APPLIED PHYSICS LETTERS VOLUME 74, NUMBER 23 7 JUNE 1999

Electron mobility exceeding 10^4 cm^2/V s in an AlGaN–GaN heterostructure grown on a sapphire substrate

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(Received 23 February 1999; accepted for publication 13 April 1999)

High-quality AlGaN/GaN undoped single heterostructures (SH) with different Al contents have been grown on sapphire substrates. The magnetotransport investigation was performed on these samples at a low temperature. The observation of Shubnikov–de Hass oscillations in the magnetic fields below 3 T and the integer quantum Hall effect confirmed the existence of the two-dimensional electron gas (2DEG) at the AlGaN/GaN interface. The $Al_{0.18}Ga_{0.82}N$/GaN SH shows a Hall mobility of 10 300 cm^2/V s at a carrier sheet density of 6.19×10^{12}/cm^2 measured at 1.5 K. To the best of our knowledge, this is the highest carrier mobility ever measured in GaN-based semiconductors grown on sapphire substrates. The Al composition dependence of the mobility and carrier sheet density were also investigated. Based on the piezoelectric field effect, the Al composition dependence of the 2DEG sheet density was calculated, which agreed well with the experimental result. The negative magnetoresistance with parabolic magnetic-field dependence in the low magnetic field was also observed in the sample with the highest 2DEG sheet density. © *1999 American Institute of Physics.* [S0003-6951(99)03323-9]

In the field of high-power and high-temperature microelectronic devices, AlGaN/GaN heterostructure field-effect transistors (HFETs) have emerged as very attractive candidates due to the wide band gap and extremely high sheet electron channel density. The origin of the sheet electron channel is the formation of a two-dimensional electron gas (2DEG) at the interface. The existence of a 2DEG in an undoped AlGaN/GaN single heterostructure (SH) grown on a sapphire substrate was first observed in 1992, which had a mobility of 2626 cm^2/V s at a low temperature.[1] In 1995, the low-temperature (LT) mobility of the 2DEG in the AlGaN/GaN SH with 5000 cm^2/V s was reported,[2] and then it was further increased to 5700 cm^2/V s in 1996 (Ref. 3) due to the improvement of material quality. After that, there is no any better report for AlGaN/GaN SH grown on sapphire substrates. In contrast, the AlGaN/GaN SH structures grown on SiC substrates showed higher mobilities. Recently, the highest LT mobility with a value of 11 000 cm^2/V s was obtained on a SiC substrate.[4] This is attributed to a much closer lattice match between SiC and GaN (about 3.4%), which results in GaN layers with improved microstructural, electrical, and optical properties. In comparison to it, the lattice mismatch between sapphire and GaN of 13.8% produces material with a high density of threading dislocations. Nevertheless, the insulating property of sapphire is advantageous for high electron mobility transistors. Therefore, it is necessary to improve the quality of AlGaN/GaN SH grown on sapphire substrates.

In this letter, we present our most recent experimental data which demonstrate that an undoped AlGaN/GaN SH grown on a sapphire substrate also showed a very high mobility in spite of the 13.8% lattice mismatch between sapphire and GaN. The LT mobility value is about 10 300 cm^2/V s, which to the best of our knowledge is the highest report ever in GaN-based semiconductors grown on sapphire substrates and is very close to the best result obtained on SiC substrates.[4] In order to further increase the quality, we also need to investigate the mechanism of the formation of 2DEG. The very high sheet density observed in the nominally undoped GaN/AlGaN SH obviously could not be explained by the standard models of the charge transfer between the AlGaN barrier and GaN layer. As suggested by some recent theoretical studies,[5–7] the formation of 2DEG may be due to the piezoelectrically induced charges at the AlGaN and GaN interface. This letter also shows that the electron mobility and 2DEG sheet density are strongly dependent on the Al content. Based on the above model, we calculated the Al content dependence of the sheet carrier density, which agrees well with the experimental results and,

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TABLE I. The electron mobilities and 2DEG sheet density measured at 1.5 K in a magnetic field of 0.2 T.

Samples	Sheet density (cm^{-2})	Mobility (cm^2/V s)
$Al_{0.10}Ga_{0.90}N/GaN$	2.78×10^{12}	5160
$Al_{0.13}Ga_{0.87}N/GaN$	4.13×10^{12}	8000
$Al_{0.18}Ga_{0.82}N/GaN$	6.19×10^{12}	10 300

in turn, this strongly supports the above model.

The AlGaN/GaN heterostructures were grown by a horizontal metalorganic chemical vapor deposition (MOCVD) system on a (0001) Union Carbide sapphire substrate. Trimethylgallium, trimethylaluminum, and ammonia were used as precursors, with H_2 as a carrier gas. Unlike two-flow MOCVD, our growth technique uses three-layer laminar flow gas injection, which is designed for a high-speed gas flow. During the growth of the AlGaN layer, the total gas flow rate is about 62 l/min. The high-speed gas flow can effectively suppress thermal convection, and thus, can greatly increase the quality of the samples. After annealing the substrate in H_2 at 1150 °C, a 25 nm thick GaN buffer layer was deposited at 450 °C, followed by 2 μm of an undoped GaN layer and a 120 nm undoped AlGaN layer grown at 1075 °C. The Al contents of the three samples used in this letter are 10%, 13%, and 18%, respectively. The Al contents were measured based on a (0006) x-ray diffraction measurement. For the low-temperature transport measurements, the samples were mounted in a liquid–helium cryostat, containing a magnetic field up to 10 T, and the standard ac lock-in technique was used. In each sample, high-purity Al/Ti was used to form the contacts.

Table I shows the electron mobilities and sheet densities which were obtained in the magnetic field of 0.2 T at 1.5 K. In the sample with 18% Al composition, the electron mobility reaches 10 300 cm^2/V s at a carrier sheet density of 6.19 $\times10^{12}/cm^2$, which to the best of our knowledge is the highest value ever in GaN-based semiconductors grown on sapphire substrates and is also very close to the best report with a value of 11 000 cm^2/V s grown on SiC. In this case, we would like to emphasize: in spite of the much higher lattice mismatch of sapphire/GaN than SiC/GaN, a high quality of the 2DEG structure can also be obtained on a sapphire substrate. Table I also indicates that the electron mobility and 2DEG sheet density can be greatly enhanced by increasing the Al composition. As suggested by some theoretical studies,[5–7] due to the large piezoelectrical constants and the large lattice mismatch between GaN and AlGaN, the AlGaN layer on a GaN surface is under tensile strain in the case of strained pseudomorphical growth, which induces a strong piezoelectrical field in the AlGaN layer. As we know, for the growth in the (0001) orientation of III–V nitrides with the wurtzite structure, there will be present in the strained layer a polarization field whose direction is opposite to the growth direction.[8] Therefore, at the AlGaN/GaN interface but on the AlGaN side, a positive piezoelectric sheet charge appears, which induces a sheet negative charge correspondingly. Thus, a 2DEG is formed at the AlGaN/GaN interface. Obviously, the 2DEG sheet density is strongly dependent on the strain which is mainly determined by the Al composition. Based on the piezoelectric field effect,[5–7] we performed the calculation of the Al composition dependence of the 2DEG sheet density without considering the carrier transfer due to the conduction-band discontinuity. The calculated result was given in Fig. 1, which is in good agreement with the measurement. From this result, one can believe that the formation of 2DEG in an undoped AlGaN/GaN SH mainly originates from the piezoelectric field.

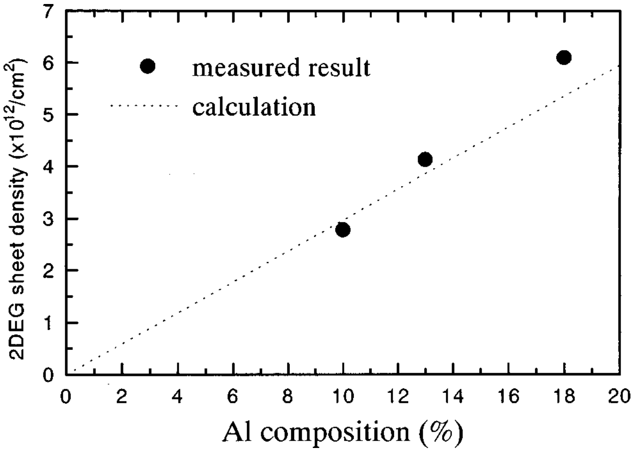

FIG. 1. Al composition dependence of 2DEG sheet density. The dashed line corresponds to the calculation result based on the piezoelectric field effect. The solid circles were obtained from Table I.

In order to confirm the existence of 2DEG, low-temperature magnetotransport measurements were performed. Figures 2(a), 2(b), and 2(c) show the magnetoresistance R_{xx} and Hall resistance R_{xy} as a function of magnetic field up to 10 T at 1.5 K for the $Al_{0.1}Ga_{0.9}N/GaN$ SH, $Al_{0.13}Ga_{0.87}N/GaN$ SH, and $Al_{0.18}Ga_{0.82}N/GaN$ SH, respectively. In each sample, strong Shubnikov–de Hass (SdH) oscillations were clearly observed. In addition, the threshold magnetic field for observation of SdH oscillations was also found to depend on the Al composition. For example, in the case of 10% Al composition, the threshold magnetic field is about 2.8 T, in the case of 13% Al composition, it decreases to about 2.2 T, and it further decreases to about 2 T for the sample with 18% Al composition. Considering the result related to the Al composition dependence of the 2DEG sheet density, one can find that the threshold magnetic field for observation of SdH oscillations decreases with increasing the 2DEG sheet density. Furthermore, in each sample, the minima of the oscillations clearly decrease as the field increases, which is indicative of the presence of a 2DEG and also shows the absence of an appreciable background due to a parallel conduction path in the material.[3] In the case of low-magnetic-field dependence of the R_{xx} measurement (below 2 T), one can note another very interesting point. As we knew, for the classic behavior, the R_{xx} is independent of the magnetic field, as shown in Fig. 2(a) for the sample with 10% Al composition. In this sample, Table I indicates that the 2DEG sheet density is about $2.78\times10^{12}/cm^2$. When the Al composition is increased up to 13%, Fig. 2(b) indicates that the R_{xx} exhibits a little negative magnetoresistance behavior. When the Al composition is further increased up to 18%, one can observe a clear negative magnetoresistance with parabolic magnetic-field dependence. This sample shows a higher sheet density of 2DEG, which is about 2.5 times of that in the sample with 10% Al composition. These

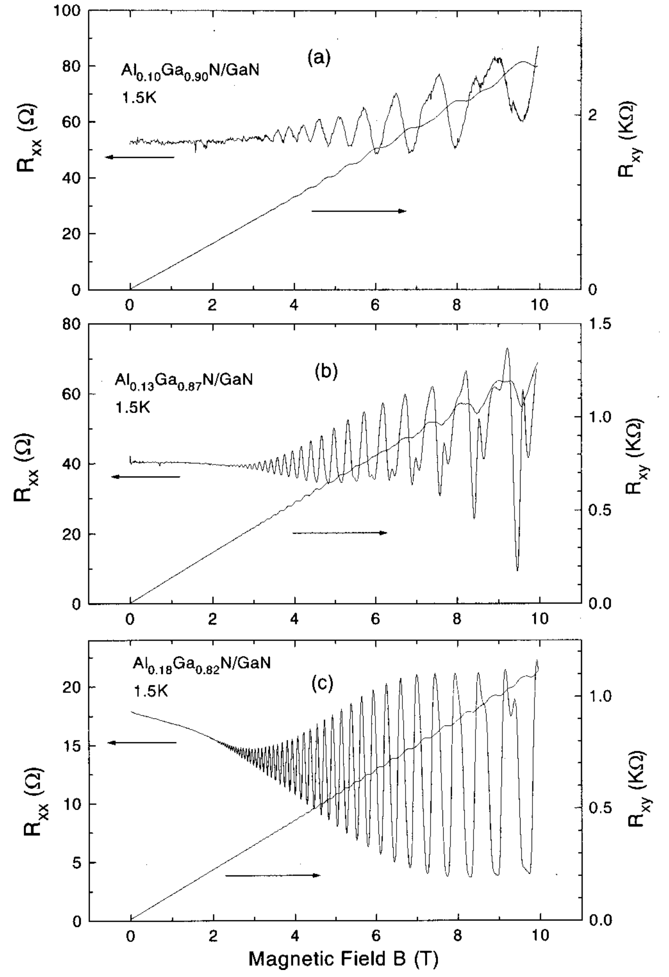

FIG. 2. Magnetic-field B dependence of magnetoresistance (R_{xx}) and quantum Hall resistance (R_{xy}) for (a) $Al_{0.10}Ga_{0.90}N/GaN$ SH, (b) $Al_{0.13}Ga_{0.87}N/GaN$, and (c) $Al_{0.18}Ga_{0.82}N/GaN$, which were measured at 1.5 K. In each case, the SdH oscillation and integer quantum Hall effect were clearly observed.

experimental data suggest that there may exist electron–electron interaction due to the enhancement of the 2DEG density, which needs further work.

The Hall resistance R_{xy} measurements were also carried out, which are given in Figs. 2(a), 2(b), and 2(c). In each sample, well-defined quantum well plateaus are clearly present at high fields. It is well known that the presence of a 2DEG is necessary for the observation of quantum Hall plateaus. Therefore, these experimental data confirm the existence of a high-quality 2DEG at the interface of these structures.

In conclusion, high-quality undoped AlGaN/GaN heterostructures with different Al compositions have been grown on sapphire substrates by MOCVD. The magnetotransport measurement confirmed the existence of the 2DEG at the interface of AlGaN and GaN. By increasing the Al composition, both the low-temperature mobility and 2DEG sheet density were enhanced. In particular, when the Al composition was increased to 18%, the sample shows a Hall mobility of 10 300 $cm^2/V\,s$ at a carrier sheet density of 6.19×10^{12} $electrons/cm^2$ measured at 1.5 K. To the best of our knowledge this mobility represents the highest value, which was obtained ever in GaN-based semiconductors grown on sapphire substrates. Based on the piezoelectric field effect, the Al composition dependence of 2DEG sheet density was calculated, which agrees well with the experimental result obtained in a low magnetic field. In addition, in the sample with the highest 2DEG sheet density, negative magnetoresistance with parabolic magnetic-field dependence was clearly observed, which implied the presence of an electron–electron interaction.

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