Direct measurement of electron transport in GaN/sapphire interface layer grown by metalorganic chemical vapor deposition

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Hall effect and capacitance–voltage measurements confirm a conductive thin layer near the GaN/sapphire interface. The temperature-dependent Hall effect of the interface layer was directly measured at temperatures above 100 K, and the results were satisfactorily described by solving the Boltzmann transport equation with various scattering mechanisms. Transport occurs in the conduction band of the layer and is characterized by two dominant scattering mechanisms due to space charge and ionized impurity. The high acceptor density and large space charge effect are related with the dislocations in the interface layer.
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Large lattice mismatch between GaN and sapphire may cause a highly dislocated layer near the GaN/sapphire interface,[1,2] resulting in a thin conductive layer (300–500 nm thick) near the interface (hereafter referred to as ''interface layer'').[3,4] In this case, a two-layer model including the interface layer and the rest of GaN layer is required to understand the electrical transport property of undoped GaN/sapphire structure.[4,5] Lacking in detailed knowledge of the mixed conduction in the GaN/sapphire structure, it is formidable to understand more complicated, useful structures such as AlGaN/GaN/sapphire. For a precise description of a two-layer structure, a reliable knowledge of, at least, one of the constituting layers is required. However, because such necessary knowledge is not available, the two-layer analyses have relied on some assumptions, and/or been applied to some limited range of experiments. Lately, the interface layer has been confirmed for the samples grown by the hydride vapor-phase epitaxial (HVPE) method.[6,7] These recent reports showed that the conduction in the interface layer arises from a donor impurity band, mainly due to oxygen. Look *et al.* measured Hall effect at low temperature, 13 K.[6] At a very low temperature, all the electrons freeze out in the impurity bands of both interface and GaN layers, but the impurity band effect of GaN layer may be trivial compared to that of the interface layer. As a result, the low-temperature Hall effect may be viewed as a single-band effect of the interface layer, and the mobility can be analyzed in terms of two scattering mechanisms due to dislocation and ionized impurity because they are dominant at low temperatures. From their results, the ''α model'' was proposed which relates donor and acceptor densities with dislocation density, N_{dis}, as $N_D = \alpha N_{\mathrm{dis}}/c$ and $N_A = N_{\mathrm{dis}}/c$, where c is the appropriate lattice constant (5.185 Å) and α a constant on the order of 1–2. In the present work, we measured the electron transport in the conduction band of the interface layer, not mixed with the GaN layer, at temperatures above 100 K. The analyses exhibit similar transport phenomena to those observed in bulk semiconductors, with exceptionally large effect of the scattering mechanisms due to space charge and ionized impurity.

We have shown in a two-layer electron transport analysis of GaN/sapphire structure that, as the edge-type dislocation (ETD) density increases, the electron density in the GaN layer decreases and accordingly the layer becomes more and more resistive.[5] It is because ETDs trap the electrons in conduction band of the GaN layer and thus the contribution of the layer reduces compared with the interface layer in the two-layer mixed transport. When ETD density is high enough to trap all the electrons in the conduction band of GaN layer, the GaN layer becomes semi-insulating and thus transport would be restricted in the interface layer. This is unambiguously shown by the capacitance–voltage ($C-V$) and Hall effect measurements in the present study.

The GaN layers were grown on sapphire as a function of the flow rate of trimethylgallium (TMGa) during buffer growth by metalorganic chemical vapor deposition, with the layer thickness of $\sim 2\ \mu$m. With decreasing TMGa flow rate, ETD density increases and thus the electron density decreases.[5] We measured $C-V$ characteristics for four different samples with different electron density by employing different TMGa flow rate for buffer layer growth, and the results are shown in Fig. 1. As the carrier density decreases, depletion extends toward the substrate and finally abrupt carrier increase is observed near the GaN/sapphire interface. As expected for sample A in Fig. 1, the Hall effect signals could not be obtained when the measurement was made with the probe contacts formed on the layer face edges as usual in van der Pauw measurement but conduction was detected with the probes formed on periphery, illustrating no other possible origins but a conductive layer near the interface. Such highly resistive samples are usually obtained when the TGMa flow rate is very low, lower than 20 μmol/min in our case, during GaN buffer growth on sapphire.[5] The ETD density is very high, high $\sim 10^9\ \mathrm{cm}^{-2}$, and the Hall mobility is in a range of 50–70 $\mathrm{cm}^2/\mathrm{V\,s}$.

The Hall effects were measured as functions of temperature and typical results are shown in Fig. 2. Room temperature Hall mobility and sheet Hall density of sample A are 58

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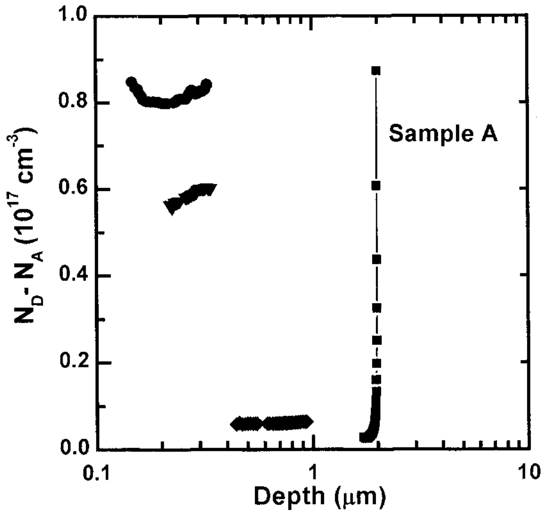

FIG. 1. Depth profile of $C-V$ measurements for the samples of different electron density.

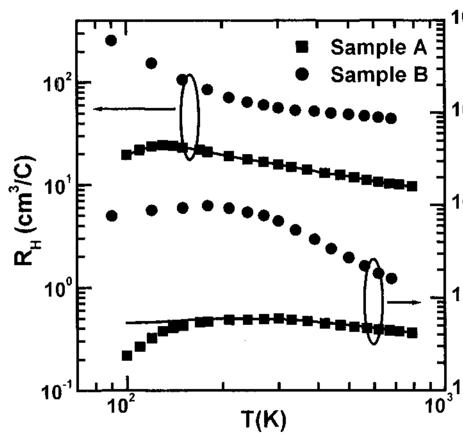

FIG. 2. Hall coefficient and Hall mobility measured as a function of temperature; A, interface layer: B, GaN layer.

cm^2/V s and 1.6×10^{14} cm^{-2}, respectively. To distinguish the interface layer from GaN layer, Hall effect data of a high quality undoped GaN layer (sample B) is compared in Fig. 2. This high quality sample (5 μm thick) shows low ETD density, $\sim1.5\times10^8$ cm^{-2}, high Hall mobility, 670 cm^2/V s, and moderate electron density, 1×10^{17} cm^{-3}. In this case, the contribution of the interface layer can be ignored compared with GaN layer in a two-layer model, and thus only a single-layer effect of GaN layer is observed.[5]

For the analyses of the interface layer of sample A in Fig. 2, the transport was assumed to occur only in the conduction band for a temperature range of present interest, 100 to 800 K. A spherical constant energy surface and Kane form[8] were assumed for the conduction band. A numerical method was adopted in solving the Boltzmann transport equation with various scattering mechanisms,[9] not relying on the relaxation time approximation. The scattering mechanisms calculated in this work are due to polar-optical phonon, deformation potential and piezoelectric acoustic phonon, ionized (CC) and neutral impurities, and space charge (SP). Scattering due to dislocation was ignored, because it is significant only for samples with low carrier density and/or at low temperature.[5,10,11] Compensating acceptor density, N_A, and effective SP cross section, $N_S Q_S$, were adjusted to simultaneously fit the experimental data of Hall coefficient R_H and mobility μ_H. Other material parameters necessary for calculations are well documented elsewhere.[12,13] Interface-layer thickness was assumed to be 4000 Å.[3,4,6,7] Solid curves in Fig. 2 are theoretical value, fitted to experimental data. Good agreements are shown between experiment and theory, except at low-temperature range where impurity-band conduction is expected to be involved.[8] The results of analyses are summarized in Table I. Some of the results for sample B are quoted from Ref. 5, where the Hall effect of sample B is analyzed in detail.

It should be noticed that the values of both N_A and $N_s Q_s$ are very high in the interface layer and two orders of magnitude higher than those in a high quality GaN layer but not much emphasis should be placed on the accuracy of the values because of the assumption on the interface layer thickness adopted in the analysis. However, it is interesting to note that according to the α model,[6] the present value of N_A gives $\sim10^{11}$ cm^{-2} for $N_{\rm dis}(=cN_A)$, which value amounts to a range of values for the samples prepared by HVPE.[6] This value of $N_{\rm dis}$ in the interface layer is about one order of magnitude higher than that of GaN layer in sample A [$\sim7\times10^9$ cm^{-2} estimated by transmission electron microscopy], conforming the highly dislocated phase in the interface layer. Also the result seems to support that the dislocation is the main origin of acceptor in the highly dislocated interface layer, in the absence of other origin with that high density.

To illustrate the relative importance for various scattering mechanisms, theoretical drift–mobility curves for sample A are shown in Fig. 3. Very interestingly, SP scattering is predominant at temperatures above 200 K. Weisberg introduced concept of space charges surrounding local inhomogeneous distributions of impurities and defects to explain anomalously low mobility especially in lightly doped semiconductors.[14] An interesting fact is that Mg-doped p-type GaN layer is highly defective, similar to the interface layer, and that the SP scattering is also very important in the

TABLE I. Sample characteristics.

Sample	n_H (10^{17} cm^{-3}) at RT[a]	μ_H (cm^2/Vs) at RT	N_D (10^{17} cm^{-3}) at RT	E_D (meV)	N_A (10^{16} cm^{-3}) at RT	N_sQ_s (10^4 cm^{-1}) at RT
A Interface layer	4.1	58	<33	37/14	230	240
B Epilayer	1.1	670	2.6	23	7.0	5.0

[a]RT indicates room temperature.

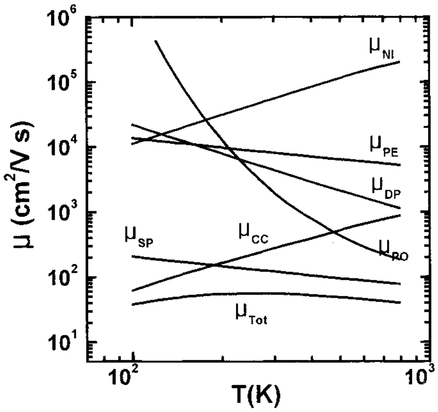

FIG. 3. Drift–mobility variations for various scattering mechanisms in interface layer (sample A).

p-type layer.[15] Therefore, a tentative conclusion is that high density defects cause a inhomogeneous impurity distribution, resulting in high N_sQ_s and short segments of line charges due to dislocations[6] might act as a scattering center of space charge. Figure 3 demonstrates also an important role of CC impurity scattering, mainly due to compensating acceptors, because ionized impurity density is defined by $N_{cc}=n+2N_A$.

Figure 4 depicts n versus $1/T$ relation for two samples in Fig. 2. The electron density is determined by $n=r/R_He$, where r is the Hall scattering coefficient and calculated in the Hall data analysis. In case of sample B, a single donor level is assumed and the n versus $1/T$ relation was fitted by the relationship, $n=N_D/\{1+g_1/g_0\exp[(-E_D+E_F)/k_BT]\}-N_A$,

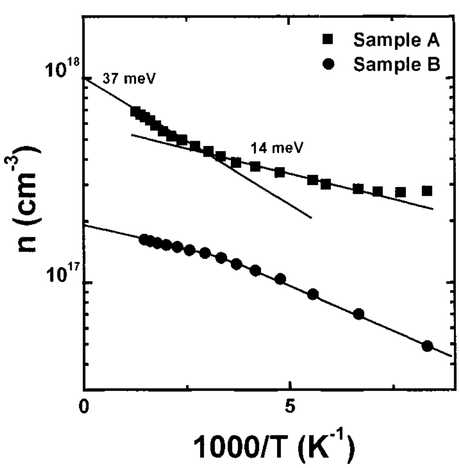

FIG. 4. Electron density variations as a function of inverse temperature.

where 0.5 was assumed for g_1/g_0 as usual and E_F is Fermi level. Donor density, N_D, and activation energy, E_D, only had to be treated as unknowns in the fitting, and other parameters are determined already in the aforementioned analysis. In the case of the interface layer (sample A), however, two levels seem to be indicated by the data in low and middle ranges of $1/T$, respectively, in Fig. 4. Two-donor-level analysis involves too many unknowns to determine the levels characteristics, and thus a simple graphic method was adopted as shown in Fig. 4. The results for the two samples are compared in Table I. The interface layer exhibits two different donor levels. According to recent reports,[6] the shallow and deeper donors may be attributed to Si and O impurities, respectively.

In summary, high electron density layer was confirmed near the GaN/sapphire interface by $C-V$ measurement, and the Hall effect was directly measured for the layer at high temperatures above 100 K. Conduction occurs in the conduction band of the interface layer at the high temperatures, and two scattering mechanisms due to space charge and ionized impurity are dominant. The layer is characterized by the high acceptor density and two donor levels. The high density of acceptor is likely to support the dislocation acceptor model.

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