High-quality two-dimensional electron system confined in an AlAs quantum well

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We report the fabrication and characterization of a high-quality two-dimensional electron system in the X-point valley of an AlAs quantum well. The modulation doped structure has a density of $n_s=2.5\times10^{11}$ cm^{-2} and low-temperature mobility $\mu=3\times10^4$ cm^2/V s. Cyclotron resonance data reveal an effective mass $m_c=0.46m_0$, indicating that the X-point conduction valleys with heavy in-plane mass are occupied. In the magnetotransport data, we observe quantum Hall states at consecutive integral Landau-level fillings (ν), implying that the degeneracy of these valleys is lifted. Our data at high magnetic fields show well-developed fractional quantum Hall states at $\nu=1/3$ and 2/3 with a gap of ${}^{1/3}\Delta=1.3K$ for the $\nu=1/3$ state at $B\approx30$ T.

Although a great deal of work has been done on two-dimensional electron systems (2DES) in GaAs quantum wells,[1] very little information is available regarding the electronic properties of 2DES in AlAs quantum wells.[2] AlAs has a sixfold degenerate conduction band minimum at the X-point of the Brillouin zone where the electron effective masses[3,4] are very similar to those of Si at the Δ-point conduction band minimum. This similarity should allow comparisons between 2DES transport in Si/SiO_2 and a III-V heterostructure. In addition, the multifold valley degeneracy in AlAs may manifest interesting new effects, such as those seen in multilayer systems.[5] Finally, the much larger effective mass of conduction electrons in AlAs compared to GaAs can significantly modify the energies of correlated states, an example of which was recently observed in 2D hole systems in GaAs where the effective mass is similarly large.[6]

Smith *et al.*[2] studied magnetotransport and cyclotron resonance of 2DES in AlAs wells. Their samples contained two or more quantum wells each with rather high density, $n_s\approx5\times10^{11}$ cm^{-2}, and low-temperature mobility, $\mu\approx4000$ cm^2/V s [for structures grown on the GaAs(100) substrates]. Despite the rather low value of the mobility, they were able to observe magnetoresistance oscillations and to extract valuable information regarding the structure and parameters of the conduction band.

In this letter, we report the growth of an $Al_xGa_{1-x}As$/AlAs modulation doped structure containing a high-quality 2DES in a single AlAs quantum well with $n_s=2.5\times10^{11}$ cm^{-2} and $\mu=30\,000$ cm^2/V s. We observe a sharp cyclotron resonance giving an effective mass $m_c/m_0=0.46\pm0.02$ for the conduction electrons. The magnetotransport data reveal well-developed quantum Hall states at integer Landau-level filling factors $\nu=1,2,3,4,...$ implying the lifting of the valley degeneracy. Moreover, we are able to observe, for the first time, the development of *fractional* quantum Hall states at $\nu=1/3$ and 2/3 and measure the energy gap for the $\nu=1/3$ state.

The sample in this study was grown by molecular beam epitaxy on an undoped (100) GaAs substrate at a growth temperature of 625 °C. Figure 1 shows the schematic cross section of the structure and the band diagram simulation. The quantum well is a 150 Å wide AlAs layer separated from two doping δ-layers of 8×10^{11} cm^{-2} Si by AlGaAs spacer layers. The spacer layer on the surface side is a 300 Å wide $Al_{0.45}Ga_{0.55}As$ layer, while the one on the substrate side is 25 periods of GaAs(10.5 Å)/AlAs(8.5 Å) superlattice that is expected to be equivalent to 475 Å of $Al_{0.45}Ga_{0.55}As$. We used the superlattice to improve the quality of the inverted interface.[7] Also, the Si sheet is placed in the barriers asymmetrically to reduce the amount of Si that may reach the well.[8] Finally, the purpose of the Si sheet near the surface is to accommodate the surface band bending.

The band diagram simulation was done assuming that

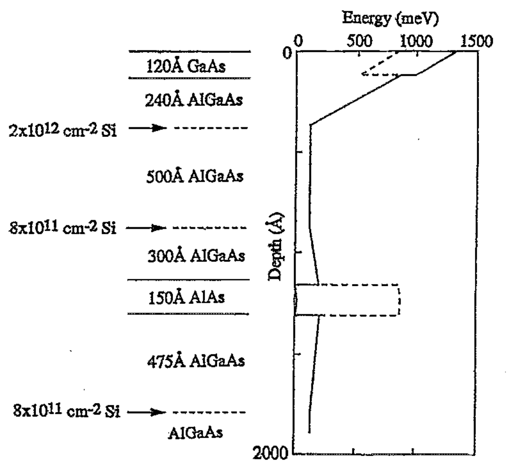

FIG. 1. Schematic cross section (left-hand side) and band diagram simulation (right-hand side) of the AlAs quantum well. In the band diagram, the conduction band edges at the Γ- and X-points are indicated by dashed and solid lines, respectively. In our simulation, these band edges nearly overlap (differ by only about 10 meV) in $Al_{0.45}Ga_{0.55}As$.

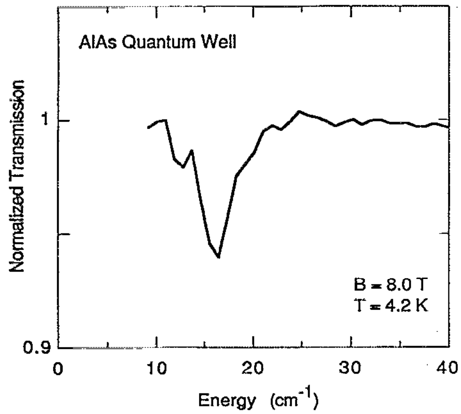

FIG. 2. Cyclotron resonance spectrum for the AlAs 2DES obtained by measuring the transmission of far-infrared radiation through the sample. Transmission at B=8 T normalized to that at B=0 is shown as a function of the incident energy.

63% of the difference between the direct gaps of GaAs (E_g^Γ=1.52 eV) and AlAs (E_g^Γ=3.13 eV) at the Γ-point occurs in the conduction band offset. The offset between the X-point conduction band of AlAs and the Γ-point conduction band of GaAs is then calculated using the direct and indirect gaps of AlAs (E_g^X=2.27 eV). The density of the 2DES in the AlAs well depends sensitively on the binding energy of Si dopants in AlGaAs, a parameter which is not well known. In our simulation, shown in Fig. 1(b), we assumed a 2DES density of 2.5×10^{11} cm^{-2}, consistent with our experimental results.[9] We believe that this simulation, although not exact, represents the band diagram of our structure fairly accurately.

Figure 2 shows the cyclotron resonance spectrum for the AlAs 2DES obtained by measuring the transmission of far-infrared radiation through the sample at a magnetic field (B) of 8 T and temperature (T) of 4.2 K. A Fourier transform spectrometer in the Faraday geometry was used. The resonance observed in Fig. 2 is much sharper than the data of Ref. 2 and reflects the high mobility of the 2DES in our sample. The data reveal a cyclotron effective mass m_c =(0.46±0.02)m_0. This m_c, which is consistent with the cyclotron mass reported in Ref. 2, is somewhat surprising. For a 2DES in the (100) plane of AlAs, one may expect that, similar to the Si inversion layer electrons, confinement lifts the valley degeneracy so that the conduction valleys with lighter in-plane mass are occupied.[10] Considering the reported effective masses (m_l=1.1m_0 and m_t =0.19m_0) for the X-point ellipsoids of bulk AlAs,[3] the measured m_c=0.46m_0 in our 2DES clearly indicates that the valleys with heavier in-plane mass are occupied. [Note that $(m_l m_t)^{1/2}$=0.46m_0 is in excellent agreement with our measured m_c.] A reason for this reversal of the valley energies may be the lattice mismatch between AlAs and GaAs that causes the AlAs to be subjected to biaxial compressive stress.[2] Our estimate[11] indicates that such compression can indeed sufficiently lower the energy of the valleys with heavier in-plane mass so that only these are occupied.[12]

The magnetotransport measurements were performed

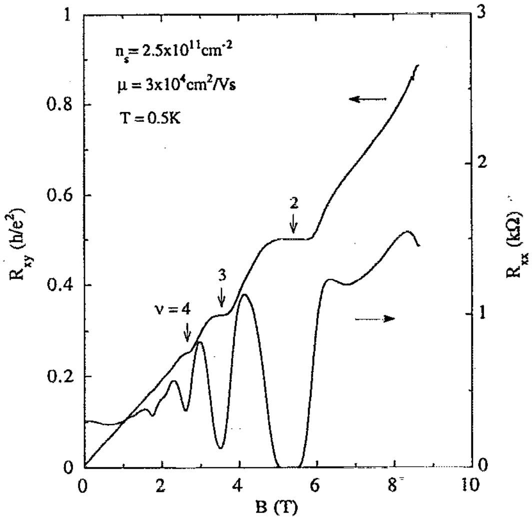

FIG. 3. The magnetotransport coefficients R_{xx} and R_{xy} vs magnetic field B at T=0.5 K. The vertical arrows indicate the Landau filling factors at which integral quantum Hall effect is observed.

on a van der Pauw geometry sample with contacts made by alloying In:Sn (80:20) in a H_2 ambience at 450 °C for about 13 min. The data were taken in ^{3}He cryostats down to T=0.5 K in a superconducting magnet (with B up to 9 T) and in a hybrid magnet (up to 30 T).

The diagonal (R_{xx}) and Hall (R_{xy}) resistances, measured in the conventional manner with B perpendicular to the sample plane, are shown in Figs. 3 and 4. The vertical arrows in these figures indicate the filling factors at which integral and fractional quantum Hall (IQH and FQH)

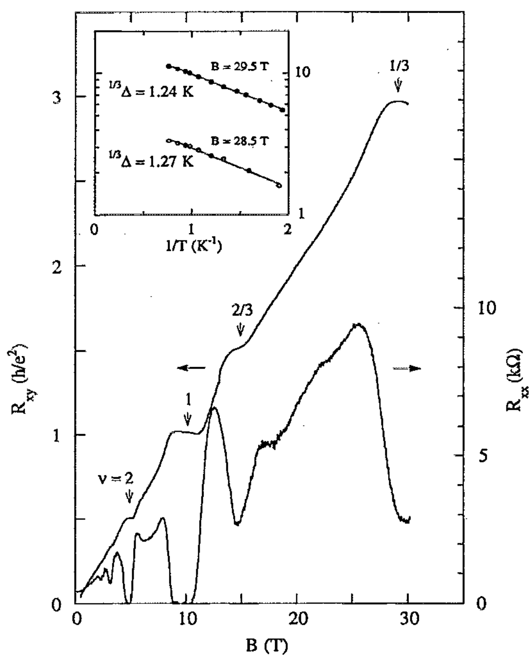

FIG. 4. R_{xx} and R_{xy} at high magnetic fields showing fractional quantum Hall states at ν=1/3 and 2/3. The inset shows an Arrhenius plot of the ν=1/3 R_{xx} minimum for two samples with slightly different n_s, giving a gap $^{1/3}\Delta$=1.3 K.

effects are observed. The IQH states at $\nu=1$, 2, 3, and 4 are clearly evident from the R_{xx} minima and R_{xy} plateaus. From these data, we deduce an electron density $n_s=2.5\times10^{11}$ cm^{-2} and mobility 3×10^4 cm^2/V s. The observation of consecutive integer IQH states reveals, surprisingly, a splitting of the valley degeneracy at high B in addition to spin splitting. Note that we expect a twofold (four half-ellipsoids) degeneracy for the occupied X-point valleys with heavy in-plane mass. The origin of this valley splitting is not presently known. It may be related to inhomogeneous stress between $Al_xGa_{1-x}As$ and AlAs[2] or many-body interactions.[13] Our available data cannot determine whether this splitting is present at $B=0$ or not; future work is planned. It is worth mentioning that the lifting of valley degeneracies has also been observed in Si/SiO_2 inversion layers[10,13] and more recently in Si/Ge heterostructures;[14,15] the origin remains unclear.

Finally, our data of Fig. 4 show the presence of fairly strong FQH states at $\nu=1/3$ and 2/3. These data were taken on another specimen ($n_s=2.3\times10^{11}$ cm^{-2}) from the same wafer. Fitting the temperature dependence of the R_{xx} minimum at $\nu=1/3$ (see inset of Fig. 4) to $R_{xx}=R_0 \exp(-{}^{1/3}\Delta/2T)$, we obtain ${}^{1/3}\Delta=1.3$ K. Our measured ${}^{1/3}\Delta$ is about an order of magnitude smaller than ${}^{1/3}\Delta$ observed for very high quality 2DES (with similar n_s) in GaAs quantum wells or GaAs/AlGaAs heterostructures.[16] The difference may be attributed to the higher level of disorder in our sample. It may also be partly related to the much larger effective mass of electrons in AlAs compared with GaAs ($m^*=0.067m_0$) which substantially reduces the Landau level spacing. The smaller spacing results in the mixing of the Landau levels, which is known to reduce ${}^{1/3}\Delta$.[6,17] It is interesting to note that recently measured FQH gaps at similar B for 2DES in Se/Ge heterostructures are also about 1 K.[15]

In summary, we report the growth and low-temperature cyclotron resonance and magnetotransport measurements of a high-quality 2DES in an AlAs quantum well. From the cyclotron resonance data, we conclude that the electrons occupy the X-point conduction-band valleys with heavy in-plane mass. We observe well-developed IQH and FQH states, and are able to determine an energy gap, ${}^{1/3}\Delta=1.3$ K, for the $\nu=1/3$ FQH state. We believe the fabrication of 2DES in AlAs quantum wells with even higher quality is possible (e.g., via using larger spacers). Such systems can exhibit exciting new phenomena as their band structure parameters differ from those of the 2DES in GaAs.

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[9] Note that in our simulation, the Fermi level at the dopants falls ≈150 meV below the conduction band edge. This energy is consistent with the binding energies typically assumed for Si in $Al_xGa_{1-x}As$ with $x\approx0.3$ [see, e.g., F. Stern, Appl. Phys. Lett. **43**, 974 (1983)].

[10] See, e.g., F. F. Fang, Surf. Sci. **98**, 416 (1980).

[11] Since we do not know the deformation potential for AlAs, we assumed the value for Si[$\Xi_u^\Delta\approx9$ eV quoted in C. G. van de Walle and R. M. Martin, Phys. Rev. B **34**, 5621 (1986)]. We find that the conduction band ellipsoids with heavier in-plane mass are lowered with respect to those with lighter in-plane mass by ≈20 meV.

[12] We emphasize that our cyclotron resonance data were taken at $B=8$ T where only the lowest Landau level is occupied. We cannot, therefore, rule out the possibility that at $B=0$ electrons occupy the ellipsoids with lighter in-plane mass while at higher B they are transferred to the ellipsoids with heavier in-plane mass.

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