Quantum Hall effect in a triple-layer electron system

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We report magnetotransport measurements in a low-disorder three-layer electron system in a GaAs/$Al_xGa_{1-x}As$ triple quantum-well structure. Fine adjustment of densities in different layers is achieved with the use of front and back gates and by monitoring the capacitance-voltage and low-field Shubnikov–de Haas data. At intermediate fields the diagonal resistance (R_{xx}) shows strong minima at every third integer filling factor, $\nu=3$, 6, 9, and 12, consistent with the subband structure. At higher fields, we observe deep R_{xx} minima at $\nu=\frac{7}{5}$ and $\frac{5}{7}$, suggesting anamalously strong $\frac{7}{5}$ and $\frac{5}{7}$ fractional quantum Hall states in this triple-layer system.

Recently, there is much interest in the fabrication and physics of remotely doped structures which contain two or more high-quality (low-disorder) layers of electrons in close proximity so that the interlayer Coulomb interactions are strong.[1] Theoretically, the possibility of novel collective states such as new integral and fractional quantum Hall (IQH and FQH) states or Wigner crystallization in multilayer structures has been proposed. There has also been some recent experimental work in these systems. Examples include the magnetic-field-driven collapse of the IQH effect at odd Landau-level fillings (ν),[2,3] and the observation of new FQH states at the even denominator $\nu=\frac{1}{2}$ filling in low-disorder *double-layer* electron systems in either a wide single quantum well[4] or a double quantum well.[5]

The physics of a system that contains *three or more* layers of electrons is also expected to be quite rich.[1] However, the experimental realization of such systems is particularly challenging since, as the number of wells in a remotely doped system increases, the electrons tend to accumulate in the two wells at the ends.[6] In this Brief Report we demonstrate the realization of a remotely doped, high-quality, *three-layer* electron system in a triple quantum well. We report self-consistent calculations for the potential and charge profile, and present capacitance-voltage (*C-V*) and magnetotransport data to characterize the system. Our transport measurements at high magnetic fields show deep R_{xx} minima at $\nu=\frac{7}{5}$ and $\frac{5}{7}$, but we are unable to observe Hall plateaus which are quantized at the correct values. Although not conclusive, the data are suggestive of anomalously strong FQH states at $\nu=\frac{7}{5}$ and $\frac{5}{7}$ in this three-layer systems.

The structure was grown on an undoped (100) GaAs substrate by molecular-beam epitaxy, and consists of three coupled wells (Fig. 1). The triple-quantum-well systems is bounded on each side by 900 Å of undoped $Al_{0.35}Ga_{0.65}As$ (spacer) and Si-doped layers. We made the center well (width equal to 170 Å) wider than the two side wells (width equal to 125 Å) to facilitate obtaining nearly equal areal electron densities in the three quantum wells. We elaborate on this point later in the paper. Barriers between the wells are made of 55-Å-wide undoped $Al_{0.2}Ga_{0.8}As$ layers. The triple-well electron system is buried 3900 Å below the surface. Ohmic contacts were made by alloying In:Sn in an H_2 ambience at 440 °C for 10 min. An evaporated Al front-side gate and an In back-side gate were used to control the densities of the electron layers. For the data reported here, the measured *total* electron density in the system is $N_s=2.0\times10^{11}$ cm^{-2} with mobility $\mu=2.3\times10^5$ $cm^2/V\,s$. The magnetotransport measurements were made in either a ^3He cryo-

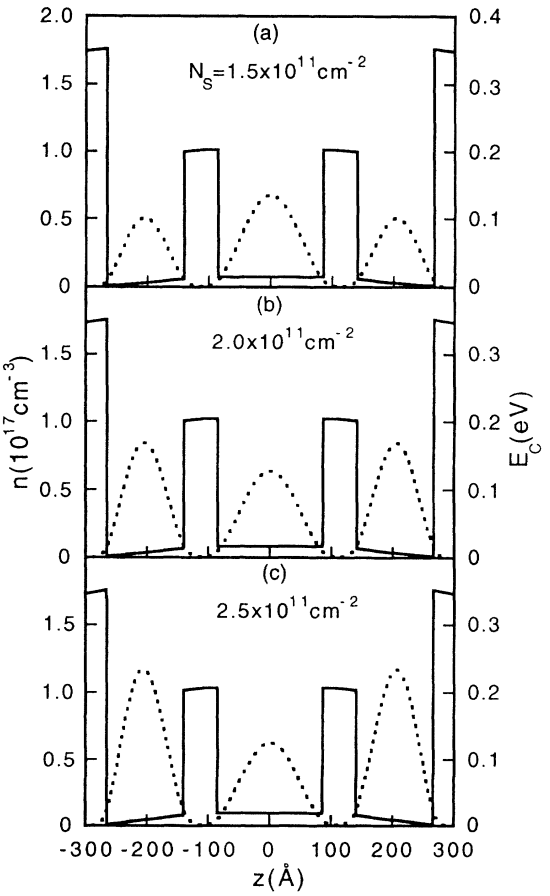

FIG. 1. Calculated electron-density profile (dashed curves) and conduction-band edge E_c (solid curves) in a triple-well structure for three different areal densities: (a) underpopulated, (b) nearly balanced, and (c) overpopulated.

stat or a dilution refrigerator.

We first describe the electronic structure of our system and its characterization. Figure 1(b) shows the results of our zero-field, Hartree-Fock calculations of the self-consistent potential and the charge-density profile for $N_s=2.0\times10^{11}$ cm^{-2} electrons distributed symmetrically in the system. At zero magnetic field the electrons occupy the lowest three electric subbands (E_1, E_2, and E_3), which are closely spaced ($E_3-E_2=0.39$ meV and $E_2-E_1=0.39$ meV). The next group of three subband energies is located about 40 meV above the lowest group. Note that for this N_s, the areal densities in each of the three wells are nearly equal. [The areal densities of the individual wells are obtained by integrating under the charge-density profile (dashed curves in Fig. 1) for each well.] For a triple-well system with given parameters (well and barrier width and barrier height), the areal electron densities in the center and side wells (N_{center} and N_{side}) depend on N_s as the self-consistent potential and charge profile change according to N_s. At higher N_s, more electrons accumulate in the side wells and $N_{\text{center}}<N_{\text{side}}$, as shown in Fig. 1(c) for $N_s=2.5\times10^{11}$ cm^{-2}. The profile for a lower density ($N_s=1.5\times10^{11}$ cm^{-2}) is shown in Fig. 1(a); here $N_{\text{side}}<N_{\text{center}}$. We denote a triple-well system such as the one in Fig. 1(b), which has a symmetric charge distribution with respect to the center of the middle well, and also has equal areal densities in each well, as *balanced.*

Before discussing the experimental data, we point out some general properties of a remotely doped triple-well system: (1) A triple well with fixed parameters is balanced only for a unique N_s. The results shown in Figs. 1 and 2 illustrate this statement. In Fig. 2 we show the calculated ($N_{\text{center}}-N_{\text{side}}$) as a function of total N_s. Note that for $N_s\approx2.0\times10^{11}$ cm^{-2}, $N_{\text{center}}\approx N_{\text{side}}$ and the well is nearly balanced. (2) The separation between the top and bottom subband energies (E_3-E_1) is smallest when the triple well is balanced. This statement is illustrated in Fig. 2 where we show the calculated (E_3-E_1) for a symmetric system as a function of N_s. Also, if the balanced triple-well system is disturbed so that N_s is kept fixed but the system is no longer symmetric, (E_3-E_1) increases from its balanced value. As we will show later in this paper, in our experiment we utilize these properties to balance the triple-well system. (3) We mentioned that the center well was made larger than the side wells so that we could obtain a balanced system more easily. In principle, the wells can all have the same width. To obtain a balanced system in a triple well with wells of equal width, however, either N_s or the width of the wells has to be very small.[7] In either case, it will be quite difficult to realize a low disorder system; e.g., a very dilute system (very low N_s) is more sensitive to ionized impurity scattering,[8] while electrons confined to a very narrow well suffer more from surface roughness scattering.[9] We therefore chose the center well to be wider so that we can achieve a balanced system with reasonably large N_s and well width.

Figure 3(a) shows our *C-V* data taken at 0.5 K by

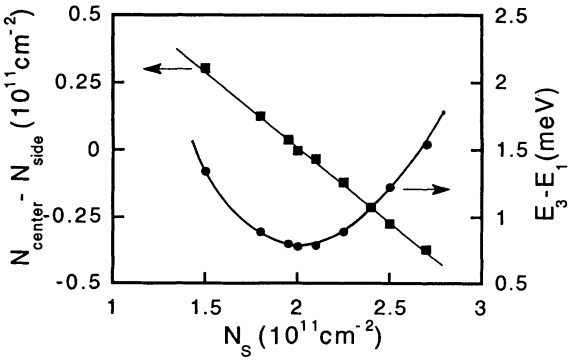

FIG. 2. Calculated subband spacing (E_3-E_1) and the areal density difference between center and side wells. The curves are a guide to the eye. For $N_s\approx2.0\times10^{11}$ cm^{-2}, subband spacing is minimum and $N_{\text{center}}\approx N_{\text{side}}$.

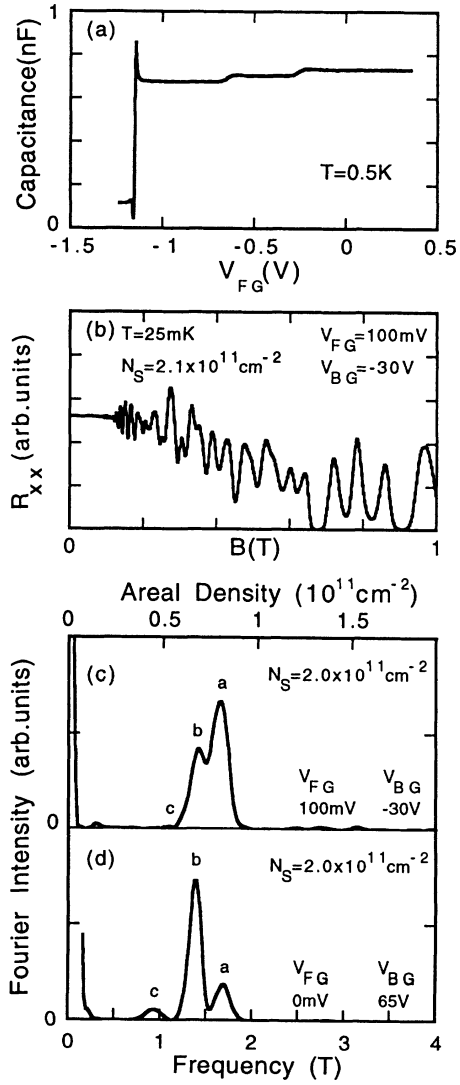

FIG. 3. (a) *C-V* data showing the presence of three electron layers in the triple-well structure. (b) Low-field R_{xx} data for a balanced system. (c) Fourier transform spectrum of (b). (d) Fourier transform spectrum for the low-field R_{xx} data of an out-of-balance system.

sweeping the front gate voltage (V_{FG}) while keeping the back gate voltage (V_{BG}) at zero. These data clearly demonstrate that the electron system contains three layers. As V_{FG} is swept from zero to negative bias, the three wells are depleted of electrons, one at a time, from front to back. This sequential depletion is evidenced by the presence of sharp steps in the C-V data. The ratio of the measured step height to the total capacitance (≈ 0.05) is consistent with the ratio of the separation between electron layers and the distance between the surface and the triple-layer electron system (≈ 200 Å/4000 Å). Since the distance between the front gate and electron system is much larger than the separation between electron layers, we can use the width of each step in the C-V data as a measure of the areal electron density in the respective well. From these data we conclude that a balanced electron system containing three layers of nearly equal areal density is obtained for $V_{FG} \approx 100$ mV and, as determined from our later measurements, $V_{BG} \approx -30$ V (to reduce the density in the back well). This conclusion is confirmed by the magnetotransport results discussed below.

We experimentally determined the subband structure of the system from the analysis of the low-field Shubnikov–de Haas oscillations [Fig. 3(b)]. The positions of the peaks in the Fourier transform of R_{xx} vs $1/B$ data give the densities of the different subbands. The sum of these subband densities should be equal to the total density N_s, which is independently determined from the slope of the Hall data or the positions of R_{xx} minima and the quantized Hall plateaus in high-field data. In our experiments we judged the balanced condition by minimizing the difference between the measured subband densities and also by examining the high-field data. This is illustrated in Figs. 3(c) and 3(d). The Fourier-transform spectrum for $N_s = 2.0\times10^{11}$ cm^{-2} ($V_{FG} = 100$ mV, $V_{BG} = -30$ V) shown in Fig. 3(c) shows only two peaks with subband densities equal to $N_a = 7.9\times10^{10}$ cm^{-2} and $N_b = 6.8\times10^{10}$ cm^{-2}. (Here we use N_a, N_b, and N_c for the subband densities obtained from measurements, and N_1, N_2, and N_3 for the values from calculations.) Note that $N_a + N_b < N_s$ and therefore we expect a third peak, corresponding to the other subband density $N_c = N_s - (N_a + N_b) = 5.3\times10^{10}$ cm^{-2}, to be present in Fig. 3(c). Evidently, the N_c peak is not resolved in these data. The calculated subband densities are $N_1 = 7.8\times10^{10}$, $N_2 = 6.6\times10^{10}$, and $N_3 = 5.6\times10^{10}$, cm^{-2}, in good agreement with the directly measured densities N_a and N_b, and the deduced density N_c. As an example of a slightly out-of-balance (asymmetric) system, we show in Fig. 3(d) the Fourier-transform spectrum measured for $V_{FG} = 0$ mV and $V_{BG} = 65$ V. Three distinct peaks are resolved giving $N_a = 8.2\times10^{10}$, $N_b = 6.8\times10^{10}$, and $N_c = 4.6\times10^{10}$ cm^{-2} with $N_a + N_b + N_c = 1.96\times10^{11}$ cm^{-2}, consistent with $N_s = 2.0\times10^{11}$ cm^{-2} (measured from the Hall and high-field data). Note that, as expected, the subband energies and their densities are now farther apart.

In Fig. 4(a) we show R_{xx} and R_{xy} data for the balanced system at $T = 330$ mK up to $B = 3.5$ T. R_{xx} shows deep

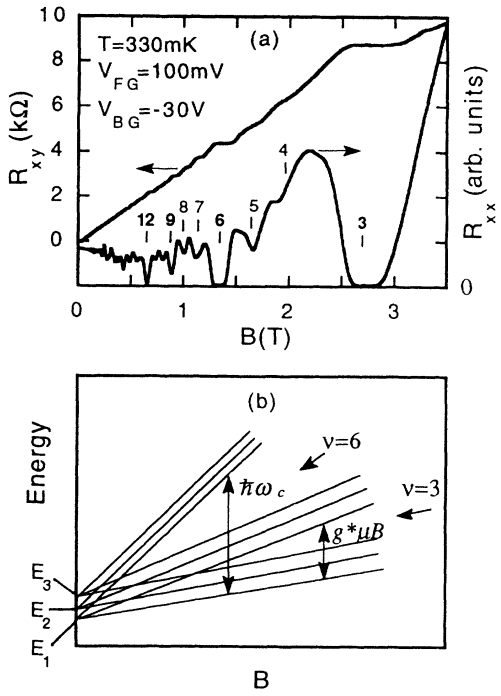

FIG. 4. (a) Magnetotransport data in intermediate fields, showing deep minima at every third integer filling factor. (b) Schematic diagram for energy vs field.

minima at every third integer filling factor $\nu = 3$, 6, 9, and 12. To explain these data, we note that in a simple picture there are four relevant energy gaps in a triple-well system [Fig. 4(b)]: (1) the cyclotron energy $\hbar\omega_c = \hbar eB/m^*$; (2) the Zeeman energy $g^*\mu_B B$; and (3) and (4) the subband separations $E_3 - E_2$ and $E_2 - E_1$. These energies are schematically shown in Fig. 4(b). For $B \geq 0.5$ T, $\hbar\omega_c$ is larger than all other energy gaps, and we associate the IQH states at $\nu = 12$ and 6 with this gap. We believe that the observed IQH state at $\nu = 3$ is related to the Zeeman gap. At $\nu = 3$ ($B = 2.7$ T), $g^*\mu_B B = 0.063$ meV if we use the bare g^* value (0.4) for GaAs. However, it is known that for partially filled Landau levels g^* is enhanced with respect to its bare value by a factor of 10 or larger.[10] Therefore it is very likely that the Zeeman gap at 2.7 T in our system is larger than $E_3 - E_1$, and leads to the IQH effect at $\nu = 3$. This implies that the $\nu = 1$, 2, 4, and 5 minima in R_{xx} are associated with the Fermi level lying in the subband gaps [Fig. 4(b)]. The origin of the $6 < \nu < 12$ IQH states is less clear; however, if a very large (about 30 times) enhancement of g^* is assumed, then the $\nu = 9$ state originates from the Zeeman gap while the R_{xx} minima at $\nu = 7$, 8, 10, and 11 are related to the subband gaps.[11]

Finally, in Fig. 5, we show R_{xx} and R_{xy} data at higher B for the same balanced system as in Fig. 4. The surprising features of the data are the deep R_{xx} minima near the fractional fillings $\nu = \frac{7}{5}$ and $\frac{5}{7}$. Note the absence of a $\nu = \frac{4}{3}$ FQH state, which is normally the strongest fractional state in the region $1 < \nu < 2$ in a single-layer, two-dimensional electron system. The $\nu = \frac{7}{5}$ R_{xx} minimum is temperature activated (see inset to Fig. 5), and we obtain

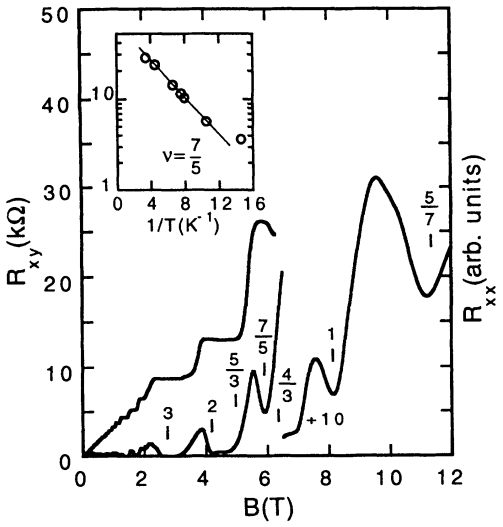

FIG. 5. High-field data showing anomalously deep R_{xx} minima at $\nu=\frac{7}{5}$ and $\frac{5}{7}$. The R_{xx} data were measured at $T=160$ mK and R_{xx} at 110 mK. The inset shows the dependence of R_{xx} minimum at $\nu=\frac{7}{5}$ on temperature.

a gap Δ equal to ≈ 430 mK from fitting the data to $R_{xx} \sim \exp(-\Delta/2kT)$. In our experiments, we could not reliably measure R_{xy} for $T \leq 400$ mK and high B as the R_{xy} signal sharply rises above $B \approx 5$ T. The origin of this rise is not clear, but it may be related to the mixing of the R_{xx} component. However, we have observed R_{xx} data similar to those presented in Fig. 5 for other samples cut from different parts of the wafer, and believe that these data are intrinsic to this triple-well system.

Assuming that the R_{xx} minima observed near $\nu=\frac{7}{5}$ and $\frac{5}{7}$ represent developing FQH states at these filling factors, we provide the following discussion. The possibility of FQH states which are particularly strong in triple-layer systems (compared to single-layer systems) has been suggested theoretically.[1] In fact, the strongest FQH state for a three-layer system has been predicted to occur at $\nu=\frac{5}{7}$.[1] This may explain our observation of an anomalously deep R_{xx} minimum near $\nu=\frac{5}{7}$.[12]

The strong minimum in R_{xx} at $\nu=\frac{7}{5}$ and the absence of a $\frac{4}{3}$ minimum may imply that a $\frac{7}{5}$ FQH state is also specially favored in a three-layer system. However, we note that absence of a $\nu=\frac{4}{3}$ state in the particular range of B between 5.5 and 6.5 T has been reported for single-layer systems,[13] and has been attributed to the change in the spin configuration (spin-unpolarized to spin-polarized) of the $\frac{4}{3}$ state in this B range. Clearly, while the data shown in Fig. 5 are intriguing and suggestive, more experimental work is need to unambiguously identify the FQH states which are specially stable in triple-layer systems.

In summary, we report the fabrication, characterization, and magnetotransport measurements of a three-layer electron system with remote doping. We show that the charge distribution in this system can be tuned and balanced by applying front- and back-gate voltages. Such structures provide very rich systems for the study of IQH and FQH effects in low-disorder multilayer electron systems.

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[1]For a review see, e.g., A. H. MacDonald, Surf. Sci. **229**, 1 (1990).

[2]G. S. Boebinger, H. W. Jiang, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **64**, 1793 (1990).

[3]Y. W. Suen, J. Jo, M. B. Santos, L. W. Engel, S. W. Hwang, and M. Shayegan, Phys. Rev. B **44**, 5974 (1991).

[4]Y. W. Suen, L. W. Engel, M. B. Santos, M. Shayegan, and D. C. Tsui, Phys. Rev. Lett. **68**, 1379 (1992).

[5]J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer, K. W. West, and Song He, Phys. Rev. Lett. **68**, 1383 (1992).

[6]A remotely doped many-layer structure can be fabricated by adding a small periodic potential to a parabolic well [J. Jo, M. Santos, M. Shayegan, Y. W. Suen, L. W. Engel, and A. M. Lanzillotto, Appl. Phys. Lett. **57**, 2130 (1990)].

[7]For example, to obtain a balanced system in a structure with three 140-Å-wide wells and barriers similar to those of Fig. 1, $N_s \approx 2\times 10^{10}$ cm^{-2} is needed. Alternatively, to have a balanced system with $N_s = 2\times 10^{11}$ cm^{-2}, each of the three (equally wide) wells has to be ≈ 70 Å wide.

[8]C. Jiang, D. C. Tsui, and G. Weimann, Appl. Phys. Lett. **53**, 1533 (1988).

[9]H. Sakaki, T. Noda, K. Hirakawa, M. Tanaka, and T. Matsusue, Apply. Phys. Lett. **51**, 1934 (1987).

[10]For example, 13 times g^* enhancement at $\nu=3$ has been reported [R. J. Nicholas, R. J. Haug, K. v. Klitzing, and G. Weimann, Phys. Rev. B **37**, 1294 (1988)].

[11]In a many-body picture, it is also possible that the subband separations may change as a function of B. For example, in a double-layer structure, the reduction and collapse of subband gap E_2-E_1 at high B has been reported (see Refs. 2 and 3).

[12]It is worth noting that the $\nu=\frac{5}{7}$ state predicted in Ref. 1 has a lower density in the central layer than the two side layers.

[13]R. G. Clark, S. R. Haynes, J. V. Branch, A. M. Suckling, P. A. Wright, P. M. W. Oswald, J. J. Harris, and C. T. Foxon, Surf. Sci. **229**, 25 (1990).