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A STUDY OF INTERSUBBAND SCATTERING IN GaAs/Al$_x$Ga$_{1-x}$As HETEROSTRUCTURES BY MEANS OF A PARALLEL MAGNETIC FIELD

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We demonstrate the influence of intersubband scattering in GaAs/AlGaAs heterostructures by means of a parallel magnetic field. For samples with a carrier density such that the second subband is lightly populated, the mobility can be increased by about 50% due to the suppression of intersubband scattering, when the subband separation is increased by a strong magnetic field parallel to the interface. This gives rise to a strong negative magnetoresistance. The onset of this negative magnetoresistance can be shifted by the application of a back-side gate voltage which varies the Fermi energy.

ELECTRONS CONFINED to the narrow potential well in GaAs at the GaAs/Al$_x$Ga$_{1-x}$As heterostructure form a quasi two-dimensional (2D) electron gas. Quantization of the electronic motion perpendicular to the interface leads to a series of 2D electric subbands, E_i ($i = 0, 1, 2, \ldots$), each corresponding to a quantized energy level of the potential well. The 2D electrons stem from donor impurities in the Al$_x$Ga$_{1-x}$As. In so-called modulation doped structures [1], the donor ions are placed at a finite distance away from the interface in order to reduce ionized impurity scattering at low temperatures. This leads to high electron mobilities of the order 100,000 cm^2/V sec at low temperatures. When the number of carriers in the layer is sufficiently low, so that only the lowest subband E_0 is occupied, impurity intrasubband scattering is in general the limiting scattering mechanism in this system. At carrier densities of the order 1×10^{12} cm^{-2}, however, depending on the material parameters, the second subband E_1 starts being populated. The population of E_1 opens up a new scattering channel, the intersubband scattering, which should lead to a strong and discontinuous decrease of the mobility in the system [2]. In a recent publication, Störmer, Gossard and Wiegmann [3] have shown from an analysis of Hall measurements and Shubnikov–de Haas (SdH) oscillations, that intersubband scattering leads to a 30% reduction in mobility, when the second subband is occupied. Previously it was found in the Si inversion layer of (1 0 0) surface orientation that the field effect mobility and also the amplitude of SdH oscillations decreases when a higher subband is occupied under uniaxial stress [4]. In the present study we used a different method to investigate the influence of intersubband scattering. We have chosen samples with a carrier density such that the Fermi energy is close to the second subband. The application of a strong magnetic field parallel to the interface allows us to increase the subband separation ($E_1 - E_0$) due to the difference in the spread of the wavefunction in the direction perpendicular to the interface [5]. The application of a parallel magnetic field, which has already been shown to give rise to hybrid quantum oscillations in InAs [6] and which was also used previously in intersubband spectroscopy in Si [7], allows us to demonstrate the influence of intersubband scattering. Starting from a situation where the second subband is slightly occupied, we increase the subband separation and thus depopulate the excited subband. When the subband separation is sufficiently large so that all the carriers can be accommodated in the lowest subband and the Fermi energy is more than kT below E_1, intersubband scattering should be suppressed. By the application of a gate voltage on the backside of the device we can change the carrier density and therefore the Fermi energy. The change in the magnetic field needed to suppress intersubband scattering can then be correlated with the change in

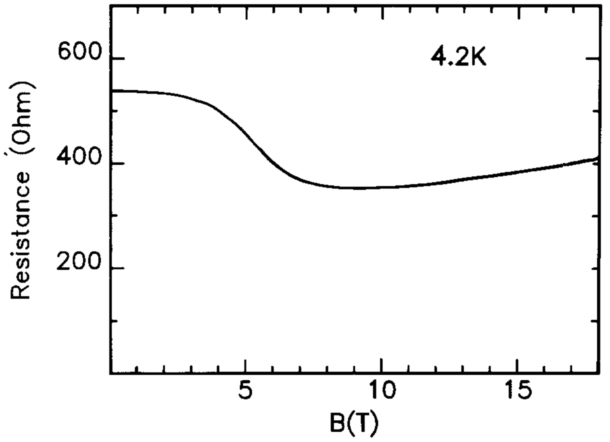

Fig. 1. Sample resistance vs magnetic field parallel to the interface.

Fermi energy.

The sample used in the present study is a standard Hall bridge of GaAs/Al$_x$Ga$_{1-x}$As ($x = 0.3$). The Si donors (N(Si) $\sim 1.5 \times 10^{18}$ cm^{-3}) are placed inside the Al$_x$Ga$_{1-x}$As layer at 50 Å away from the interface. The 2D carrier density in the GaAs layer obtained from the period of SdH oscillations in a magnetic field perpendicular to the interface is $n = 7.3 \times 10^{11}$ cm^{-2}. Only one period of oscillations is observed, and there was no clear indication for the occupation of a second subband in the SdH data. The density n_H, derived from the magnetic field dependence of the Hall voltage, assuming the single carrier model, is slightly higher ($n_H = 7.69 \times 10^{11}$ cm^{-2}) indicating some population in the second subband. Figure 1 shows a plot of the sample resistance as a function of the magnetic field parallel to the interface at 4.2 K. The current direction is perpendicular to B. The resistance decreases strongly between about 3 and 8 T and increases slightly at higher fields. We attribute this strong negative magnetoresistance, which was not observed in samples of much lower carrier density, to the suppression of intersubband scattering, when the subband separation is increased by the parallel magnetic field. The weak positive magnetoresistance at higher B is possibly due to a slight increase in scattering rate in the lowest subband when the density of states is modified by the strong parallel field.

In order to demonstrate that the negative magnetoresistance is related to the occupation of the second subband, we have changed the carrier density in the system by applying a gate voltage between a back contact at the substrate and the 2D layer [8]. A gate voltage of about $+115$ V (-115 V) leads to a decrease (increase) of the sample resistance at zero magnetic field. The slope of the Hall voltage in a perpendicular field varies by $\pm 4.2\%$. However, there was no noticeable change in the period of the SdH oscillations. Table 1 is a summary of the results as a function of the gate voltage.

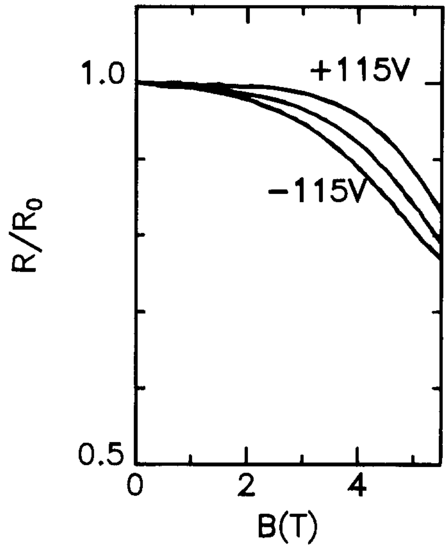

Fig. 2. Magnetoresistance for different gate voltages, -115 V, 0 V and $+115$ V.

Table 1. Mobility under back-side gate bias

U_g (V)	μ_H (cm^2/Vsec)	n_H (10^{11} cm^{-2})	n_{SdH} (10^{11} cm^{-2})
-115	47,000	7.39	7.3
0	45,300	7.69	7.3
$+115$	45,200	8.02	7.3

Figure 2 shows the influence of the gate voltage on the magnetoresistance in a parallel field. The onset of the decrease in resistance clearly shifts to higher magnetic fields by about 1 T, when the gate voltage is increased from -115 V to $+115$ V. The corresponding shift in the Fermi energy due to the change in carrier density is of the order of 1 meV. The correlation between the occupation of the second subband and the behavior of the negative magnetoresistance clearly demonstrates that the decrease in resistance is due to a suppression of intersubband scattering.

The mobility determined from the Hall carrier density and the sample resistance at the magnetic field where the minimum occurs is $\mu = 73{,}400$ cm^2/Vsec. The Hall mobility at zero (parallel) magnetic field, where intersubband scattering is present, is 45,300 cm^2 V sec^{-1}. From this we infer that intersubband scattering reduces the average carrier mobility by about 50%. Mori and Ando [2] have calculated the mobilities in the lowest and the first excited subband due to intra- and intersubband scattering by impurities for a modulation doped GaAs/Al$_x$Ga$_{1-x}$As superlattice. Since this situation is not very different from a single heterostructure, we compare their theoretical result with our experiment. Figure 3

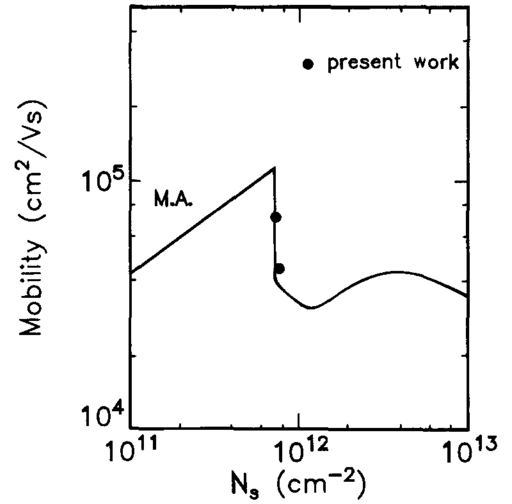

Fig. 3. Theoretical Hall mobility calculated by Mori and Ando [2] and experimental data points.

shows the calculated average Hall mobility and the two data points obtained in the present study at situations where intersubband scattering is present ($B = 0$), and where the intersubband scattering is suppressed by a strong parallel magnetic field. There is reasonable agreement between theory and experiment.

A rather surprising result is obtained when the sample is slightly tilted away from the parallel configuration in a strong magnetic field. As can be seen in Fig. 4, only a small component of the perpendicular magnetic field is needed to suppress the negative magnetoresistance. Measurements at different total magnetic field values show that the effect is not due to an anisotropy, but depends on the absolute value of the perpendicular field. The perpendicular component is related to the tilt angle θ through $B = B \cos \theta$. For a total magnetic field of 18.95 T (Fig. 4), the negative magnetoresistance is limited to a range of angles 90 ± 1.5°. At first sight this result seems to be difficult to reconcile with the interpretation of the negative magnetoresistance as being due to the diamagnetic-like shift of the subbands. In a simple perturbational treatment one would expect that such a diamagnetic term shows an anisotropy $\cos^2 \theta$ [9]. However, it is important to note, that at tilt angles where the negative magnetoresistance is suppressed, the perpendicular field is already high enough so that $\omega\tau > 1$. It is known that a strong magnetic field of arbitrary orientation mixes electric and magnetic subbands [10, 11] and its influence on the scattering cannot be inferred in a simple way. Both the negative magnetoresistance and its strong dependence on the tilt angle reported here were observed on two different samples with comparable carrier density.

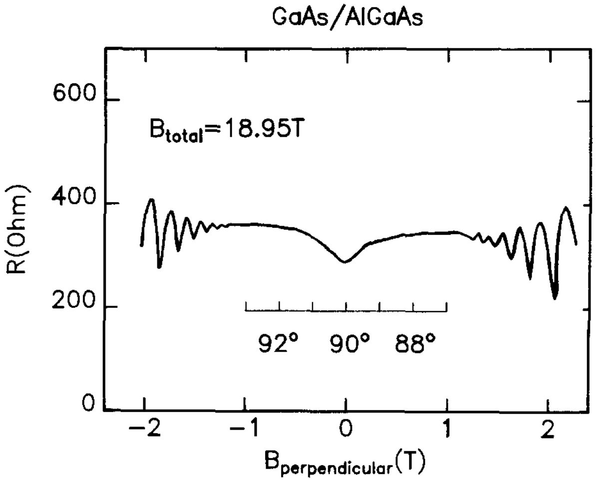

Fig. 4. Sample resistance as a function of a perpendicular magnetic field at a constant total magnetic field of 18.95 T. The additional scale at the bottom shows the corresponding tilt angles.

In summary, we have demonstrated in a direct way the influence of intersubband scattering on the mobility in GaAs/Al$_x$Ga$_{1-x}$As heterostructures. We found a decrease in mobility by about 50% when the second subband starts being occupied. The results are in good agreement with theory. Moreover, a surprisingly strong dependence of the negative magnetoresistance on the perpendicular component of the magnetic field is observed. This strong dependence is not fully understood at present.

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