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High mobility in *n*-type GaN substrates

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High peak electron mobilities were observed in freestanding *c*-plane GaN layers. Two well-defined electrical layers, a low mobility degenerate interface layer, and a high mobility nondegenerate bulk layer, were present in these samples. The carrier concentrations and mobilities for the layers were extracted using two methods: (1) magnetic field dependent Hall effect analysis; and (2) a simple two layer Hall model with the assumption that one of the layers is degenerate. The electron Hall mobility of the bulk layer is found to peak at nearly 8000 cm²/V s at low temperature using the magnetic field dependent Hall effect analysis. © 2001 American Institute of Physics. [DOI: 10.1063/1.1348304]

Many applications exist for the III nitrides in high-power and high-temperature electronics,¹ solar-blind ultraviolet photodetectors,² and blue and ultraviolet light emitting and laser diodes.³ However, materials issues still dominate. One of the remaining issues is the lack of availability of high quality GaN substrates. GaN substrates with low dislocation densities and low concentrations of point defects such as impurities and vacancies can be expected to have much higher mobilities than those which have been observed in highly defective thin films or bulk materials which typically have high impurity concentrations. In this letter, the electrical properties of a type of GaN substrate have been studied. Different methods will be compared for separating the electrical properties of the different layers in these freestanding hydride vapor phase epitaxy (HVPE) grown substrates.

Figure 1 plots the carrier concentration and mobility for one of the bulk GaN samples. Temperature dependent Hall effect and resistivity measurements were taken in the van der Pauw configuration. First, data from a single magnetic field of 0.5 T is shown as “uncorrected” in the plots. A very high peak mobility of nearly 4000 cm²/V s is seen in Fig. 1(b). However, the assumption that the sample is made up of a single layer, used to make the uncorrected plots, is obviously seen to be incorrect by the apparent decrease in carrier concentration with increasing temperature [Fig. 1(a)]. At low temperatures (<30 K), a degenerate layer dominates, as evidenced by the flat lines in this set of figures. The electron mobility of this degenerate layer is about 33 cm²/V s, and the sheet electron concentration is 8.4×10^{15} cm⁻².

Next, a two-layer Hall model was used since it was found that these free-standing GaN substrates exhibit electrical properties similar to those of other HVPE grown layers

with a degenerate layer at the interface with the substrate.⁴ The corrected data for the high mobility bulk layer was obtained using the equations in Ref. 4 and is plotted as “two-layer” in Fig. 1. This model assumes that the low mobility degenerate layer retains its properties over the entire temperature range of interest and can therefore be “subtracted” simply by knowing its properties at low enough temperatures for the bulk-like layer to be frozen out. The resulting corrected data are much more realistic for the bulk portion of the sample. Figure 1(a) shows a corrected carrier concentration that increases with temperature, as it should, although the shape hints at the possibility of multiple levels. Figure 1(b) shows a peak mobility in the data from the two-layer Hall model of about 5500 cm²/V s, a significantly higher value than the uncorrected data, which include a combination of the high and low mobility layers. The highest mobility reported for a GaN layer previously was about 3000 cm²/V s at 70 K in a 4-μm-thick film.⁵ This value is also much higher than previously reported⁴ peak mobilities of about 2000 cm²/V s for HVPE grown material.

In order to better determine the parameters of the different layers, magnetic field dependent Hall effect measurements were taken. The data taken at 70 K are plotted in Fig. 2(a) along with the fit as in the analysis of Kim *et al.*⁶ The reduced conductivities, *X* and *Y*, are σ_{xx} and $2\sigma_{xy}$, respectively, divided by the zero field conductivity. When the reduced conductivities are plotted in this manner and only a single electron mobility μ is present, then at a magnetic field $B = 1/\mu$, *X* passes through 0.5 and *Y* peaks with a magnitude of 1. It is clear from this data that there are multiple conduction paths in this sample. The solid lines in Fig. 2(a) are from a two-carrier fit, which yielded $\mu_1 = 7800$ cm²/V s, $n_{1\text{sheet}} = 2.9 \times 10^{13}$ cm⁻², $\mu_2 = 38$ cm²/V s, and $n_{2\text{sheet}} = 9.5 \times 10^{15}$ cm⁻². The dashed lines are a simulation using the values obtained from the two-layer Hall model (not with magnetic field dependent data). This shows that this model is less satisfactory than the fit to the magnetic field dependent data.

The data at the two ends of the temperature range were

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FIG. 1. (a) Carrier concentration as a function of reciprocal temperature. Shown are the uncorrected single magnetic field Hall effect data (■), a simple two layer model plot derived from the single magnetic field Hall effect data (◇), and plots derived from a fit to magnetic field dependent Hall effect data (▲)(○). All concentrations are normalized to the entire substrate thickness. (b) Electron Hall mobility as a function of the temperature. The solid line is a fit to the data from the magnetic field dependent Hall effect analysis.

more difficult to separate by a two-layer analysis. Figure 2(b) shows the magnetic field dependent data taken at 300 K. The solid lines are from a two-carrier fit, which yielded $\mu_1 = 870$ cm²/V s, $n_{1\text{sheet}} = 2.4 \times 10^{14}$ cm⁻², $\mu_2 = 19$ cm²/V s, and $n_{2\text{sheet}} = 3.1 \times 10^{16}$ cm⁻². At this temperature, the highest mobility electrons have a lower mobility than $1/B$ for the highest field used in this experiment. Therefore, the peak in Y is not contained in the acquired data. This makes the fit for the highest temperature data points more uncertain.

The magnetic field dependent data taken at 45 K is shown in Fig. 2(c). The solid lines are from a two-carrier fit, which yielded $\mu_1 = 6900$ cm²/V s, $n_{1\text{sheet}} = 2.5 \times 10^{12}$ cm⁻², $\mu_2 = 39$ cm²/V s, and $n_{2\text{sheet}} = 7.5 \times 10^{15}$ cm⁻². The high mobility conductivity is less than 6% of the total conductivity, resulting in only a small change in the shape of the curves. Below this temperature, it becomes even more difficult to obtain reliable values for the high mobility channel since its conductivity becomes an even smaller fraction of the total conductivity as the carriers continue to freeze out.

In all cases, the simulated data using the two-layer model (dashed lines) deviates significantly from the experimentally obtained magnetic field dependent data (points) indicating that the assumptions going into that model are not valid for this sample. This is most easily explained by looking at Fig. 1(a). The carrier concentration of the low mobility

FIG. 2. Reduced conductivities as a function of magnetic field at (a) 70, (b) 300, and (c) 45 K. Solid lines are the fit to the magnetic field data with two carriers. Dashed lines are simulated data using the values obtained from the two-layer Hall model.

FIG. 3. Carrier concentration corrected for Hall factor ($n = n_H \times r_H$) and fit (solid line) as a function of reciprocal temperature.

TABLE I. Ionization energies, donor concentrations, acceptor concentrations, degenerate layer sheet concentration, and mobility.

Sample	E_{a1} (meV)	N_{D1} (cm ⁻³)	E_{a2} (meV)	N_{D2} (cm ⁻³)	N_A (cm ⁻³)	N_{sheet} (cm ⁻²) (10 K)	μ (cm ² /V s) (10 K)
S703	27.1	8.2×10^{15}	189	1.6×10^{17}	2.6×10^{15}	8.4×10^{15}	33
S729	26.9	1.3×10^{16}	170	1.3×10^{17}	2.4×10^{15}	2.2×10^{16}	44

“degenerate” layer increases significantly with temperature, while the two-layer Hall model assumes that this remains constant.

The resulting data points from the fits to the magnetic field dependent Hall effect data are plotted in Fig. 1 as “high-mobility-field fit” and “low mobility-field fit” for the bulk like and thin degenerate layers, respectively. Both were normalized to the entire sample thickness for easy comparison with the other plots.

The high mobility data were then fitted as a function of temperature. First, the mobility data were fitted only for N_A , with the rest of the parameters, which were taken from the literature, being held fixed. The solid line in Fig. 1(b) is the simulated data using the resulting value of N_A . The relatively poor fit may be due to errors in the GaN parameters taken from the literature since most are not yet very well known. The values used and other assumptions for the fit are given in Ref. 4. The fit resulted in an acceptor concentration of $2.6 \times 10^{15} \text{ cm}^{-3}$.

The acceptor concentration obtained from the mobility fit was then used as a fixed parameter in the fit of the carrier concentration.⁴ The Hall concentration ($n_H = 1/qR_H$) obtained from the magnetic field dependent measurement is replotted in Fig. 3 along with the concentration corrected using the computed Hall factor ($n = n_H \times r_H$). The fit to the corrected data is shown as a solid line. The parameters from the fit are shown in Table I. The deeper level parameters could have large errors because of the uncertainties in obtaining the high temperature data points as mentioned earlier and because of the small number of points at higher temperatures. More work is needed to verify the existence of this deeper donor.

A second sample was also studied and was found to be qualitatively similar, giving only slightly different numerical results as shown in Table I. The donor energy of 27 meV is the least screened donor energy ever reported for GaN by Hall effect measurements. Previously reported values⁷ include 17 and 19 meV for Si and Ge doping respectively at a donor concentration of $3 \times 10^{17} \text{ cm}^{-3}$, and 16 meV⁴ for a donor concentration of $2 \times 10^{17} \text{ cm}^{-3}$. The higher energy results from the lower carrier concentrations because the donor energy, $E_D = E_{D0} - \alpha N_D^{1/3}$ where E_{D0} is the unscreened do-

nor energy, N_D is the donor concentration, and α is the screening factor (which has been given as $2.1 \times 10^{-5} \text{ meV/cm}$).⁸ E_{D0} has been given as 29 meV for Si donors.⁹ Therefore, E_D would be 24–25 meV for these samples, which is slightly lower than the 27 meV obtained from the fit. We do not believe that this shallow level is the deeper level which has been attributed to oxygen doping ($E_D = 29 \text{ meV}$ for $N_D = 10^{18} \text{ cm}^{-3}$).⁷

In summary, both samples had two layers, one with a low carrier concentration and high mobility and a second degenerate layer with low mobility. Different techniques were used to separate the two layers. The best data resulted from the magnetic field dependent Hall effect analysis although this was also the most time consuming technique. Record high mobilities of nearly 8000 cm²/V s for bulk GaN were observed at low temperatures. The high mobility is believed to be due to the reduced scattering from ionized acceptors. The lower acceptor concentration in these samples could be the result of reduced impurities, dislocations, and native defects such as gallium vacancies. In addition to shallow donors with an ionization energy of 27 meV, a second deeper donor may also be present. This requires further investigation, however.

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