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Determination of two-dimensional electron and hole gas carriers in AlGaN/GaN/AlN heterostructures grown by Metal Organic Chemical Vapor Deposition

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Abstract

Resistivity and Hall effect measurements on nominally undoped $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures grown on sapphire substrates prepared by metal organic chemical vapor deposition have been carried out as a function of temperature (20–300 K) and magnetic field (0–1.4 T). Variable magnetic field Hall data have been analyzed using the improved quantitative mobility spectrum analysis technique. The mobility and density of the two-dimensional electron gas at the AlGaN/GaN interface and the two-dimensional hole gas at the GaN/AlN interface are separated by quantitative mobility spectrum analysis. The analysis shows that two-channel conduction is present in nominally undoped $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures grown on sapphire substrate.

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Keywords: Aluminium gallium nitride/gallium nitride; Quantitative mobility spectrum analysis; Two-dimensional electron gas; Two-dimensional hole gas

1. Introduction

AlGaN/GaN heterostructures are excellent candidates for high voltage, high power operations at microwave frequencies [1]. A conventional AlGaN/GaN heterostructure is generally formed depositing a layer of AlGaN on a thick GaN epilayer on a semi-insulating substrate. Spontaneous and strain induced polarization lead to a high positive polarization in the AlGaN, resulting in a two-dimensional electron gas (2DEG) induced at the AlGaN/GaN interface [1–3]. Recently, to improve the device performance, conventional AlGaN/GaN heterostructures were grown on directly a bulk AlN substrate and on an AlN epilayer on a semi-insulating substrate [3,4]. By use of a bulk AlN substrate or the insertion of an AlN layer between GaN and a sapphire substrate, the dislocation scattering mechanism and the electron spillover into the bulk are reduced [3,4] and the 2DEG confinement is improved. However, in the case of AlGaN/GaN/AlN a 2D-carriers can be formed at both the AlGaN/GaN and GaN/AlN interfaces. A negative polarization charge at the GaN/AlN interface can cause an accumulation of holes at the interface if the valance band edge of the AlGaN/GaN/AlN heterostructures crosses the Fermi level. On the other hand, the formation of the two-dimensional hole gas (2DHG) at the GaN/AlN interface has reported in the AlGaN/GaN/AlN heterostructures [3,4].

The mobility and sheet carrier density of the 2DEG are the most important parameters in the describing of electronic properties of AlGaN/GaN/AlN heterostructures. Generally these quantities are obtained from the single field Hall measurements. Conventional Hall measurements at a single field provide only a weighted average of the carrier mobility and density, whereas in AlGaN/GaN/AlN heterostructures a 2DHG occurring at the GaN/AlN interface can also contribute to the measurements in addition to the 2DEG occurring at the AlGaN/GaN interface.

In this study, to characterize the multi carrier properties of multi-layered $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures, variable magnetic field and variable temperature Hall effect measurements have been carried out. Variable magnetic field measurements were analyzed using the improved quantitative mobility spectrum analysis (i-QMSA) technique. The QMSA

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technique were described and improved in a number of papers [5–9]. Variable field Hall effect measurements in conjunction with the QMSA technique [10–12] allow extraction of individual carrier mobilities and densities in $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures. Thus, both the 2DEG carriers formed at the $Al_{0.25}Ga_{0.75}N$/GaN interface and the 2DHG carriers formed at the GaN/AlN interface have been investigated in $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures.

2. Experimental details

The sample investigated in this work was grown on c-plane (0001) sapphire (Al_2O_3) substrate in a low-pressure metal organic chemical vapor deposition (MOCVD) reactor. Prior to epilayer growth, the sapphire substrate was cleaned in H_2 ambient at 1100 °C, and then a 10 nm-thick AlN nucleation layer was grown at 840 °C. The reactor pressure was set to 5000 Pa during the substrate cleaning and nucleation growth. After the deposition of the AlN nucleation layer, the wafers were heated to a high temperature for annealing. For the samples, approximately a 0.25 µm thick AlN buffer layer was deposited on the annealed nucleation layers at 1125 °C with a reactor pressure of 2500 Pa. After the deposition of buffer layers, an approximately 0.32 µm GaN layer and a 2.143 µm high growth-rated GaN layer were grown. Finally, a 27 nm thick $Al_{0.25}Ga_{0.75}N$ with 3 nm GaN cap layer was grown. All layers are nominally undoped. The details of samples are given in Fig. 1.

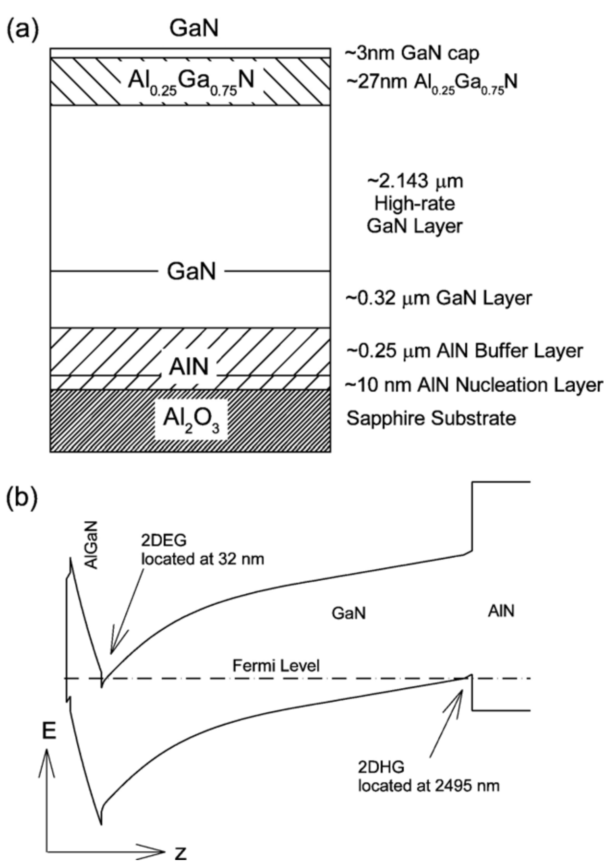

Fig. 1. (a) Layer structure and (b) simulated band diagram with *nextnano*^{3} in the case of zero bias for the $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures.

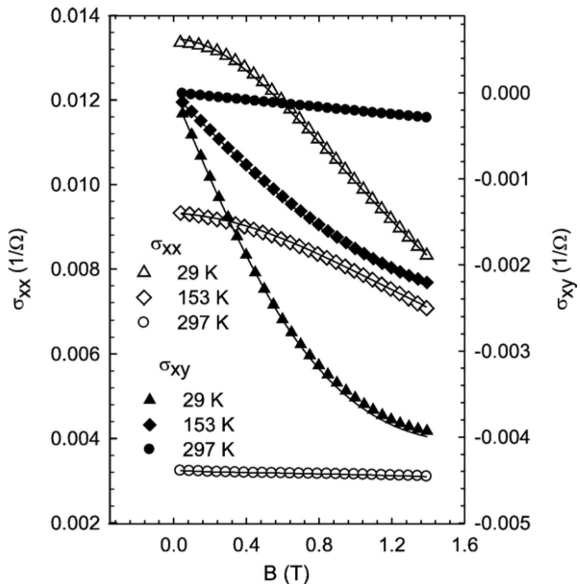

Fig. 2. Conductivity tensors vs. magnetic field at 29, 153 and 297 K. The symbols are the experimental data and the lines are fits from QMSA.

For the resistivity and Hall effect measurements by the van der Pauw method, square shaped (5×5 mm^2) samples were prepared with four evaporated Ti/Al/Ni/Au ohmic contacts in the corners. Using gold wires and In soldering the electrical contacts were made and their ohmic behavior was confirmed by the current voltage characteristics. The measurements were made at 17 temperature steps over a temperature range 20–300 K using a Lake Shore Hall effect measurement system (HMS). At each temperature step the Hall coefficient and resistivity were measured for both current directions, both magnetic field polarization, and all possible contact configurations at 28 magnetic field steps between 0 and 1.4 T. The magnetic field dependent data are analyzed using i-QMSA provided by Lakeshore.

3. Result and discussion

Resistivity and Hall measurements as a function of magnetic field were carried out in the temperature interval of 20–300 K. At each temperature step, to obtain conductivity tensors (σ_{xx} and σ_{xy}) the field dependent Hall coefficient and resistivity data were used as input parameters in QMSA. For the demonstration, the derived experimental conductivity tensors (symbols) and the fitted results (solid lines) from QMSA are given in Fig. 2 for the only three temperatures. The near perfect fit (solid lines) to the data is a good indication of the validity of the QMSA spectrum presented below.

We have performed the application of the QMSA technique to the measured field-dependent data to obtain the multi carrier mobility spectra at each temperature step in the studied temperature range. Fig. 3 shows the mobility spectrums for the $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures at 110 K. The electron peak placed at 5.6×10^3 cm^2/Vs corresponds to the 2DEG formed at $Al_{0.25}Ga_{0.75}N$ /GaN interface. The hole peak placed at 7.6×10^3 cm^2/Vs corresponds to 2DHG formed at

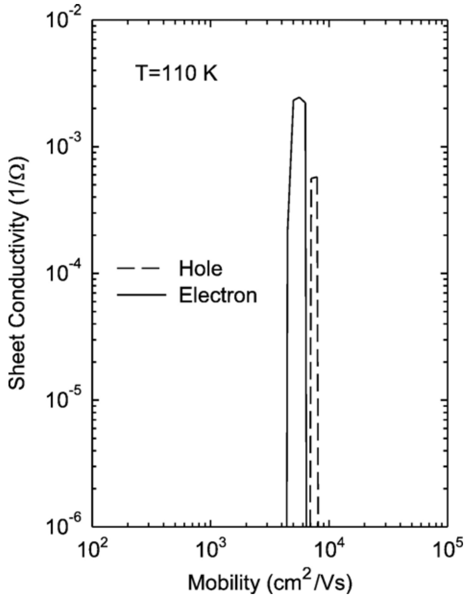

Fig. 3. QMSA spectra for $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructure at 110 K. The solid peak corresponds to 2DEG carrier and the dashed peak corresponds to 2DHG carrier.

GaN/AlN interface. The QMSA produces one electron peak and one hole peak at each temperature step in the studied temperature range of 20–300 K. The hole peaks obtained from QMSA for $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures can not be accepted as "ghost holes" as for AlGaN/GaN heterostructures grown on sapphire substrate [12]. In their structures there is no possibility to occur positive charge carriers because of the layer and band structures, polarization mechanisms and growth conditions. Our structure contains GaN layer grown on AlN buffer layer, which causes positive charge formation at the interface as a consequence of the change in the polarizations between GaN and AlN layers. On the other hand, because of the difference in the band gap between AlN and GaN, the valance band edge of $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures can cross the fermi level near the GaN/AlN interface. Therefore, the induced positive charge can accumulate to form a 2DHG at the GaN/AlN interface.

Since the studied sample is undoped, the 2DEG formed at the $Al_{0.25}Ga_{0.75}N$ /GaN interface is due to spontaneous and strain induced positive polarizations. The GaN layer with a thickness of 2.4 μm, which is much larger than the critical thickness of GaN/AlN heterostructures [13], is treated as fully relaxed, and therefore only negative spontaneous polarization charges appear at the GaN/AlN interface. The negative polarization charges cause an accumulation of holes at the GaN/AlN interface since the valance band edge of the $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures crosses the Fermi level near the GaN/AlN interface. The calculated band diagram for the $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures shown in Fig. 1(a) is depicted in Fig. 1(b). It is clear from Fig. 1(b) that the *nextnano*^{3} [14] simulation results indicate the formation of the 2DHG at the GaN/AlN interface. On the other hand, in the AlGaN/GaN/AlN heterostructures a formation of 2DHG at the GaN/AlN interface has also been reported elsewhere [3,4].

Fig. 4(a) and (b) summarize the QMSA results as a function of temperature for the integrated density and mobility for the each electrons (2DEG) and holes (2DHG) observed. In the Fig. 4(a) and (b) the mobility and carrier density measured at 0.5 T are also given with circles for a comparison. From the Fig. 4(a) and (b), it can be clearly understood that the density of both the 2DEG and the 2DHG carriers, which are obtained from QMSA, is considerable smaller than the measured sheet carrier density taken at single field ($B=0.5$ T) Hall measurements while the mobilities related with the 2DEG and the 2DHG carriers are considerable higher than the measured mobility. However, the 2DHG density is rather smaller than that of the measured one. At low temperatures the measured sheet carrier density and the densities of the 2DEG and 2DHG with the values of 2.2×10^{13} cm^{-2}, 9.2×10^{12} cm^{-2}and 1.2×10^{12} cm^{-2}, respectively, are independent of temperature. This behavior is typical of two-dimensional gas structure. At high temperatures the measured sheet carrier density tends to remain constant while the densities of 2DEG and 2DHG slightly decrease with increasing temperature.

At low temperatures the measured mobility and the extracted mobilities related to the 2DEG and 2DHG are independent of temperature and their values are 4×10^3 cm^2/Vs, 6.2×10^3 cm^2/Vs and 7.5×10^3 cm^2/Vs, respectively. At high temperatures both mobilities decrease with increasing temperature, as an expected consequence of the increased dominance of polar optical scattering. However, the conductivity and density of the 2DHG are rather smaller than that of 2DEG while the 2DHG mobility is

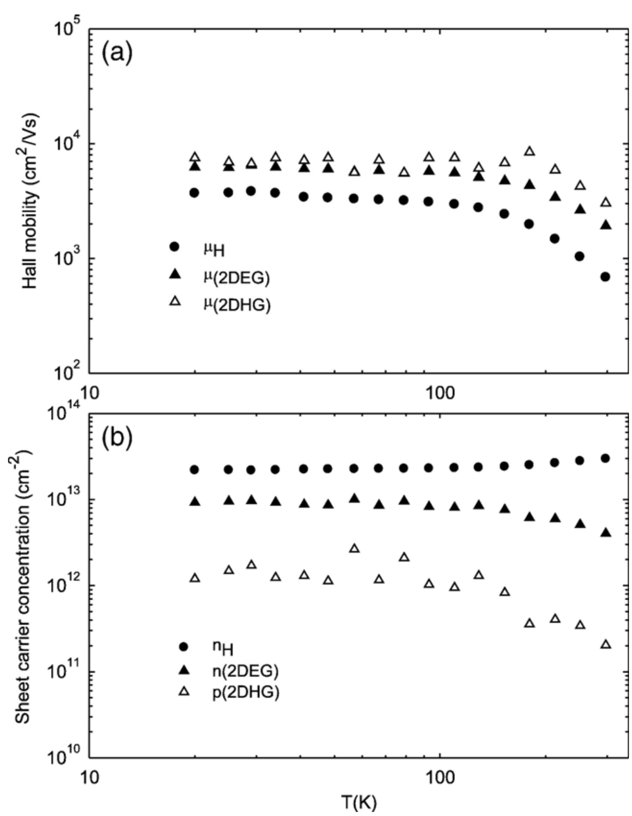

Fig. 4. (a) Mobility and (b) carrier concentration vs. temperature. Circles represent measured mobility and sheet carrier density at 0.5 T. Triangles represent the mobilities and carrier densities extracted from QMSA.

slightly higher than the 2DEG mobility in the studied temperature range. On the other hand, the hole effective mass is heavier than that of electrons. This normally implies that the electron mobility is higher than that of holes. Because of the absence of alloy scattering at the GaN/AlN interface and an increase in the 2DHG mobility at low carrier densities via acoustic and interface roughness scatterings [15], the 2DHG mobility is slightly higher than the 2DEG mobility.

4. Conclusions

In summary, experimental magnetic field dependent resistivity and Hall effect data have been presented as a function of temperature (20–300 K) for undoped $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures grown by MOCVD. The experimental data has been analyzed using the QMSA technique. Analysis show that two carrier species are present in undoped $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures: The 2DEG carriers due to positive spontaneous and strain-induced polarization at the AlGaN/GaN interface and the 2DHG carriers due to only negative spontaneous polarizations at GaN/AlN interface. Below 100 K, it is found that the values of the measured sheet carrier density and the extracted 2DEG and 2DHG densities are to be 2.2×10^{13} cm^{-2} with corresponding mobility value of 4×10^{3} cm^{2}/Vs and 9.2×10^{12} cm^{-2} with corresponding mobility value of 6.2×10^{3} cm^{2}/Vs and 1.2×10^{12} cm^{-2} with corresponding mobility value of 7.5×10^{3} cm^{2}/Vs, respectively. As a result, any conclusions drawn from single field Hall data would be highly misleading since the two-channel conduction is present in nominally undoped $Al_{0.25}Ga_{0.75}N$/GaN/AlN heterostructures grown on sapphire substrate.

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