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Two-dimensional magnetotransport in AlAs quantum wells

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We have made magnetotransport measurements on two-dimensional electronic systems confined to AlAs by $Al_xGa_{1-x}As$. We have determined the effective mass ($m_{111}=0.49m_0$), the effective g factor (3.1), and the relaxation time. Even though the lattice constants of GaAs and AlAs are nearly equal, the stress arising from this small mismatch strongly influences the electronic properties of AlAs. For [111]-oriented samples the valley degeneracy is one, and there is an anomalous phase shift in the Shubnikov–de Haas oscillations.

Over the past decade the study of compound III-V semiconductors has rapidly expanded. In particular, a great deal of research has been devoted to GaAs-$Al_xGa_{1-x}As$ quantum wells, superlattices, and heterostructures and their two-dimensional properties. Most of these studies have focused on the optical and transport properties of GaAs. Although some work has been done on two-dimensional transport in $Al_xGa_{1-x}As$,[1] very little information is available on the electronic properties of two-dimensional systems in AlAs.[2] AlAs is particularly interesting for a number of reasons. First, its band structure is very similar to that of Si. Although the conduction-band minima in AlAs lie at the X point of the Brillouin zone rather than 84.5% of the way from the Γ point to the X point as they do in Si, the calculated values for the effective masses for electrons in these two semiconductors are very similar. This provides the opportunity for comparison of metal-oxide-semiconductor devices and semiconductor heterostructures in two materials with similar band structure. In addition, the properties of AlAs are directly related to the properties of $Al_xGa_{1-x}As$ and, in turn, the study of GaAs heterostructures. Nonetheless, AlAs remains a largely unexplored material.

In this Rapid Communication we report the results of magnetotransport measurements on electrons in AlAs quantum wells. We have measured the effective mass, effective g factor, and single-particle relaxation times, and have observed a phase shift in the Shubnikov–de Haas oscillations. Our results represent the first experimental determination of several parameters which have only been calculated in the past.

The samples studied were grown by molecular-beam epitaxy on (100) and (111) semi-insulating GaAs substrates at 600 °C. A 0.5-μm GaAs buffer layer and 1200 Å of undoped $Al_xGa_{1-x}As$ ($x=0.4$) were deposited first. Next we grew 4 to 10 periods of 150-Å AlAs quantum wells sandwiched between modulation-doped $Al_xGa_{1-x}As$ layers with spacers between 7 and 200 Å thick. Finally, an extra 150 Å of Si-doped $Al_xGa_{1-x}As$ and a 70-Å undoped GaAs cap were deposited.

Hall bars were fabricated for transport measurements, and sample parameters for five of the samples studied are summarized in Table I. Samples with the same numerical designation were grown at the same time. For those samples grown side by side the mobilities at 4.2 K were higher for (111)-oriented samples than for (100)-oriented samples. This is surprising, since two-dimensional electronic systems on the (100) surfaces of Si and GaAs generally have the highest mobilities. The higher mobility of the (111)-oriented samples may be due in part to the growth conditions, but other effects which we will discuss below may also be involved.

Figures 1 and 2 show the magnetoresistance for samples 1 and 2b, respectively. There is almost no structure in the magnetoresistance at 3.8 K and above. At low magnetic fields there is a negative magnetoresistance which is probably due to weak localization. However, as the temperature is lowered, Shubnikov–de Haas oscillations appear and become stronger. The failure of the minima in the magnetoresistance to reach zero and the fact that the plateaus in the Hall voltage are not flat may indicate that there is a parallel conduction in layers other than the AlAs quantum wells.

By comparing the filling factor determined from the Shubnikov–de Haas oscillations and the values of the Hall voltage at the same magnetic field one can extract the val-

TABLE I. Parameters (at 4.2 K) for the samples used in this study.

Sample	Orientation	Number of wells	n_s (10^{11} cm^2)	Mobility (cm^2/V s)	τ_t (psec)	τ_s (psec)
1	(111)	7	6.0	4800	1.11	0.62
2a	(100)	2	4.96	4600	1.28	· · ·
2b	(111)	4	4.17	7000	1.63	1.03
3a	(100)	2	5.00	3100	0.86	· · ·
3b	(111)	4	4.18	8100	1.86	0.94

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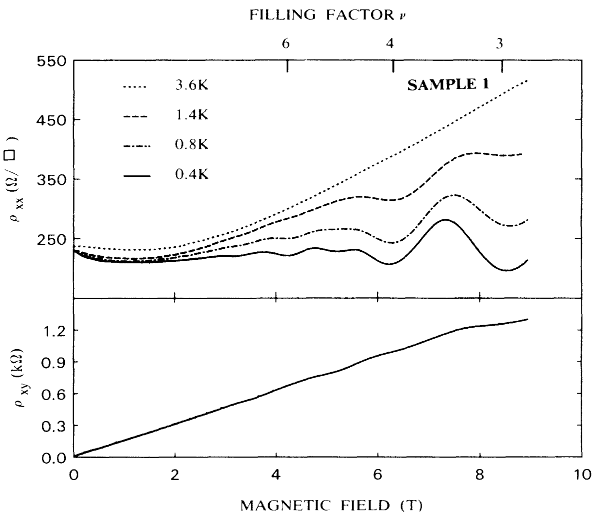

FIG. 1. ρ_{xx} and ρ_{xy} vs magnetic field for sample 1, a (111)-oriented AlAs multi-quantum-well sample with 150-Å AlAs wells and 70-Å $Al_xGa_{1-x}As$ spacers.

ley degeneracy of the two-dimensional electronic system (2DES). In all the (111) samples studied the valley degeneracy was 1 (not 3 as expected). This is reminiscent of the early results for Si(111) for which a valley degeneracy of 2 not 6 was observed for a number of years.[3,4] Ultimately, Tsui and Kaminsky[5] were able to fabricate samples such that the sixfold degeneracy could be seen. This ruled out the possibility that the lifting of the valley degeneracy in the early studies was a result of various many-body interactions,[6] and led them to conclude that inhomogeneous stress at the Si-SiO_2 interface in most samples was responsible for lifting the valley degeneracy. In our samples we cannot rule out the existence of inhomogeneous strain even though the lattice mismatch between AlAs and GaAs is very small (~0.1% at 300 K). There may be sufficient local stress present to shift the valleys a few meV with respect to one another. Because the density of states is very large for conduction-band electrons, and the carrier concentration is relatively small ($<10^{12}$ cm^{-2}), only a 3- to 6-meV shift is required to place all the carriers in one valley.

Additional evidence of stress is also found in (100) samples. All (100) samples have a large positive magnetoresistance at low magnetic fields and a complex set of Shubnikov–de Haas oscillations (see Fig. 3). Both these effects are indicative of two-carrier transport. The simplest explanation is that compressive stress in the AlAs lowers the energy of the two valleys with larger in-plane masses. They are further split due to the inhomogeneous stress, causing them to become unequally populated. This is supported by the fact that only one cyclotron effective mass is observed for (100)-oriented samples and it is larger than the cyclotron effective mass for (111)-oriented samples.[7] It is also consistent with the effects of stress observed in Si (100) inversion layers.[8,9]

Despite the possible presence of stress in our samples, a great deal of information can be extracted from an analysis of the Shubnikov–de Haas oscillations. This is particularly true for the (111)-oriented samples, and we will discuss them first. The expression for the amplitude of the Shubnikov–de Haas oscillations in a 2DES is[10]

$$\frac{\delta R}{R} \simeq \frac{\delta\sigma_{xx}}{\bar{\sigma}_{xx}} \simeq \frac{2(\omega_c\tau_s)^2}{1+(\omega_c\tau_s)^2}\exp\left(-\frac{\pi}{\omega_c\tau_s}\right)\frac{\xi}{\sinh\xi} \qquad (1)$$

in the limit $\omega_c\tau_s \lesssim 1$ and in the presence of short-range scatters. In Eq. (1) $\bar{\sigma}_{xx}$ is the mean transverse magnetoconductance, which was shown to be equal to the low-field-limit ($\omega_c\tau \ll 1$) value,[11] $\xi = 2\pi^2 k_B T/\hbar\omega_c$, ω_c is the cyclotron frequency (eB/m^*), and τ_s is the single-particle relaxation time. The effective mass m^* and the relaxation time can be determined by examining the temperature and magnetic-field dependence of the amplitude of the Shubnikov–de Haas oscillations, respectively.[11]

Using m^* as a fitting parameter in Eq. (1) we deter-

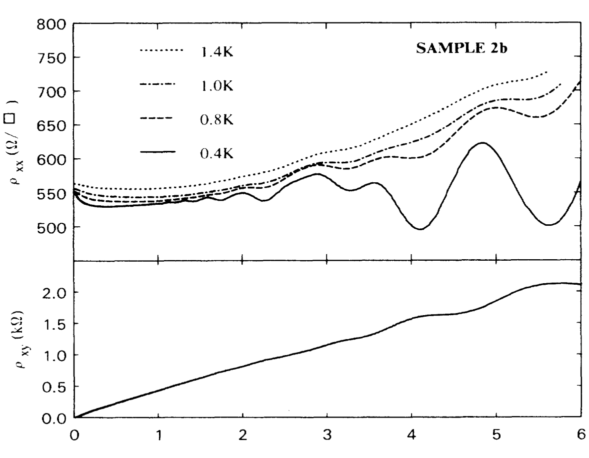

FIG. 2. ρ_{xx} and ρ_{xy} vs magnetic field for sample 2b, a (111)-oriented AlAs multi-quantum-well sample with 150-Å AlAs wells and 150-Å spacers.

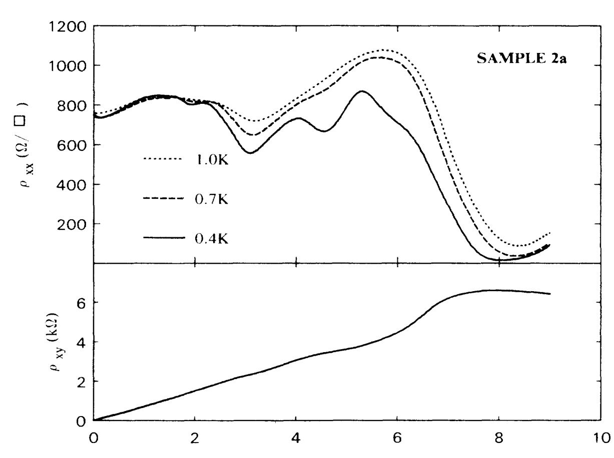

FIG. 3. ρ_{xx} and ρ_{xy} vs magnetic field for sample 2a, a (100)-oriented AlAs multi-quantum-well sample with 150-Å AlAs wells and 150-Å spacers.

mined the effective mass at several magnetic-field strengths for sample 2b (see Fig. 4). Our values for m_{111} are between $0.45m_0$ and $0.51m_0$ and are somewhat larger than the cyclotron mass ($m_{111}=0.41\pm0.02$) measured recently.[7] It should be noted that the mass determined from the temperature dependence of the Shubnikov–de Haas amplitude reflects many-body enhancement,[12] while the cyclotron resonance gives the band mass, and this probably accounts for the difference between the two. Taking the value for m_{111} as $0.41m_0$ and using the theoretical value for the transverse effective mass ($m_t/m_0=0.19$) (Ref. 13), the longitudinal effective mass is given by $m_l=(3m_{111}^2-m_t^2)/2m_t=1.23m_0$. This value is to be compared with the value of $1.1m_0$ determined by Rheinlander, Neumann, Fischer, and Kuhn,[13] using the same value for m_t and calculating m_l from the results of Faraday rotation experiments. A value for m_{111} of 0.39 m_0 is implied from Ref. 13, and it is tempting to regard the difference here as due to band nonparabolicity. However, the value of m_t remains to be measured directly.

We measured the effective g factor (g^*) using the rotating-sample technique of Fang and Stiles.[14] Figure 5 shows the magnetoresistance of sample 1 when oriented at three different angles with respect to the applied magnetic field. The shallow minimum in the magnetoresistance at 8.5 T becomes weaker as the sample is rotated away from 0° and becomes a peak at about 41°. The minimum then reappears and becomes stronger at larger angles. This indicates that the spin-up and spin-down levels from two adjacent Landau levels cross at 41°. At this point the spin splitting ($g^*\mu_B B$) is equal to the Landau-level splitting ($\hbar\omega_c$). Using the average value, we measured for m_{111} ($m^*=0.49m_0$) as the value for the effective mass, $g^*=2m_0\cos\theta/m^*=3.1$. The theoretical value of g^* (calculated using the formula of Roth, Lax, and Zwerdling,[15] and taking 2.23 and 0.275 eV as the energy gap and spin-orbit splitting, respectively) is 1.9 for a mass of $0.49m_0$. The difference between these two values of g^* is likely due to many-body enhancement of the g factor,[16,17] as is the difference between the cyclotron and Shubnikov–de Haas mass.[12]

As mentioned above, analysis of the magnetic-field dependence of the Shubnikov–de Haas oscillations allows determination of the single-particle relaxation time. As first observed by Paalanen, Tsui, and Hwang,[18] the relaxation time determined from the Shubnikov–de Haas effect is much smaller than the scattering time τ_t determined from the zero-magnetic-field mobility for electrons in GaAs heterostructures. However, the two are nearly equal for electrons in Si inversion layers.[11,19] One of the important parameters determining the ratio of these two times is the average distance between the ionized impurities and the 2DES.[20] In Si metal-oxide-semiconductor field-effect transistors the ionized impurities lie at the Si-SiO_2 interface, while in high-mobility GaAs heterostructures most ionized impurities can be separated from the 2DES by more than 200 Å. For samples 2b and 3b this distance is about 220 Å for donors intentionally added to the $Al_xGa_{1-x}As$. Extending the results of Das Sarma and Stern[20,21] and using the parameters appropriate for our samples, we would expect a value of 30 for τ_t/τ_s if scattering by remote impurities were the only scattering mechanism. Experimentally we find that the ratio of the scattering time to the single-particle relaxation time is about 2 for our (111) samples using the effective masses

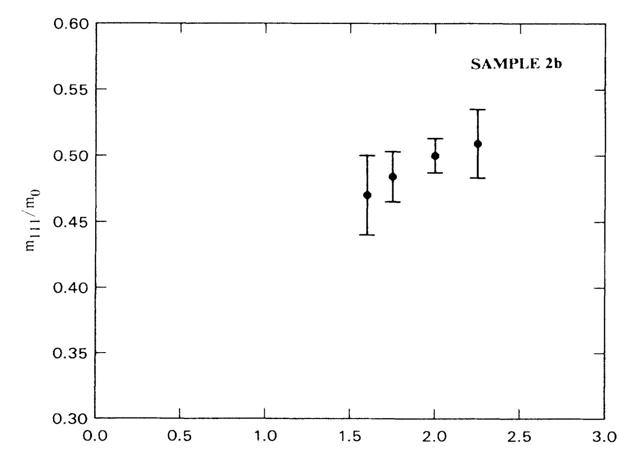

FIG. 4. The effective mass as a function of magnetic field determined from the temperature dependence of the Shubnikov–de Haas oscillations in sample 2b.

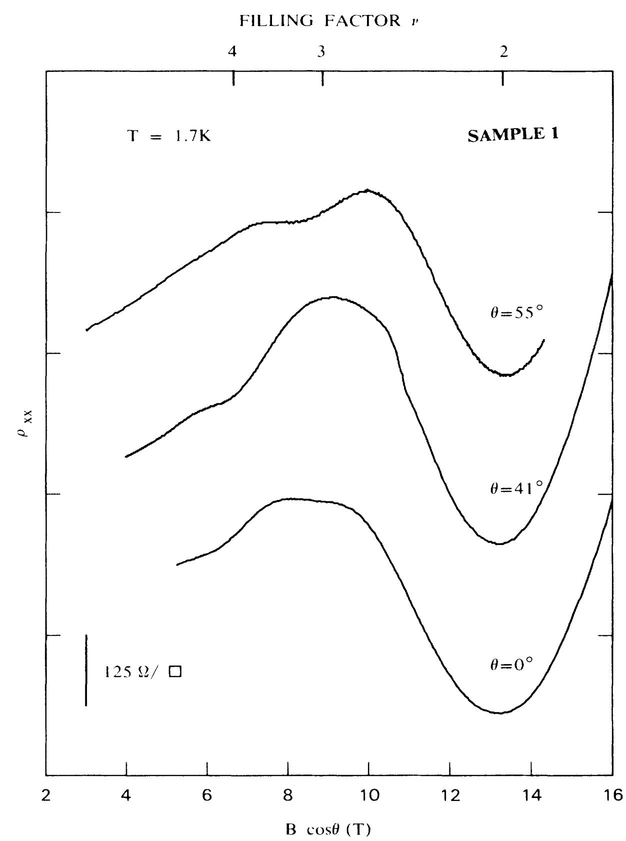

FIG. 5. ρ_{xx} vs magnetic field for sample 1 oriented at three different angles with respect to the applied magnetic field. The low-field data were not taken due to the background field of the hybrid magnet used.

determined by cyclotron resonance to calculate τ_t (see Table I). However, this is not surprising considering the low mobility of our samples. We can infer that scattering by ionized impurities at the AlAs-$Al_xGa_{1-x}As$ interface or in the AlAs is significant in our samples.

In determining the single-particle relaxation time for sample 2b only the Shubnikov–de Haas oscillations below 2.5 T were analyzed, since they were essentially sinusoidal. In addition, there is an anomaly in the Shubnikov–de Haas effect at about 2.5 T (see Fig. 2). If one plots the indexed extrema of the Shubnikov–de Haas oscillations versus $1/B$ there is a break in the slope at 2.5 T. The ratio of the slopes is very close to 2.0, which is indicative of the lifting of the spin degeneracy of the Landau levels at high magnetic fields. However, there is also an anomalous phase shift in the Shubnikov–de Haas oscillations at this point. One possibility is that there is a zero-field splitting of the spin levels arising from the asymmetry of our AlAs quantum wells.[22] Another explanation is that g^* is such that at 2.5 T spin levels from adjacent Landau levels coincide. This is possible in light of the tilted-field results for sample 1. If the enhancement of g^* is magnetic-field dependent and is larger for sample 2b, which is consistent with the longer single-particle relaxation time, then this crossing could occur at 0° at 2.5 T and 0.4 K where the data were taken. However, this would require an effective g factor of about 4 and this must be examined further.

In summary, we have examined the properties of two-dimensional electronic systems confined to AlAs quantum wells and have measured the effective mass, effective g factor, valley splitting, and single-particle relaxation time. Our results show that stress effects cannot be ignored in GaAs/AlAs heterostructures even though the lattice mismatch is very small. This has important implications for other studies involving these materials.

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