electrons within the 3 μm thick GaN layer. The mobility of this bulk carrier is 1400 cm^2/Vs and the sheet carrier density is 3.2×10^{11} cm^{-2}. Taking the 3 μm thickness into account, the carrier density of this bulk carrier is determined as ~1.1×10^{15} cm^{-2}, which is in close agreement with the results obtained from C-V measurements.

The temperature-dependent mobilities and carrier concentrations extracted from the QMSA are compared with the experimental values in Figures 2(c) and 2(d), respectively. The experimental and

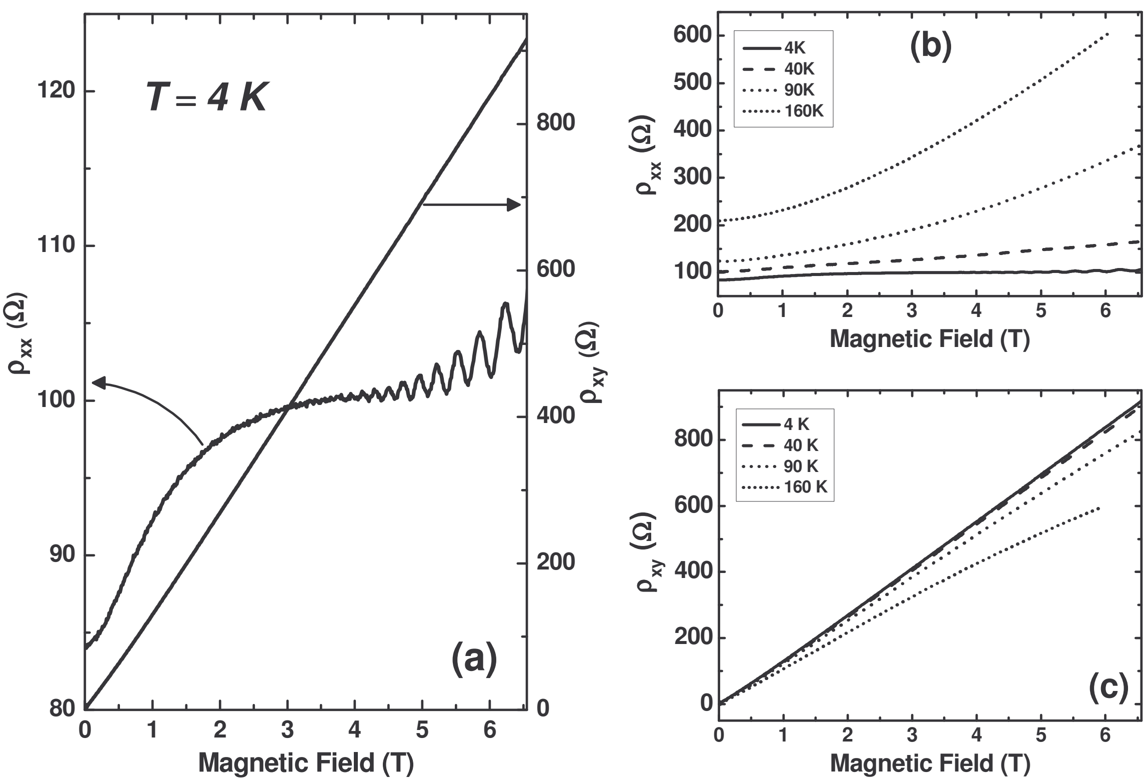

Fig. 1. (a) Measured magnetoresistivity and Hall resistivity curves at 4 K. (b) Temperature dependent experimental magnetoresistivity and (c) Hall resistivity data for $Al_{0.15}Ga_{0.85}N$/GaN sample.

theoretical mobility values are in close proximity at 40 K and 90 K. Since the measured mobility corresponds to the average carrier mobility in the heterostructure, at 160 K, the measured value is lower than the calculated 2DEG mobility. Similarly, the carrier density values obtained from experiment and QMSA are in close agreement except 160 K where bulk electron carrier significantly influences the cumulative sample mobility and carrier density.

An interesting observation of the QMSA data is that the 2DEG carrier density shows a decreasing behavior as temperature increases. The opposite characteristic was observed in the measurements. The reason for this discrepancy is not fully understood yet. One of the possible mechanisms can be the annealing effect. Since GaN/AlGaN structures are known to exhibit persistent photoconductivity [8], the sample may not have fully recovered at 160 K, leading to a decrease in carrier density with annealing. Another possible source may be due to the temperature dependence of strain at the GaN/AlGaN hetero-interface. Further experiments are planned to explore the responsible mechanism.

Conclusions

In summary, we have demonstrated that the QMSA technique can indeed be applied to the AlGaN/GaN heterostructure system, in conjunction with measurements of magnetoresistance and Hall effect. QMSA successfully separated the 2DEG and bulk carriers within the investigated heterostructure. The analysis led to 2DEG and bulk electron mobility values of 6280 cm^2/Vs and 1400 cm^2/Vs at 160 K, respectively. The maximum mobility values measured and calculated are 16980 and 15200 cm^2/Vs at 4 K, respectively.

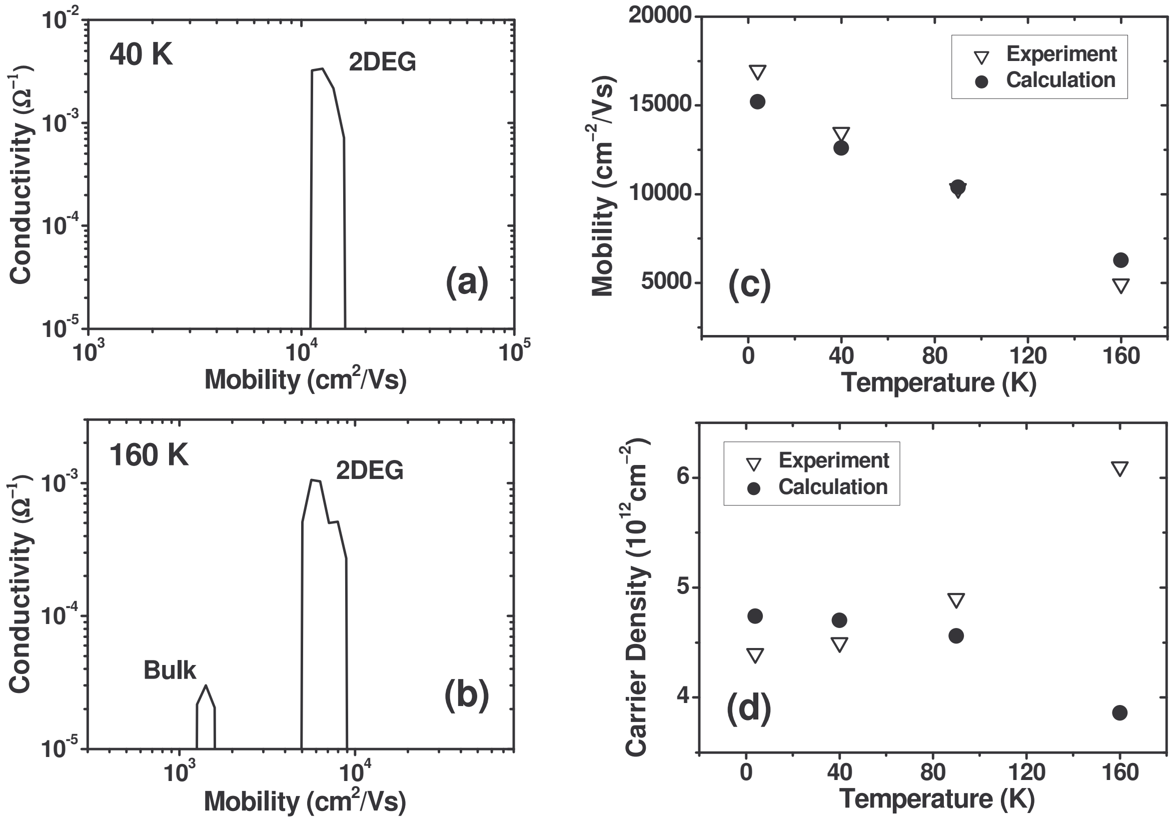

Fig. 2. (a,b) Mobility spectrum calculated with QMSA at 40 K and 160 K. (c) Measured and calculated temperature dependent mobility and (d) temperature dependent carrier density curves.

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