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Effect of the Inter-Subband Scattering in Modulation-Doped $Al_xGa_{1-x}N$/GaN Heterostructures

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ABSTRACT

Magnetotransport properties of $Al_{0.22}Ga_{0.78}N$/GaN modulation-doped heterostructures have been studied at low temperatures and high magnetic fields. The inter-subband scattering of the two-dimensional electron gas was observed. The inter-subband scattering is very weak and depends weakly on temperature when temperature is between 1.3 K and 10 K and becomes stronger with increasing temperature when temperature is higher than 10 K. The strain relaxation of the $Al_{0.22}Ga_{0.78}N$ layer influences the inter-subband scattering. It is suggested that the inter-subband scattering is dominant by the elastic scattering when temperature is lower than 10 K, and changes to be dominant by the inelastic scattering of the acoustic phonons when temperature is higher than 10 K.

INTRODUCTION

Due to the large conduction band offset and the large piezoelectric field in $Al_xGa_{1-x}N$/GaN heterostructures, the two-dimensional electron gas (2DEG) are confined to a much more narrow stripe in the triangular well at the heterointerface in comparison with that in $Al_xGa_{1-x}As$/GaAs heterostructures. This leads to the quantized energy levels of the first two subbands separated as large as 75 meV[1]. The research of recent works on magnetotransport properties of the 2DEG in $Al_xGa_{1-x}N$/GaN heterostructures were concentrated on the systems that only the lowest quantized electronic subband in the triangular well was occupied. Therefore, the scattering mechanism of the 2DEG in $Al_xGa_{1-x}N$/GaN heterostructures is probably different from that in $Al_xGa_{1-x}As$/GaAs ones

It is found that the 2DEG mobility in $Al_xGa_{1-x}As$/GaAs heterostructures is affected evidently by the inter-subband scattering[2, 3]. With improving the quality of $Al_xGa_{1-x}N$/GaN heterostructures, it has been possible to investigate the inter-subband scattering of the 2DEG in $Al_xGa_{1-x}N$/GaN heterostructures, in which two subbands in the triangular well are occupied by the 2DEG. To our knowledge, there is little report about the research on the inter-subband scattering of the 2DEG in $Al_xGa_{1-x}N$/GaN heterostructures until now. In this work, we studied the inter-subband scattering of the 2DEG in $Al_xGa_{1-x}N/GaN$ heterostructures by means of magnetotransport measurements at low temperatures and high magnetic fields.

EXPERIMENTAL DETAILS

Four samples were prepared in our experiments. They were fabricated by metal-organic chemical vapor deposition (MOCVD). On the (0001) surface of a sapphire substrate, a nucleation GaN buffer layer was grown at 488 ℃, followed by a 2.0-μm–thick unintentionally doped GaN (i-GaN) layer deposited at 1071 ℃. Then, a 3–nm-thick unintentionally doped $Al_{0.22}Ga_{0.78}N$ layer, followed by a Si-doped $Al_{0.22}Ga_{0.78}N$ layer were deposited at 1080 ℃. The thickness of the Si-doped $Al_{0.22}Ga_{0.78}N$ layer is 25 nm for Sample 1, 50 nm for Sample 2, 75 nm for Sample 3, and 100 nm for Sample 4, respectively.

The 2DEG mobility was measured at 77 K by Van der Pauw Hall configuration. It is determined to be 2730 cm^2/V.s for Sample 1, 3070 cm^2/V.s for Sample 2, 915 cm^2/V.s for Sample 3, and 978 cm^2/V.s for Sample 4, respectively. The high-resolution X-ray diffraction reciprocal space mapping has demonstrated that the $Al_xGa_{1-x}N$ layer on GaN was pseudomorphic growth in Sample 1 and Sample 2, but was partially relaxed in Sample 3 and Sample 4[4]. The decrease of the 2DEG mobility in Sample 3 and Sample 4 is due to the partial relaxation of the $Al_{0.22}Ga_{0.78}N$ layer on GaN when the $Al_{0.22}Ga_{0.78}N$ layer is thicker than 65 nm[4].

Magnetoresistance measurements were performed with the Van der Pauw configuration at temperatures between 1.3 K and 13 K and at the magnetic field up to 9.0 T.

EXPERIMENTAL RESULTS

The diagonal magnetoresistance ρ_{xx} of Sample 2 as a function of magnetic field is shown in Fig. 1. As shown in Fig. 1 (a), the double periodicity of the Shubnikov-de Hass (SdH) oscillation at 1.3 K indicates that at least two subbands in the triangular quantum well have been occupied

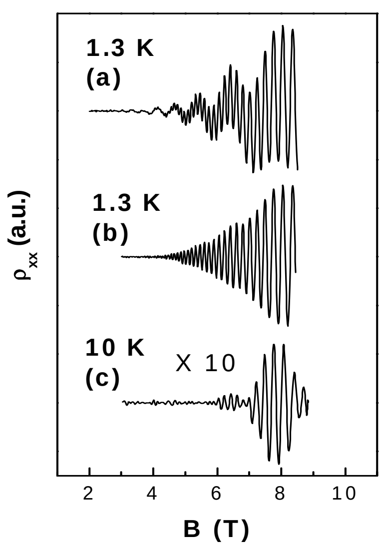

Figure 1. Diagonal magnetoresistivity ρ_{xx} of the 2DEG in Sample 2 as a function of magnetic field normal to the heterointerface, (a) the double periodicity of the SdH oscillation at 1.3 K, (b) the high frequency component of the SdH oscillation extracted from (a) by the FFT filtering at 1.3 K, and (c) the clear beating of the SdH oscillation at 10 K.

by the 2DEG. The SdH oscillation of the first subband extracted from Fig. 1(a) by the FFT filtering is shown in Fig. 1(b). By the FFT filtering the SdH oscillation from the second subband has been filtered. It indicates that a weak amplitude modulation of the SdH oscillation occurs at 1.3 K. There is no evident change of such weak amplitude modulation of the SdH oscillation between 1.3 K and 10 K. When temperature increases to 10 K, a clear amplitude modulation is observed as shown in Fig. 1(c). Similar phenomena are also observed in Sample 1.

The SdH oscillation of the first subband in Sample 3 by FFT filtering is shown in Fig. 2 at 1.5 K and 11 K, respectively. The amplitude modulation can hardly be identified at 1.5 K and there is no evident change until 10 K. But a clear modulation is observed at 11 K.

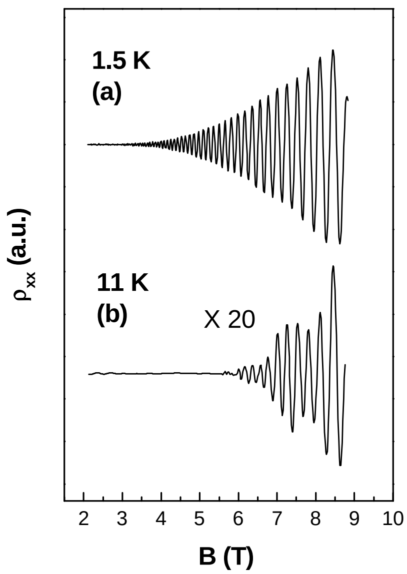

Figure 2. High frequent component of the SdH oscillation of Sample 3, at (a) 1.5 K and (b) 11 K, respectively.

As shown in Fig. 3, the amplitude modulation of the SdH oscillation in Sample 4 can't be observed at 1.3 K. When temperature increases to 10 K, only a very weak modulation is distinguished. The clear beating is observed at 13 K.

DISCUSSION

When two subbands in the triangular well are occupied by the 2DEG the total conductivity σ represents a sum $\sigma = \sigma_1 + \sigma_2$. Where conductivity σ_1 and σ_2 correspond to the contribution from the 2DEG located at the first and the second subbands, respectively[5, 6]. In the case of multi-subband occupation, the coupling between the distribution functions F_n ***(k)*** of electrons in different subbands arises due to the inter-subband scattering. The amplitude modulation of the SdH oscillation observed in our experiments indicates that the inter-subband scattering exists in the transport process of the 2DEG as illustrated by Coleridge et al.[7].

Several of the inter-subband scattering mechanisms have been suggested by Coleridge and Leadely et al.[7, 8], who intended to explain the characteristics of the amplitude modulation of the SdH oscillation in semiconductor heterostructures. There are two basic points of the view in their models on the inter-subband scattering of the 2DEG in semiconductor heterostructures. One

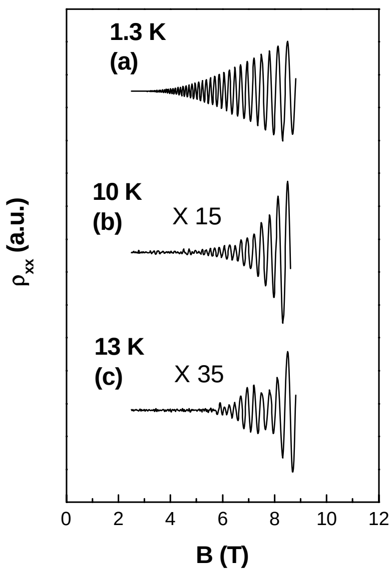

Figure 3. High frequent component of the SdH oscillation in Sample 4, at (a) 1.3 K, (b) 10 K and (c) 13 K, respectively.

is that the acoustic phonons mediate in the inter-subband scattering[9]. Based on this mechanism, the inter-subband scattering depends strongly on temperature. Another one is the elastic inter-subband scattering mechanisms[10]. Base on this mechanism, the inter-subband scattering depends weakly on temperature.

From our experiment results the inter-subband scattering depends weakly on temperature for all samples when temperature is between 1.3 K and 10 K. This means that the inter-subband scattering in this temperature range is dominant by the elastic scattering due to the alignment of staircases of Landau levels corresponding to the different subbands in the triangular well at the heterointerface. The inter-subband scattering becomes stronger when temperature increases to 13 K in Sample 4 or 10 K in other samples. This probably indicates that the inter-subband scattering is changed to be dominant by the acoustic phonons when temperature is higher than 10 K.

According to the results in our experiments, the temperature dependencies of the inter-subband scattering oscillation are influenced by the relaxation. The strain states of the $Al_{0.22}Ga_{0.78}N$ barrier on GaN changed when relaxation happened. There is probably another mechanism related to both the acoustic phonon scattering and the strain state of the $Al_{0.22}Ga_{0.78}N$ layer to explain the experimental phenomena.

In an $Al_xGa_{1-x}N$/GaN heterostructure there is a large piezoelectric polarization. Both deformation potential and the piezoelectric scattering play an important role in the magnetotransport processes[11]. In the theoretical study on the electron mobility in modulation-doped $Al_xGa_{1-x}N$/GaN heterostructures by Hsu and Walukiewicz[12], the acoustic-phonon scattering was the important mechanism in limiting the 2DEG mobility through both deformation potential and piezoelectric scattering when temperature was higher than 10 K. Therefore, the inter-subband scattering oscillation observed in our experiments is probably influenced by the acoustic phonons via both the deformation potential and the piezoelectric potential. As mentioned above, an $Al_xGa_{1-x}N/GaN$ heterostructure is partially relaxed when the $Al_{0.22}Ga_{0.78}N$ layer is thicker than 65 nm. When the barrier is relaxed, the triangular quantum well becomes broader, and thus the 2DEG distribution becomes farer from the heterointerface in comparison with that in an un-relaxed sample. In this case, the 2DEG suffers less scattering from the deformation and piezoelectric potential. Since the $Al_{0.22}Ga_{0.}N$ layer is partially relaxed in Sample 3 and Sample 4, the amplitude modulation of the SdH oscillation related to the inter-subband scattering in these two samples can only be observed at higher temperatures than that in Sample 1 or Sample 2.

The relaxation degree of the $Al_{0.22}Ga_{0.78}N$ layer in Sample 4 is larger than that in Sample 3 [4], and thus the 2DEG in Sample 4 suffers weaker scattering from the deformation and piezoelectric potentials in comparison with that in Sample 3. In Sample 4, the oscillation of the magnetoresistivity represents a simple addition of the SdH oscillations resulting from the two subbands when temperature is below 10 K. The inter-subband scattering assisted by the acoustic phonon scattering can not be distinguished until 10 K. The strong modulation of the SdH oscillation in Sample 4 can only be observed when temperature increases to 13 K. Meanwhile, the strong modulation is observed clearly at 11 K in Sample 3. From the analysis above, the mechanism that the inter-subband scattering is mediated by the acoustic phonons via deformation potential and piezoelectric potential can be used to explain the experimental phenomena well.

CONCLUSIONS

The inter-subband scattering of the 2DEG in modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructures was studied by means of magnetotransport measurements at the temperature range between 1.3 and 13 K. When temperature is below 10 K, the inter-subband scattering of the 2DEG is dominant by the elastic scattering. When temperature is higher than 10 K the inter-subband scattering becomes dominant by the acoustic phonons via deformation potential and the piezoelectric potential near the $Al_{0.22}Ga_{0.78}N/GaN$ heterointerface.

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