Realization of an Interacting Two-Valley AlAs Bilayer System

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By using different widths for two AlAs quantum wells comprising a bilayer system, we force the X-point conduction-band electrons in the two layers to occupy valleys with different Fermi contours, electron effective masses, and g factors. Since the occupied valleys are at different X points of the Brillouin zone, the interlayer tunneling is negligibly small despite the close electron layer spacing. We demonstrate the realization of this system via magnetotransport measurements and the observation of a phase-coherent, bilayer $\nu = 1$ quantum Hall state flanked by a reentrant insulating phase.

Two-dimensional (2D) electron systems subjected to large perpendicular magnetic fields exhibit a wealth of phenomena, such as the fractional quantum Hall effect, that are associated with electron-electron interaction. When two 2D electron systems are brought in close proximity, the additional, interlayer interaction can lead to new many-body states that have no analogue in the single-layer case. Examples include quantum Hall states (QHSs) at even-denominator fillings $\nu = 1/2$ and $3/2$ [1,2] and a special, bilayer $\nu = 1$ QHS with interlayer phase coherence [3] (ν is the Landau level filling factor of the bilayer system). Such states form when the interlayer distance is on the order of or smaller than the magnetic length. It is also often desirable to have as little interlayer tunneling as possible so that, e.g., independent contacts can be made to the two layers [4]; moreover, negligible tunneling makes the theoretical treatment of the phenomena in these systems easier.

We report the fabrication of a novel bilayer system composed of two AlAs quantum wells (QWs) with different widths, wherein the electrons in the two layers occupy different conduction-band valleys. The key to the fabrication of our sample is the following. Bulk AlAs has an indirect band gap with the conduction-band minima at the X points of the Brillouin zone. The constant energy ellipsoids (or valleys) formed at these minima are anisotropic with two characteristic effective masses (measured in units of the free electron mass): $m_t = 0.2$ for the two transverse directions, and $m_t = 1$ for the longitudinal direction. This is similar to Si, except that in Si there are six ellipsoids centered around six equivalent points along the Δ lines of the Brillouin zone, while in AlAs we have three (six half-) ellipsoids at the X points. When electrons are confined along the growth (z) direction in an AlAs QW, one might expect that only the out-of-plane (X_Z) valley would be occupied because the larger electron mass along the confinement direction should lower the energy of this valley. This is indeed the case in Si metal-oxide-semiconductor field-effect transistors (MOSFETs) and QWs. However, in AlAs QWs grown on GaAs substrates, the strain induced by the lattice mismatch between AlAs and GaAs causes the in-plane (X_X and

X_Y) valleys to be occupied, unless the QW is narrower than a threshold value of approximately 55 Å [5–9]. By growing a modulation-doped, double QW sample with well widths on either side of the threshold, we force the electrons in each AlAs QW to occupy differently oriented valleys.

Because the occupied valleys are at different points of the Brillouin zone, the interlayer tunneling is strongly suppressed even though the layers are very closely spaced. Another novel aspect of this system is that the Fermi contour shapes, effective masses, and g factors in the two layers are different. We demonstrate the realization of this system via magnetotransport measurements. We also report the observation of a phase-coherent QHS at filling factor $\nu = 1$, surrounded by a reentrant insulating phase. In our sample, the $\nu = 1$ QHS is insensitive to the application of an in-plane magnetic field, evincing that tunneling is indeed negligible despite the very small interlayer separation.

We studied a Si-modulation doped AlAs bilayer grown by molecular beam epitaxy on a GaAs (100) substrate. The structure consists of a 100 Å wide AlAs QW in the front and a 45 Å wide AlAs QW in the back (substrate side), surrounded by $Al_{0.4}Ga_{0.6}As$ barriers and separated by a 28 Å GaAs barrier, giving a QW center-to-center separation of approximately 100 Å. The sample was lithographically patterned in a Hall bar configuration, and Ohmic contacts to both layers were made by depositing a AuGeNi layer and alloying in a reducing atmosphere. Metallic front and back gates were added to allow for adjustment of the total charge density in the bilayer (n_{tot}) and the densities in the narrow and wide wells (n_N and n_W) individually. We determined n_{tot}, n_N, and n_W from Shubnikov–de Haas (SdH) and Hall measurements. Typical values of n_{tot} were in the range of 2 to 5×10^{11} cm^{-2} with a mobility of ~ 2.2 m^2/Vs. We made measurements in ^{3}He and dilution refrigerators with base temperatures of 300 and 40 mK, respectively. In both refrigerators, the sample was mounted on a tilting stage so that the angle, θ, between the normal to the sample and the magnetic field could be varied from 0° to 90° *in situ*.

We first demonstrate how we change and monitor the densities in each QW. In Fig. 1 we show the Fourier transform (FT) spectra (main figures) of SdH oscillations (upper insets) at different values of front and back gate biases (V_{FG} and V_{BG}), corresponding to different n_W and n_N. The X-point conduction-band energies and the orientation of the occupied valleys in each layer are shown schematically in the lower insets of each panel (for clarity, only one valley is shown for the wide well even though two are occupied). For each pair of V_{FG} and V_{BG}, we also measure n_{tot} from the slope of the Hall resistance at low magnetic fields. To make the connection to the frequency of the SdH oscillations, we divide the measured n_{tot} by the Landau level degeneracy per unit field, e/h, and show the resulting frequency by a vertical arrow marked as n_{tot}. Figure 1(a) corresponds to the simplest case where all the electrons reside in the narrow QW. We observe strong SdH oscillations, with ρ_{xx} minima at every integer $\nu \leq 5$. Surprisingly, the minima at even-integer fillings are weaker than those at odd-integer fillings, and disappear at the lowest fields. This is consistent with our measurements of 2D electrons occupying the X_Z valley in single, narrow AlAs QWs, and comes about

because of the ratio (~ 0.7) of the Zeeman and cyclotron energies [10]. The FT spectrum of the oscillations exhibits two peaks as commonly observed in a single-layer 2D electron system [11]: a higher frequency peak stems from the spin-resolved Landau levels (at sufficiently large fields) and its position coincides with n_{tot}, while a peak at half this frequency originates from the spin-unresolved Landau levels (at low fields). In Fig. 1(b), we have increased n_{tot} and shifted the balance of electrons between the two layers so that now $n_N = n_W$. The SdH trace and its FT spectrum are characteristic of a balanced bilayer electron system with negligible interlayer tunneling, namely, two 2D layers in parallel: ρ_{xx} minima are observed only at even-integer fillings (for $\nu > 1$), and the FT spectrum does not show a peak at n_{tot} but rather at a value corresponding to $n_{tot}/2$. We also have SdH and Hall data for other configurations where the electrons are distributed unevenly between the two layers. From such data, we can determine n_{tot}, n_N, and n_W. However, we are not able to shift all the electrons into the wide QW because of experimental limitations on the maximum gate biases we could apply to the sample.

Next, we measured the carrier effective mass (m^*), from the temperature dependence of the amplitude of the SdH oscillations, for the case where all the electrons reside in the narrow QW. At a density of $n_N = 1.8 \times 10^{11}$ cm^{-2}, we measured a mass of 0.44 ± 0.03, much larger than $m^* = 0.2$ expected for in-plane motion if the electrons occupy the X_Z valley. This surprising result, however, is consistent with our results in single, narrow AlAs QW samples that have shown a dependence of m^* on the density: in a single, 45 Å wide AlAs QW, we have measured an m^* that changes from 0.23 at a high density of 7.2×10^{11} cm^{-2} to 0.44 at a low density of 1.8×10^{11} cm^{-2} [10,12]. A similar m^* enhancement at low densities was also reported in Si-MOSFETs [13]. We could not measure m^* in our wider AlAs QW since we were not able to put all the electrons in this well only. However, for an in-plane valley, electron-electron interactions can enhance the effective electron mass beyond the expected bare value of $m^* = (m_l m_t)^{1/2} = 0.45$, and our measurements of mass in single wide AlAs QWs are consistently higher than this bare value. It is therefore likely that, in our balanced bilayer system [Fig. 1(b)], m^* in the wider QW is larger than m^* in the narrow QW.

Our main evidence that the electrons in our sample occupy different valleys in the two layers is provided by the response of the system to a magnetic field, $B_{||}$, applied parallel to the sample plane. In Fig. 2 we show magneto-resistance traces, as a function of $B_{||}$, for two distributions of charge, similar to Fig. 1: one in which all the electrons are in the narrow QW, and one where the charge density is distributed evenly between the two QWs. In both cases, there are pronounced kinks in the magnetoresistance traces, indicated by the vertical arrows in Fig. 2. Previous investigations in single-layer 2D systems, both theoretical and experimental [14,15], have identified the
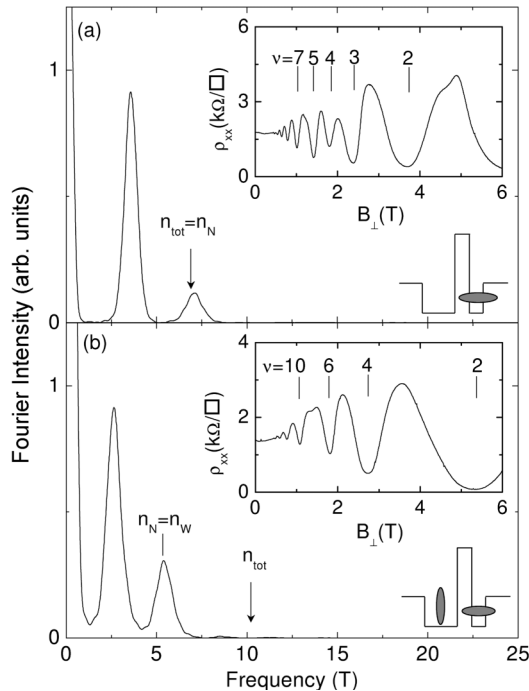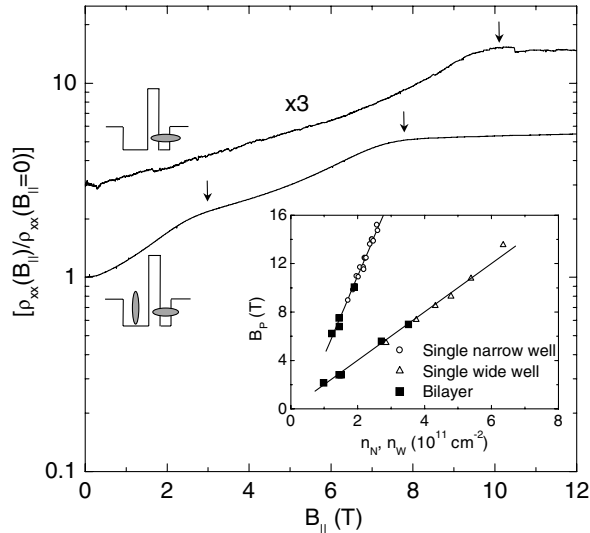

FIG. 1. Fourier transform spectra of the Shubnikov–de Haas oscillations (shown in the insets), measured at 0.3 K, for different values of front and back gate biases. The arrows indicate the expected peak positions, corresponding to the total bilayer density n_{tot} (1.7×10^{11} cm^{-2} and 2.5×10^{11} cm^{-2} in the top and bottom traces, respectively), as determined from the Hall resistance; the bilayer total filling factor ν is also labeled in the insets. As illustrated by the lower insets, in (a) the electrons are all in the narrow well and occupy the X_Z valley, while in (b) they equally occupy the narrow well (X_Z valley) and the wide well (X_X and X_Y valleys).

FIG. 2. Parallel field magnetoresistance for different charge distributions; top trace: $n_N = 1.9 \times 10^{11}$ cm^{-2}, $n_W = 0$; bottom trace: $n_N = n_W = 1.5 \times 10^{11}$ cm^{-2}. The arrows mark the fields, B_P, above which the layer(s) become fully spin polarized. The inset shows B_P versus layer density.

position of this kink (B_P) as the onset of complete spin polarization of the carriers, that is the field beyond which the Zeeman energy exceeds the Fermi energy of the 2D system. In a simple picture, where a linear spin polarization with $B_\parallel$ is assumed, the field at which the full polarization occurs is determined by the product $g^* m^*$ (g^* is the effective g factor). In the inset to Fig. 2, we have plotted the measured values of B_P as a function of n_N and n_W, determined from the Hall and SdH data for different pairs of V_{FG} and V_{BG}. In the same figure, we have also included B_P measured in *single* wide and narrow AlAs QWs. The data fall on two distinct curves, approximately straight lines, but with very different slopes. We will discuss the quantitative details and implications of this data in a future communication [10]. It is clear, however, that B_P is nearly a factor of 2 larger for electrons occupying the narrow QW (X_Z valley) than for those occupying the wide QW (X_X and X_Y valleys), implying that $g^* m^*$ is twice as small in the former case [16]. This conclusion is corroborated by our measurements in tilted magnetic fields where we observe crossings of the Landau levels at particular tilt angles, θ, whose values are a measure of the product $g^* m^*$ of the 2D system. In the narrow AlAs QW of the present sample, or in our single, narrow AlAs QWs, we observe crossings at values of θ that are very different from the values at which the Landau levels in our wide AlAs QWs cross. We emphasize that, in addition to the different mass and g factor, there is a basic difference in the shapes of the (in-plane) Fermi contours for the two layers: circular for the X_Z valley in the narrow QW and elliptical for the $X_{X,Y}$ valleys in the wide QW.

Next, we present evidence that interlayer tunneling is small in our bilayer and that the system exhibits phenom-

ena arising from strong interlayer interaction. In Fig. 3(a) we show ρ_{xx} versus perpendicular magnetic field traces for a balanced state of the bilayer at three different temperatures. Up to $B \sim 6$ T, QHSs are observed only at even ν, consistent with two 2D parallel layers with little or no interlayer tunneling. At $\nu = 1$, however, a strong ρ_{xx} minimum is observed, which we associate with the phase-coherent, bilayer QHS. Such a QHS has been reported in GaAs bilayer electron [3,4] and hole [17,18] systems; it is stabilized by strong interlayer interaction, exists even in the limit of vanishing interlayer tunneling, and occurs when d/l_B is less than about 1.6, where d is the distance between the electron layers and l_B is the magnetic length. For the trace in Fig. 3(a), $d/l_B = 1.27$, consistent with these previous reports. From the temperature dependence of ρ_{xx} at $\nu = 1$, we obtain an energy gap of approximately 1 K for this state.

In Fig. 3(a), we also see the emergence of a reentrant insulating phase (IP) around the $\nu = 1$ minimum, extending from approximately $\nu = 1.29$ to 1.04 and beyond $\nu = 0.97$. Previous results have suggested that this phase may represent a pinned, bilayer, Wigner crystal state, where interlayer interaction stabilizes the state at a filling that is higher than what would be expected based on single-layer data [18,19]. We note that the presence of the IP near the $\nu = 1$ minimum in the present bilayer system is consistent with previous experimental results. In particular, interacting GaAs bilayer holes, whose
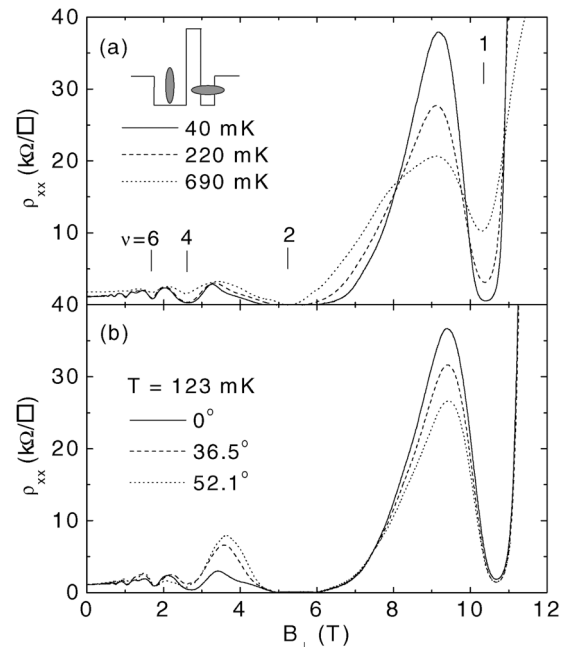

FIG. 3. (a) Magnetoresistance, ρ_{xx}, versus perpendicular magnetic field for the balanced bilayer system, with $n_N = n_W = 1.26 \times 10^{11}$ cm^{-2}, at three different temperatures, showing a $\nu = 1$ QHS flanked by a reentrant insulating phase. (b) The dependence of ρ_{xx} at balance on tilt angle. Here, $n_N = n_W = 1.30 \times 10^{11}$ cm^{-2}.

effective mass is comparable to the mass of AlAs electrons, show an IP that is also reentrant around $\nu = 1$ [18].

To examine the interlayer tunneling in our system, we measured ρ_{xx} traces in tilted magnetic fields [Fig. 3(b)]. The parallel component of the field suppresses tunneling by shifting the electron Fermi contours in the two layers with respect to one another in momentum space [20]. Consequently, one would expect that, as the parallel field component is introduced, the strength of the $\nu = 1$ minimum will change if single-particle tunneling is playing a role in stabilizing it. Even a small amount of tunneling can lead to noticeable weakening of the $\nu = 1$ QHS with parallel field [3,21]. The fact that the ρ_{xx} minimum at $\nu = 1$ in our bilayer does not depend on the tilt angle and the parallel field provides additional evidence that interlayer tunneling in our system is small.

We conclude by making several remarks. First, while all our data point to the small value of tunneling in our bilayer system, we do not know the strength of tunneling quantitatively. Theoretically, the tunneling should be quite small; indeed, in an ideal system, mixing between $X_{X,Y}$ and X_Z valleys is forbidden. Optical measurements in GaAs/AlAs superlattices, however, have indicated that interface disorder can lead to some mixing [22]. Direct measurements of tunneling in our system will therefore be needed to assess the amount of tunneling quantitatively. Second, we note that the difference in effective masses and well widths for the layers implies that the ground state subband energies for the two layers are different, even when the layers have equal densities. This, together with the difference in g factors, means that the resulting Landau level fan diagram is rather complex. One can achieve a situation, for example, where all the electrons in one layer are spin polarized while there is only partial polarization in the other layer. Also, keeping the Fermi energies of the layers equal as a function of sweeping magnetic field requires some charge transfer between the wells. There are, therefore, possibly interesting phenomena at high magnetic fields, such as instabilities in layer charge densities even in the case of balanced wells [23], that can be explored in this system. Third, the system has some remarkable properties at zero or small magnetic fields. For example, as shown in Fig. 2, one can significantly tune the g^*m^* product in this system by applying gate biases. A system with a gate-tunable g^*m^* may find application in emerging fields such as quantum computing [24]. Fourth, measurements of interlayer Coulomb drag in a system where the electrons occupy different valleys can be interesting. Finally, a bilayer system with different effective masses in the two layers might host a novel superconducting state [25].

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