Magnetotransport properties of two-dimensional electron gas in AlGaN/AlN/GaN heterostructures*

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Magnetotransport measurements are carried out on the AlGaN/AlN/GaN in an SiC heterostructure, which demonstrates the existence of the high-quality two-dimensional electron gas (2DGE) at the AlN/GaN interface. While the carrier concentration reaches 1.32×10^{13} cm^{-2} and stays relatively unchanged with the decreasing temperature, the mobility of the 2DEG increases to 1.21×10^{4} cm^2/(V·s) at 2 K. The Shubnikov–de Haas (SdH) oscillations are observed in a magnetic field as low as 2.5 T at 2 K. By the measurements and the analyses of the temperature-dependent SdH oscillations, the effective mass of the 2DEG is determined. The ratio of the transport lifetime to the quantum scattering time is 9 in our sample, indicating that small-angle scattering is predominant.

Keywords: AlGaN/AlN/GaN/SiC heterostructures, two-dimensional electron gas, Shubnikov–de Haas oscillations, magnetotransport properties

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1. Introduction

The III-nitride materials have the advantages of wide bandgap, high breakdown field, high saturation electron velocity and excellent radiation hardness. They have attracted particular attention due to their application in high-frequency, high-temperature and high-power electronic devices.[1] Among the III-nitride materials, the AlGaN/GaN heterostructure is a new low-dimensional semiconductor material with a strong polarization-induced electric field and a large conduction-band offset.[2] Some experimental studies have shown that the insertion of a thin AlN interlayer can indeed result in an improvement in the quality.[3,4] Consequently a detailed study on the transport properties of the 2DEG in the AlGaN/AlN/GaN heterostructure is important for the development of low-dimensional semiconductor physics.

2. Sample fabrication

AlGaN/AlN/GaN heterostructures were grown on an SiC substrate using metal-organic chemical vapour deposition (MOCVD). The heterostructure consisted of an unintentionally doped GaN buffer, a 1 nm-thick AlN interlayer, an undoped 14 nm-thick AlGaN barrier layer, and a 2 nm-thick GaN cap layer. The Al mole fraction was determined by using the X-ray diffraction to be 30%. To perform the measurement, the sample material was made into the hall bar geometry through reactive ion etching (RIE) with Cl_2 as shown in Fig. 1. Ohmic contacts consisting of Ti/Al/Ni/Au were annealed in a nitrogen ambient at 840 °C for 30 s. Then the sample was packaged in CQFP24 and was fixed at the bottom case of the package by the Au/Sn alloy bonding. The gold leads were bonded to the base pins of the package. Magnetotransport measurements were carried out on

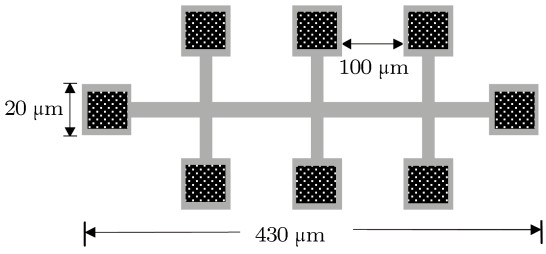


Fig. 1. Eight-contact 1-3-3-1 Hall bar geometry.

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the sample using a physics property measurement system in a temperature range from 2 K to 20 K. The Shubnikov–de Haas (SdH) oscillation effect was used to extract important 2DEG transport parameters. The standard, low-frequency, and low-current lock-in techniques were used.

3. Results and discussion

The existence of the AlN insert layer enhances the conduction band offset and reduces the penetration of the electron wave function into the AlGaN barrier. Therefore the scatterings at the rough interface and due to the dislocation in the bulk each play an important part in affecting the transport characteristics of the 2DEG, especially at the cryogenic temperature. One of the results is the great increase in mobility.[5,6] Figure 2 shows that the carrier concentration n hardly changes from 10 K down to 2 K, indicating that the parallel conduction is not significant. The mobility μ does not change from 20 K to 2 K either. The relation between these two parameters and the temperature is very important for characterizing the 2DEG behaviour.[7] The mobility of the 2DEG at 2 K is 1.21×10^4 cm^2/(V·s) and is an order of magnitude higher than that at room temperature, which is due to the suppression of the phonon scattering at lower temperature.[8,9] The variations of reduced conductances $X = \sigma_{xx}/\sigma_0$ and $Y = 2\sigma_{xy}/\sigma_0$ with magnetic intensity B are shown in Fig. 3, where σ_{xx}, σ_{xy}, and σ_0 denote the reluctance conductance, the hall conductance, and the conductance in zero magnetic field, respectively.

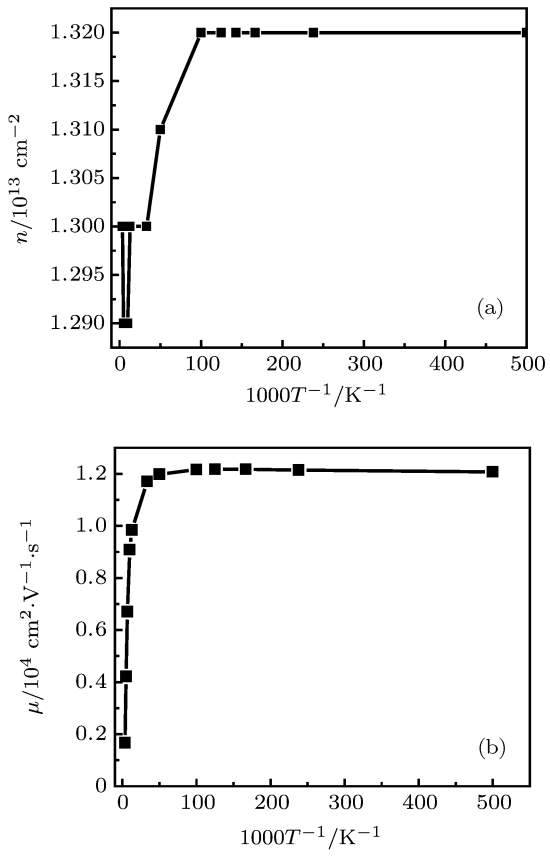


Fig. 2. Variations of (a) concentration and (b) mobility of 2DEG with temperature.

As shown in Fig. 3, when $X = 0.5$, Y reaches its minimum under the same B, which suggests that there is only one kind of carriers participating in the conduction.[10]

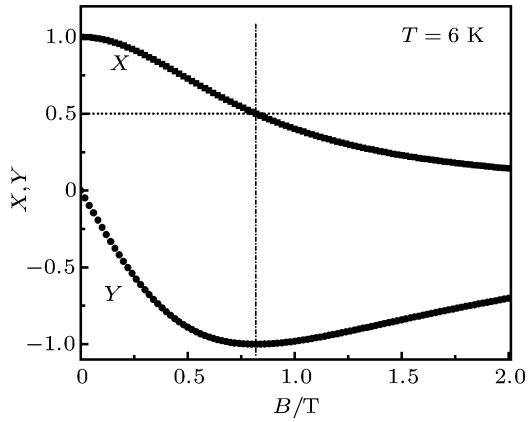


Fig. 3. Variations of reduced conductances X and Y with B.

The SdH measurement at several temperatures was performed to further study the transport properties of the 2DEG. Figure 4 shows that when B is close to 4 T at 4.2 K and higher than 2.5 T at 2 K, the onset of the SdH oscillations of magnetoresistance R_{xx} is observed, which is a clear indication of the reduced scattering. It can be observed at temperature as high as 10 K in our experiment but disappears at 20 K. The minimum of R_{xx} decreases with the increasing field, which indicates the absence of significant parallel conductance. The fast Fourier transform (FFT) spectrum has been obtained, each peak corresponds to the oscillation frequency of a subband. In Fig. 4, there is only one dominant peak, indicating that only one subband is occupied by electrons despite the high n. The quantum Hall plateaus in the Hall resistance observed at 2 K, as can be seen in Fig. 5, are clear evidence of the high-quality 2DEG. It is worth taking a moment to flag the fact that plateaus are rarely observed in the traditional AlGaN/GaN structures under the same experimental conditions. Though their widths are short because of the high n and the relatively weak fields,

they still indicate the good quality of the structures.

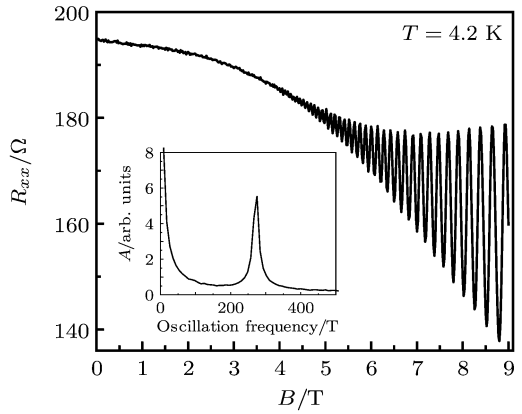


Fig. 4. Magnetoresistance R_{xx} as a function of B. The inset shows the FFT spectrum of the SdH data.

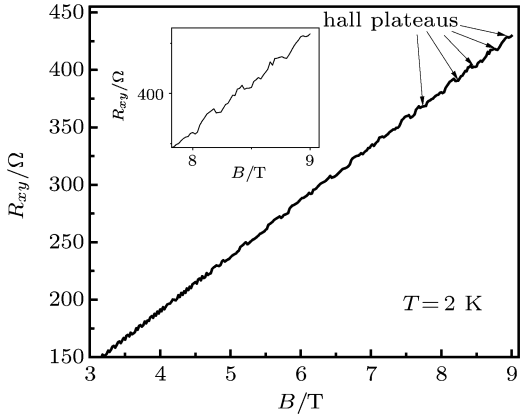


Fig. 5. Hall resistance R_{xy} as a function of B. The inset shows the magnified high field data.

The amplitude of the SdH oscillation A as a function of temperature can be expressed as $\ln(A/T) \approx C - (2\pi^2 k_{\rm B} m^*/e\hbar B)T$, where $k_{\rm B}$ is the Boltzmann constant, e is the charge of an electron, m^* is the electron effective mass, and $\hbar$ is the reduced planck constant. Using the fitting line shown in Fig. 6, we can derive that $2\pi^2 k_{\rm B} m^*/e\hbar B = 0.49857$. When $B = 6.74$ T, the electron effective mass $m^* = 0.23m_0$, which is in agreement with the results obtained by Elhamri *et al.*[11] The quantum scattering time $\tau_{\rm q}$ can be extracted from the magnetic field dependence of the amplitude of the SdH oscillation.[12] Figure 7 is plotted according to the equation $\ln[AB\sinh(\chi)] = C' - (\pi m^*/e\tau_{\rm q}B)$, where $\chi = 2\pi^2 k_{\rm B}T/\hbar\omega_{\rm c}$, with $\omega_{\rm c}$ the cyclotron frequency.

By calculating the slope of the fitting line, a value of 0.176 ps is obtained for $\tau_{\rm q}$. The classic scattering time $\tau_{\rm c} = 1.584$ ps can be obtained using $\mu = e\tau_{\rm c}/m^*$. The ratio of $\tau_{\rm c}$ to $\tau_{\rm q}$ can often reflect the dominant scattering mechanism, which is expected to be near unity in the case that the interface scattering dominates. When the small-angle scattering is more important, the ratio will be larger. The ratio is 9 in our sample, indicating that the small-angle scattering is predominant in the structure.

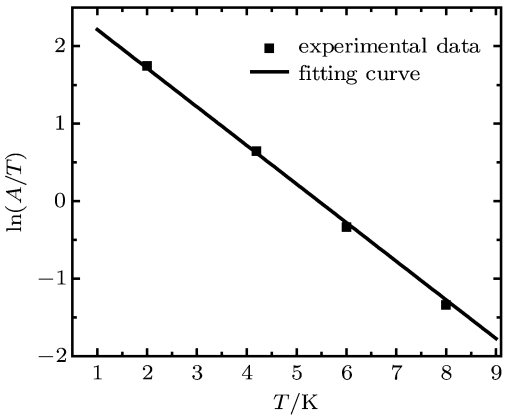


Fig. 6. $\ln(A/T)$ versus T when $B = 6.74$ T.

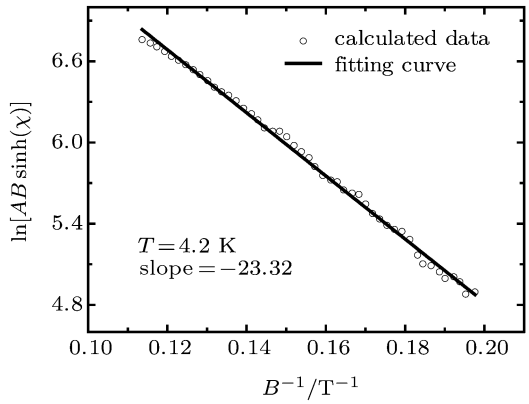


Fig. 7. Linear fitting of the SdH data at 4.2 K.

4. Conclusion

We report the magnetotransport properties of the 2DEG in an AlGaN/AlN/GaN/SiC heterostructure. The relationships between μ, n and temperature are studied by using the Hall measurement at different temperature. Only one kind of carrier is found to participate in the conductance at the cryogenic temperature. By analysing the SdH effect, we are able to extract important 2DEG transport parameters and find that the AlN layer significantly reduces the overall scattering, resulting in a distinct improvement in the mobility at low temperatures. Using the SdH data, we calculate the effective mass of the 2DEG and the quantum scattering time, reaching a conclusion that the small-angle scattering is predominant in the structure. The results show the importance of the SdH

measurements, because they provide much more information about the structure than the typical Hall measurements.

References

[1] Keller S, Wu Y F, Parish G, Naiqian Z, Xu J J, Keller B P, DenBaars S P and Mishra U K 2001 *IEEE Trans. Electron Devices* **48** 552

[2] Hao Y, Wang C, Zhang J F and Zhang J C 2006 *Chin. Phys.* **15** 1060

[3] Shen L, Heikman S, Moran B, Coffie R, Zhang N Q, Buttari D, Smorchkova I P, Keller S, DenBaars S P and Mishra U K 2001 *IEEE Electron Device Lett.* **22** 457

[4] Smorchkova I P, Chen L, Mates T, Shen L, Heikman S, Moran B, Keller S, DenBaars S P, Speck J S and Mishra U K 2001 *Appl. Phys. Lett.* **90** 5196

[5] Elhamri S, Mitchel W C, Mitchell W D and Landis G R 2007 *Appl. Phys. Lett.* **90** 042112

[6] Elhamri S, Mitchel W C, Berney R, Ahoujja M, Roberts J C, Rajagopal P, Cook Jr J W, Piner E L and Linthicum K J 2008 *Phys. Stat. Sol.* (c) **5** 1962

[7] Zhang J C, Zheng P T, Zhang J, Xu Z H and Hao Y 2009 *Chin. Phys.* B **18** 2998

[8] Maeda N, Tsubaki K, Saitoh T and Kobayashi N 2001 *Appl. Phys. Lett.* **79** 1634

[9] Zhang J F, Mao W, Zhang J C and Hao Y 2008 *Chin. Phys.* B **17** 2689

[10] Kim J S, Seiler D G and Tseng W F 1993 *Appl. Phys. Lett.* **73** 8324

[11] Elhamri S, Newrock R S and Mast D B 1998 *Phys. Rev.* B **57** 1374

[12] Coleridge P T 1991 *Phys. Rev.* B **44** 3793