Electron mobility in modulation-doped AlGaN–GaN heterostructures

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We report on the measurements of the electron mobility in modulation-doped $Al_{0.2}Ga_{0.8}N$–GaN heterostructures grown on sapphire, conducting 6H–SiC, and insulating 4H–SiC substrates as a function of the sheet electron density, n_s, at the heterointerface in a wide temperature range. The mobility increases with an increase in n_s up to approximately $1\times10^{13}\,cm^{-2}$ and decreases with a further increase in n_s. This is explained by the electron spillover at high values of n_s from the two-dimensional states at the AlGaN/GaN heterointerface into the delocalized states in the doped GaN channel. The maximum electron Hall mobility in excess of $2000\,cm^2/V\,s$ at room temperature and $11\,000\,cm^2/V\,s$ at 4.2 K was measured in the heterostructures grown on 6H–SiC at the values of n_s close to $10^{13}\,cm^{-2}$ and $7\times10^{12}\,cm^{-2}$, respectively. © *1999 American Institute of Physics.* [S0003-6951(99)05301-2]

Recent efforts in developing high power AlGaN–GaN heterostructure field effect transistors (HFETs) have led to a significant progress in improving material quality and reducing thermal self-heating in these devices.[1–5] A large conduction band offset and strong piezoelectric effects in AlGaN–GaN heterostructures result in much higher sheet electron densities than in similar AlGaAs–GaAs heterostructures.[6] The Hall electron mobility, μ_H, in excess of $2000\,cm^2/V\,s$ at room temperature and $10\,000\,cm^2/V\,s$ at 4.2 K was measured in heterostructures grown on 6H–SiC.[4] These values are considerably higher than those found in similar epitaxial structures grown on sapphire, which indicates a better quality of AlGaN–GaN layers grown on SiC substrates. The highest two-dimensional (2D) electron mobility was measured at sheet electron densities as high as $n_s=10^{13}\,cm^{-2}$. A large $n_s\mu$ product, (over $2\times10^{16}\,V^{-1}\,s^{-1}$) is attributed to two factors: (i) electron mobility in GaN is less sensitive to doping than, for example, that in GaAs (see, e.g.,[7]); (ii) a large fraction of the 2D electrons is induced by strong piezoelectric effects (piezoelectric doping).[8–10]

In addition to AlGaN barrier doping and piezoelectric doping, the AlGaN–GaN HFET current carrying capabilities can be further improved by using a doped channel design.[3] A thin (on the order of 100 nm) doped GaN layer (doped channel) near the AlGaN–GaN interface can dramatically increase the number of electrons in the vicinity of the heterointerface. However, one can expect that a high channel doping will reduce the electron mobility.

In this letter, we report on electron transport studies in $Al_{0.2}Ga_{0.8}N$–GaN heterostructures with the doped channel design. We compare heterostructures grown on sapphire, conducting 6H–SiC, and semi-insulating 4H–SiC substrates. We investigate the electron mobility in a wide range of electron densities near the AlGaN–GaN heterointerface, corresponding to the transition from a purely two-dimensional electron gas to a mixture of electrons in 2D and delocalized three-dimensional (3D) states.

The $Al_{0.2}Ga_{0.8}N$–GaN heterostructures were grown by low-pressure metal organic chemical vapor deposition (MOCVD). The epilayer design of the samples is described in Refs. 3 and 5. The electron sheet density, n_s, and Hall mobility, μ_H, were obtained from Hall measurements using (i) van der Pauw contact configuration, and (ii) Hall bar with geometry factor $\gamma=7$ (ratio of the bar length to the bar width). The samples were fabricated by reactive ion etching of the mesa.[4] The measurements were performed in the temperature range from 4.2 to 300 K. The electron density near the AlGaN–GaN heterointerface was modulated by varying the doping level in the GaN channel (approximately 0.1 μm thick) or by using a Schottky barrier gate deposited on top of the entire Hall bar.

Figure 1 shows the electron Hall mobility in $Al_{0.2}Ga_{0.8}N$–GaN heterostructures grown on sapphire, conducting 6H–SiC and semi-insulating 4H–SiC with different levels of the GaN channel doping. The measured sheet electron density varied from $3\times10^{12}\,cm^{-2}$ to approximately $3\times10^{13}\,cm^{-2}$. One can see that for highly doped channel heterostructures ($n_s>2\times10^{13}\,cm^{-2}$), the Hall mobilities for all three types of substrates are similar. However, for $n_s<1.5\times10^{13}\,cm^{-2}$, a reduction in the 2D electron density leads to a significant increase in the electron Hall mobility in the samples grown on 6H–SiC, pointing to a better quality of the heterointerface. The Hall mobility for the structures grown on semi-insulating 4H–SiC is larger than that for the structures grown on sapphire, but smaller than that for the heterostructures grown on 6H–SiC. One of the possible reasons for this may be a better quality of 6H–SiC substrates available from Cree Research, Inc.

The difference in electron Hall mobility for heterostruc-

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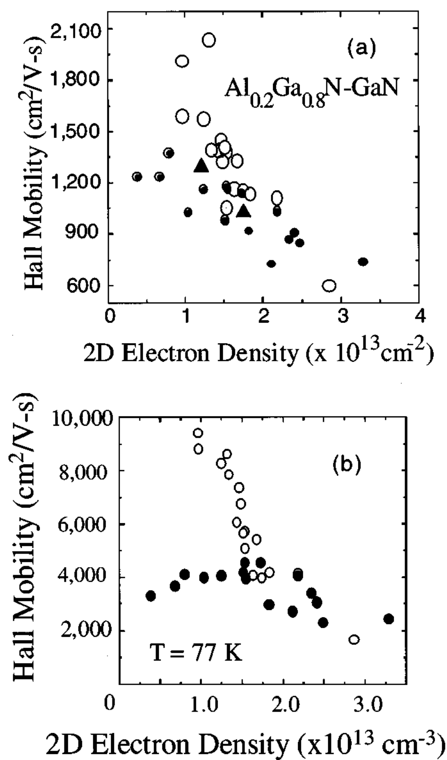

FIG. 1. Electron Hall mobility in $Al_{0.2}Ga_{0.8}N$–GaN heterostructures grown on sapphire (solid dots), conducting 6H–SiC (open circles) and semi-insulating 4H–SiC (triangles) with different GaN channel doping measured at room temperature (a) and $T=77$ K (b).

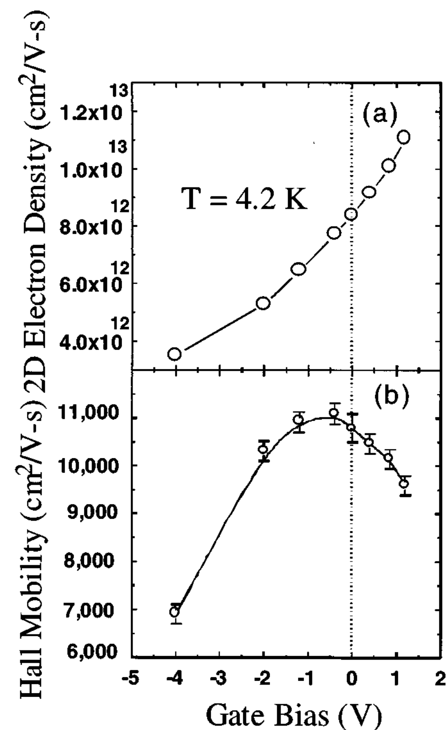

FIG. 2. 2D electron density (a) and electron Hall mobility (b) vs gate bias in an $Al_{0.2}Ga_{0.8}N$–GaN gated Hall bar sample grown on n-type 6H–SiC measured at temperature $T=4.2$ K.

tures on sapphire and silicon carbide becomes even more dramatic at cryogenic temperatures. The Hall mobility in the heterostructures grown on sapphire increases with a decrease in temperature and saturates at approximately $4500\,cm^2/V\,s$ at 77 K. The highest 2D electron Hall mobility in the heterostructures grown on 6H–SiC exceeded $9000\,cm^2/V\,s$ at $T=77$ K and $11\,000\,cm^2/V\,s$ at $T=4.2$ K [see Figs. 1(b) and 2].

Our calculations based on the theory developed in Ref. 7 show that very high sheet electron densities ($n_s>2\times10^{13}\,cm^{-2}$) could not be attributed to a pure 2D-electron gas at the $Al_{0.2}Ga_{0.8}N$–GaN heterointerface. These high values of n_s are achieved by doping a thin GaN layer at the heterointerface. Therefore, at higher doping levels of the GaN channel, a significant fraction of electrons remains in delocalized states in the vicinity of the AlGaN–GaN heterointerface.

Three major contributions determine the sheet electron density near the AlGaN–GaN heterointerface: (i) the contribution from the electrons induced by the doped AlGaN barrier; (ii) the contribution from the dopants in the GaN channel; (iii) the contribution from the electrons generated by the piezoelectric effect (piezoelectric doping).

When the sheet electron density in AlGaN–GaN heterostructures with doped GaN channels exceeds the critical value $n_{2D\,max}\sim1\times10^{13}\,cm^{-2}$,[6] the electrons spill from the quantum well near the heterointerface and occupy the delocalized states in the channel. This leads to a reduction of the electron mobility. This reduction can be explained by a less effective screening and by a more pronounced ionized impurity scattering when electrons occupy a much wider doped region near the heterointerface.[7]

The results shown in Fig. 1 were obtained using different samples. We also measured the electron Hall mobility dependence on the sheet electron density in one sample using a gated Hall bar design. Due to the large conduction band offset in AlGaN–GaN heterostructure, this design allows us to investigate electron mobility in both depletion and enhancement modes by applying negative and positive gate biases, V_g, respectively. Figure 2 shows sheet electron density (a) and electron Hall mobility (b) in an $Al_{0.2}Ga_{0.8}N$–GaN heterostructure grown on n-type 6H–SiC substrate versus gate bias at temperature $T=4.2$ K. The measured Hall mobility at 4.2 K first increases with the gate bias (from approximately $7000\,cm^2/V\,s$ at $V_g=-4$ V up to $11\,100\,cm^2/V\,s$ at $V_g=-0.5$ V) and then decreases with a further increase in V_g (down to $9500\,cm^2/V\,s$ at $V_g=1.5$ V). With an increase in the gate bias from -4 to 1.5 V, the sheet electron carrier concentration increases from approximately 3.5×10^{12} to $1.1\times10^{13}\,cm^{-2}$. At gate bias between -0.5 and -1.0 V, which corresponds to the maximum Hall mobility, the electron sheet concentration is approximately $8\times10^{12}\,cm^{-2}$ and is close to the maximum n_s estimated for the 2D channel near the $Al_{0.2}Ga_{0.8}N$–GaN heterointerface. An increase in the mobility of the 2D-electron gas with an increase in n_s is in agreement with the mobility calculations reported in Ref. 7. The gate voltage range for the measurements at ($-4\,V<V_g<1.5\,V$) was limited by the gate leakage.

In Fig. 3, the electron Hall mobility is plotted as a function of the sheet electron density. Open circles correspond to the data measured in the gated Hall bar at $T=4.2$ K and are shown in Fig. 2. Solid dots correspond to the electron Hall mobility in the $Al_{0.2}Ga_{0.8}N$–GaN heterostructures grown on

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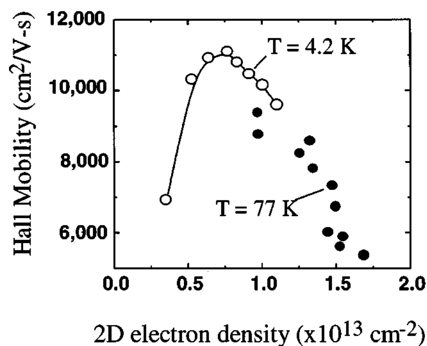

FIG. 3. Electron Hall mobility vs sheet electron density in an $Al_{0.2}Ga_{0.8}N$–GaN heterostructure grown on 6H–SiC. Open circles correspond to data from Fig. 2. Solid dots show the electron Hall mobility measured at temperature $T=77$ K in $Al_{0.2}Ga_{0.8}N$–GaN heterostructures with different GaN channel doping.

6H–SiC with different GaN channel doping and shown in Fig. 1(b). When the sample is cooled down from $T=77$ to 4.2 K, the electron Hall mobility increases by approximately 20%. When we account for this increase, the agreement between mobility values at $n_s > 7\times10^{12}\,cm^{-2}$ measured in the samples with different levels of the GaN channel doping and in the gated Hall bar is quite good.

In conclusion, we have measured electron Hall mobility in modulation doped $Al_{0.2}Ga_{0.8}N$–GaN heterostructures grown on sapphire, conducting 6H–SiC, and semi-insulating 4H–SiC for different sheet electron densities at the heterointerface. The electron mobility is higher for the structures grown on SiC substrates. The mobility first increases with an increase in the sheet carrier density, n_s, up to approximately $1\times10^{13}\,cm^{-2}$ and decreases with a further increase in n_s. This is explained by the electron spillover at high values of n_s from the two-dimensional states at the AlGaN/GaN heterointerface into the delocalized states in the device channel.

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[1] G. J. Sullivan, M. Y. Chen, J. A. Higgins, J. W. Yang, Q. Chen, R. L. Pierson, and B. T. McDermott, IEEE Electron Device Lett. **19**, 198 (1998).
[2] B. J. Thibeault, B. P. Keller, Y.-F. Wu, P. Fini, U. K. Mishra, C. Nguyen, N. X. Nguyen, and M. Le, Tech. Dig. Int. Electron Devices Meet. , 569 (1997).
[3] R. Gaska, Q. Chen, J. Yang, A. Osinsky, M. A. Khan, and M. S. Shur, IEEE Electron Device Lett. **18(10)**, 492 (1997).
[4] R. Gaska, J. W. Yang, A. Osinsky, Q. Chen, M. Asif Khan, A. O. Orlov, G. L. Snider, and M. S. Shur, Appl. Phys. Lett. **72**, 707 (1998).
[5] R. Gaska, A. Osinsky, J. Yang, and M. S. Shur, IEEE Electron Device Lett. **19**, 89 (1998).
[6] R. Gaska, J. Yang, A. Osinsky, A. D. Bykhovski, and M. S. Shur, Appl. Phys. Lett. **71**, 3673 (1997).
[7] M. S. Shur, B. Gelmont, and M. Asif Khan, J. Electron. Mater. **25**, 777 (1996).
[8] A. Bykhovski, B. Gelmont, and M. S. Shur, J. Appl. Phys. **74**, 6734 (1993).
[9] P. M. Asbeck, E. T. Yu, S. S. Lau, G. J. Sullivan, J. Van Hove, and J. M. Redwing, Electron. Lett. **33**, 1230 (1997).
[10] E. T. Yu, G. J. Sullivan, P. M. Asbeck, C. D. Wang, D. Qiao, and S. S. Lau, Appl. Phys. Lett. **71**, 2794 (1997).

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