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Influence of Al Composition on Transport Properties of Two-Dimensional Electron Gas in $Al_xGa_{1-x}N/GaN$ Heterostructures*

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Abstract: Magnetotransport properties of two-dimensional electron gases (2DEG) in $Al_xGa_{1-x}N/GaN$ heterostructures with different Al compositions are investigated by magnetotransport measurements at low temperatures and in high magnetic fields. It is found that heterostructures with a lower Al composition in the barrier have lower 2DEG concentration and higher 2DEG mobility.

Key words: $Al_xGa_{1-x}N/GaN$ heterostructure; two-dimensional electron gas; transport property
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1 Introduction

$Al_xGa_{1-x}N/GaN$ heterostructures have been extensively studied because of their applications for high-power, high-frequency, and high-temperature microwave devices[1~3]. The performance of electronic devices based on $Al_xGa_{1-x}N/GaN$ heterostructures depends on the transport properties of the two-dimensional electron gas (2DEG) confined in the triangular quantum well at the $Al_xGa_{1-x}N/GaN$ heterointerface. Due to the large conduction band offset and the large polarization-induced field in $Al_xGa_{1-x}N/GaN$ heterostructures, a 2DEG with large sheet carrier concentration can be obtained. The conduction band offset and the polarization-induced field are influenced by the Al composition. In this paper, the transport properties of 2DEGs in $Al_xGa_{1-x}N/GaN$ heterostructures with different Al compositions are investigated by magnetotransport measurements.

2 Experiment

Two samples of modulation-doped $Al_xGa_{1-x}N/GaN$ heterostructures were used in this study. The samples were grown by metalorganic chemical vapor deposition (MOCVD) on the (0001) surface of sapphire substrates. A nucleation GaN buffer layer was grown at 488 ℃, followed by a 2.0μm-thick unintentionally doped GaN (i-GaN) layer deposited at 1071 ℃. Then a Si-doped $Al_xGa_{1-x}N$ (n-AlGaN) layer with a thickness of 25nm was grown at 1080 ℃. Between the n-AlGaN and i-GaN layers, a 5nm-thick unintentionally doped $Al_xGa_{1-x}N/GaN$ (i-AlGaN) spacer was incorporated to reduce ionized impurity scattering. The Al composition of samples 1 and 2 are x =

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0.15 and x = 0.22. X-ray diffraction measurements indicate that the $Al_xGa_{1-x}N/GaN$ heterostructures fabricated here are of high quality.

Magnetotransport measurements were performed over the magnetic-field range of 0～10T at 1.5K. The sample was in van der Pauw geometry. The Al/Ti Ohmic contacts were prepared by e-beam evaporation and rapid thermal annealing.

3 Results and discussion

Figure 1 shows the longitudinal resistance R_{xx} as a function of magnetic field for the $Al_xGa_{1-x}N/GaN$ heterostructure at 1.5K. R_{xx} increases with the magnetic field due to the parallel conductance. The oscillatory part $\Delta\rho_{xx}$ of the magnetoresistivity is expressed as[4]

$$\frac{\Delta\rho_{xx}}{2\rho_0} = 2\frac{\chi}{\sinh(\chi)}\exp\left(\frac{-\pi}{\omega_c\tau_q}\right)\cos\left(\frac{2\pi\varepsilon}{\hbar\omega_c}-\pi\right)$$

where $\chi = 2\pi^2 k_B T/\hbar\omega_c$, $\omega_c = eB/m^*$, $\varepsilon = \pi\hbar^2 n/m^*$ is the Fermi energy, τ_q is the quantum scattering time, B is the magnetic field, k_B is the Boltzmann constant, T is the absolute temperature, $\hbar$ is the reduced Plank constant, and n is the sheet electron concentration of the 2DEG.

In order to obtain the oscillation frequency, which is periodic in B^{-1}, fast Fourier transform (FFT) analysis was used. The data are shown in Fig. 2. The Shubnikov-de Haas (SdH) frequency f only depends on the 2DEG concentration: $f = hn/2e$, where h is Planck's constant. From the frequency, the 2DEG concentrations in samples 1 and 2 are $n_1 = 4.98\times10^{12}cm^{-2}$ and $n_2 = 9.33\times10^{12}cm^{-2}$. Sample 2 has a much larger 2DEG concentration than sample 1. In $Al_xGa_{1-x}N/GaN$ heterostructures, the band offset is very large, resulting in a deep triangular quantum well. Piezoelectric doping can also contribute to the large 2DEG concentration. The 2DEG concentration in $Al_xGa_{1-x}N/GaN$ heterostructures can be very large. Comparing the 2DEG concentration between sample 2 and our sample in Ref. [5], the doping in the barrier has little effect on the concentration. The large concentration mainly comes from the piezoelectric doping. With the increase of Al composition in the barrier, the band offset and the piezoelectric effect become large. Sample 2 has a much larger 2DEG concentration than sample 1. The Al concentration in the barrier has

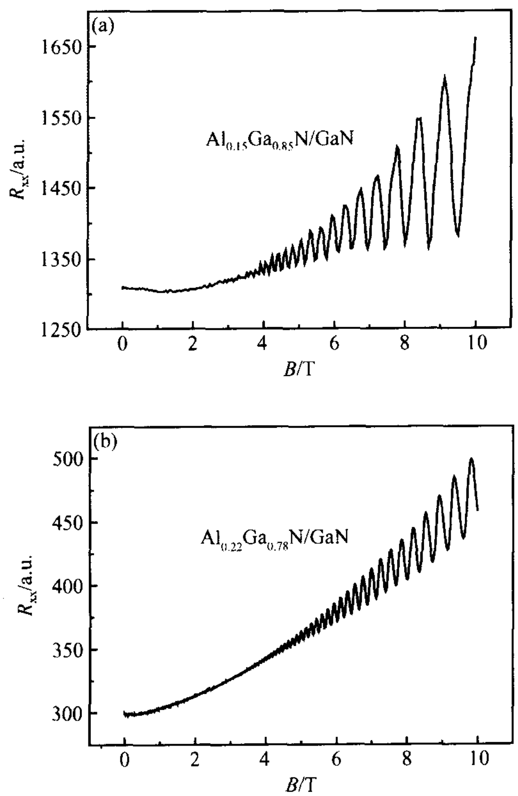

Fig. 1 Magnetoresistance R_{xx} of the 2DEG in the $Al_xGa_{1-x}N/GaN$ heterostructures as a function of magnetic field B at 1.5K

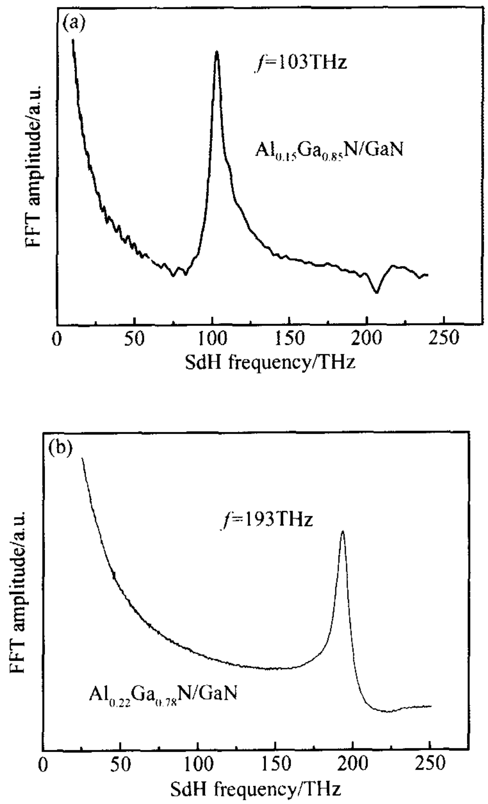

Fig. 2 Fast Fourier transform of the magnetoresistance oscillation of the $Al_xGa_{1-x}N/GaN$ heterostructures at 1.5K

a strong influence on the 2DEG concentration.

The quantum scattering time, also called the single-particle lifetime τ_q differs from the more commonly used transport lifetime, or the classical scattering time τ_c in that the former includes all scattering events while the latter is dominated by large-angle scattering events. The quantum scattering time is a measure of the collision broadening of the broadened Landau levels and is related to the half-width of the broadened Landau level by $\Gamma = \hbar/2\tau_q$ and can be obtained from the amplitude of the SdH oscillations at a given temperature using a "Dingle plot". At a fixed temperature T, we can evaluate the quantum scattering time from the slope of the line described by

$$\ln\left(\frac{1}{4}\times\frac{\Delta R}{R_0}\times\frac{\sinh(x)}{x}\right) = C - \frac{\pi m^*}{e\tau_q}\times\frac{1}{B}$$

The quantum mobility μ_q of the 2DEG can be obtained by $\mu_q = e\tau_q/m^*$. The quantum mobility was extracted from the Dingle plot of our data. The result is shown in Fig. 3. The 2DEG quantum mobility in samples 1 and 2 are 1854 and 1595$cm^2/(V \cdot s)$. Sample 1 has larger quantum mobility. With the increase of the Al composition, the triangular quantum well becomes narrow and the electron wave function comes closer to the heterointerface. The interface scattering strongly affects the 2DEG mobility. A large Al composition results in a large alloy disorder, which contributes to the scattering. Therefore, the sample with low Al composition in the barrier has higher 2DEG mobility.

4 Conclusion

Magnetotransport properties of the 2DEG in $Al_xGa_{1-x}N/GaN$ heterostructures with different Al compositions have been investigated by magnetotransport measurements at low temperatures and high magnetic fields. With the increase of Al composition in the barrier, the band offset and the piezoelectric effect become large. The triangular quantum well becomes narrow and the electron wave function comes closer to the heterointerface. The interface scattering strongly affects the 2DEG mobility. A large Al composition results in a large alloy disorder, which contributes to the scattering. Therefore, heterostructures with lower Al composition in the barrier have a lower 2DEG concentration and higher 2DEG mobility.

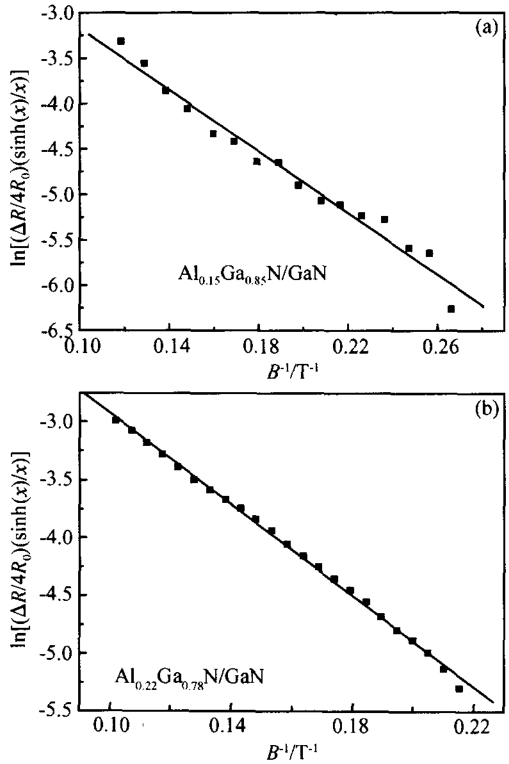

Fig. 3 ln[($\Delta R/4R_0$)($\sinh(x)/x$)] as a function of 1/B for T = 1.5K

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Al 组分对 $Al_xGa_{1-x}N/GaN$ 异质结构中二维电子气输运性质的影响*

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摘要：在低温和强磁场下，通过磁输运测量研究了不同 Al 组分调制掺杂 $Al_xGa_{1-x}N/GaN$ 异质结二维电子气(2DEG)的磁电阻振荡现象．观察到低 Al 组分异质结中的 2DEG 有较低的浓度和较高的迁移率．

关键词：$Al_xGa_{1-x}N/GaN$ 异质结构；二维电子气；输运性质
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