RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 44, NUMBER 11 15 SEPTEMBER 1991-I

# Missing integral quantum Hall effect in a wide single quantum well

Y. W. Suen, J. Jo, M. B. Santos, L. W. Engel, S. W. Hwang, and M. Shayegan
*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544*
(Received 17 December 1990; revised manuscript received 10 May 1991)

We report magnetotransport measurements in a weakly coupled double-layer electron system realized in a wide quantum well. This system has the unique property that the distance and the coupling between the layers can be changed continuously by varying the electron density in the well. We observe the absence of quantum Hall states at odd filling factors. Our results complement earlier experimental work and are consistent with a recent theoretical model proposed for the magnetic-field-driven destruction of the quantum Hall effect in double quantum wells.

The two-dimensional electron system (2DES) has provided the means for the observation of many new physical phenomena, such as the integral[1] and fractional[2] quantum Hall effects (IQHE and FQHE). Recently, there is much interest in the fabrication and physics of structures which contain two or more layers of electrons in close proximity so that the interlayer Coulomb interactions are strong.[3–10] Theoretically, the possibility of new collective states such as the FQHE at even-denominator Landau-level fillings ($\nu$), or Wigner crystallization in such multilayer structures has been proposed.[3–5] There has also been some experimental work in these systems. The observation of the IQHE in multilayer systems with significant interlayer tunneling has been reported.[6,7] Boebinger *et al.*[8] recently studied the IQHE in strongly coupled, high-quality double quantum wells (DQW) in which the symmetric to antisymmetric energy gap ($\Delta_{SAS}$) is expected to give rise to the IQHE at odd $\nu$. They observed a remarkable effect, namely the *absence* of certain IQHE states at low-odd $\nu$ for sufficiently small $\Delta_{SAS}$ and large interlayer distance ($d$). The origin of this phenomenon is not clear yet although recent calculations relate it to the Coulomb-driven destruction of $\Delta_{SAS}$ in a strong magnetic field.[9,10] According to these calculations, if the magnetic field ($B$) is sufficiently strong, $\Delta_{SAS}$ collapses and the DQW system makes a transition to a different ground state with weak interwell, but strong intrawell correlations.[9]

In this Rapid Communication, we report magnetotransport measurements in a novel high-quality double-layer system realized in a wide, *single,* GaAs quantum well (Fig. 1). The idea is that when electrons are introduced in a wide quantum well, the electrostatic repulsion between the electrons forces them into a stable configuration in which two 2DES's are formed at the well's sidewalls. A major advantage of this system over a conventional DQW is the minimization of alloy scattering since the barrier between the two 2DES's is GaAs rather than $Al_xGa_{1-x}$As. Also, both $\Delta_{SAS}$ and $d$ can be changed by varying the electron density ($n_s$) in the well (Figs. 1 and 2). Our study of this system in a regime where the two 2DES's are weakly coupled reveals the absence of IQHE states at odd $\nu$. Our data can be qualitatively explained by the theories proposed by MacDonald, Platzman, and Boebinger[9] and Brey.[10]

Before discussing the experimental results we briefly describe the electronic structure of our system. Figure 1 shows the conduction-band edge ($E_c$) of a 1200-Å-wide GaAs well when it is empty [Fig. 1(a)] and after $n_s$ electrons are transferred into it [Figs. 1(b)–1(c)]. The electron distribution function, which is calculated self-consistently in the Hartree-Fock approximation at zero magnetic field, i.e., by solving the Poisson and Schrödinger equations simultaneously, is also shown in Fig. 1. Local density functional approximation[11] is used for the

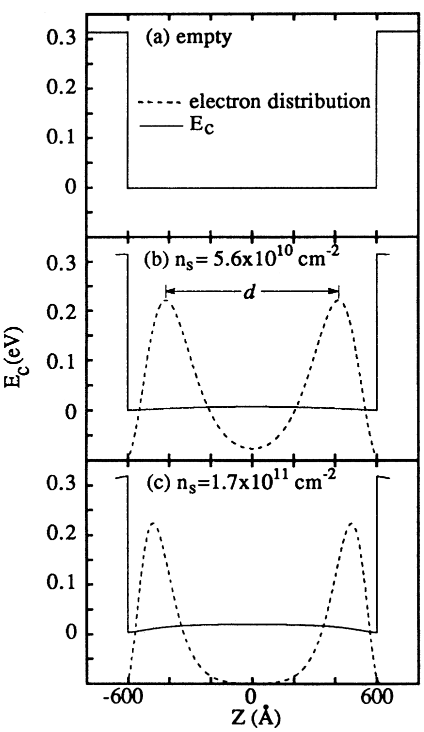


FIG. 1. Results of self-consistent calculations of the conduction-band edge (solid curves) and the electron distribution function (dashed curves) are shown for a 1200-Å-wide well: (a) when the well is empty, and (b) and (c) after $n_s$ electrons are transferred into the well. We used $\Delta E_c = 0.9x$ eV for the conduction-band offset of GaAs/$Al_xGa_{1-x}$As and $m^*/m_0 = 0.067$ for the effective mass.

 

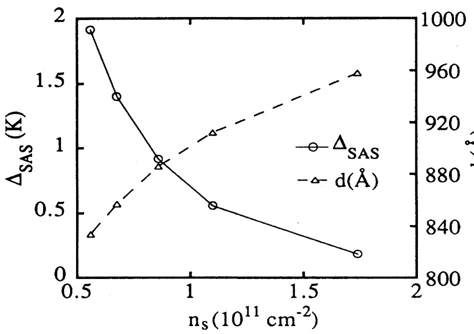


FIG. 2. Calculated $\Delta_{SAS}$ and $d$ for a 1200-Å-wide well vs total density $n_s$.

exchange term. The electron distribution functions in Fig. 1 indicate the presence of two weakly coupled electron layers in this system. Figure 2 shows our calculated $\Delta_{SAS}$ and $d$ vs $n_s$ for the 1200-Å-wide well. We note that in this structure $\Delta_{SAS}$ can be varied by 1 order of magnitude by changing $n_s$ from $\sim 6\times 10^{10}$ to $\sim 1.7\times 10^{11}$ cm$^{-2}$.

We studied two wide, single quantum wells with similar structures but different well widths, 1200 and 800 Å. The structures were grown on undoped (100) GaAs substrates by molecular-beam epitaxy. They consist of a wide, undoped GaAs quantum well, bounded on each side by an 885-Å-thick undoped $Al_{0.35}Ga_{0.65}As$ spacer layer, and five periods of $1.3\times 10^{11}$ cm$^{-2}$ Si $\delta$-layers, each separated by 35 Å of undoped $Al_{0.35}Ga_{0.65}As$.

In order to make transport measurements, contacts were made by alloying In in a $H_2$ ambience at 400 °C for about 10 min. A front-side gate, made by evaporating Al on the surface with photoresist-protected Ohmic contacts, and an In back-side gate were used to change and balance the densities of the two 2DES's. The magnetotransport coefficients $R_{xx}$ and $\rho_{xy}$ were measured in a van der Pauw geometry in a top-loading Oxford TLM-200 dilution refrigerator. The sample was mounted on a pivoted platform so that the angle ($\theta$) between the sample plane normal and the direction of the magnetic field could be varied *in situ*. Use of tilted fields is necessary especially for weakly coupled 2DES's to differentiate the IQHE due to $\Delta_{SAS}$ from an artifact due to the possible density imbalance of the two 2DES's.[12]

First, we concentrate on the data for the 1200-Å-wide well. By tuning the gate voltages, we were able to vary $n_s$ in this well in the range $5.6\times 10^{10} \le n_s \le 1.7\times 10^{11}$ cm$^{-2}$ while keeping the well balanced. Note that at the lowest $n_s$, there are only $2.8\times 10^{10}$ cm$^{-2}$ electrons in each 2DES. The mobility measured in this density range varies from $1.2\times 10^5$ to $3.6\times 10^5$ cm$^2$/V s, and increases linearly with increasing $n_s$, similar to what is observed in our high quality 2DES at the GaAs/$Al_xGa_{1-x}As$ interfaces.[13] We carefully studied the magnetotransport coefficients for $n_s = 1.7\times 10^{11}$, $1.1\times 10^{11}$, $8.6\times 10^{10}$, $6.7\times 10^{10}$, and $5.6\times 10^{10}$ cm$^{-2}$. For each $n_s$, we took special care to make sure that the two 2DES's are balanced by checking the low-field and high-field magnetotransport data for different gate biases and in tilted magnetic fields. Figure 3 shows $R_{xx}$ and $\rho_{xy}$ as a function of $B$ for $n_s = 1.7\times 10^{11}$

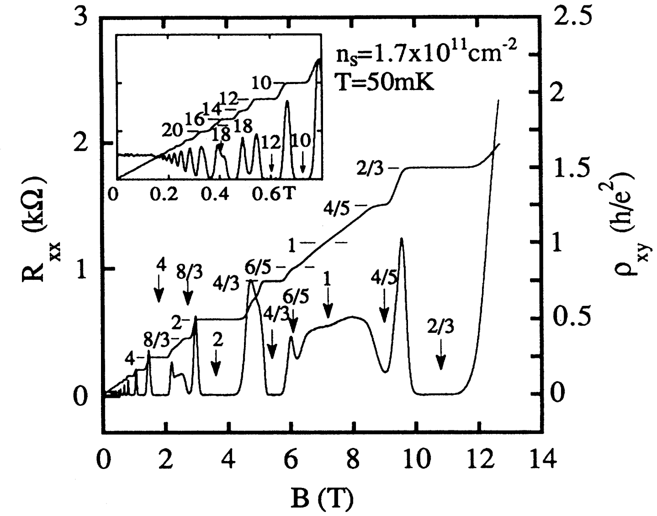


FIG. 3. The diagonal resistance ($R_{xx}$) and Hall resistivity ($\rho_{xy}$) in a perpendicular magnetic field for $n_s = 1.7\times 10^{11}$ cm$^{-2}$ in a 1200-Å-wide well are shown. The inset shows an expansion of the low-field data. All the IQHE states at odd $\nu$ are missing.

cm$^{-2}$ in the high-field range and at low $B$. The filling factor $\nu$ is assigned according to the quantization of the Hall resistance, $\rho_{xy} = h/e^2\nu \simeq 25.8$ k$\Omega/\nu$. The filling factor for each 2DES is half of $\nu$. The observation of well-resolved FQHE states at $\nu = \frac{2}{3}, \frac{4}{3}, \frac{4}{5}, \frac{6}{5}$, and $\frac{8}{3}$ ($\frac{1}{3}, \frac{2}{3}, \frac{2}{5}, \frac{3}{5}$, and $\frac{4}{3}$ for each 2DES) indicates the high quality of this double-layer electron system. Figure 4 shows the magnetotransport data for $n_s = 6.7\times 10^{10}$ cm$^{-2}$. The FQHE state at $\nu = \frac{2}{3}$ is still very clear.

In our system, when the magnetic field is sufficiently large so that $\hbar\omega_c \gg \Delta_{spin} > \Delta_{SAS}$, where $\hbar\omega_c = \hbar eB/m^*$ is the cyclotron energy and $\Delta_{spin} = g^*\mu_B B$ is the Zeeman energy, we expect $\Delta_{SAS}$ to lead to IQHE at odd $\nu$. In the entire density range that we studied, we found no evidence for any IQHE states at odd $\nu$ down to our lowest temperature of 50 mK, even though $\Delta_{SAS}$ is as high as 2 K for $n_s = 5.6\times 10^{10}$ cm$^{-2}$ (Fig. 2). We attribute our experimental observation to the magnetic-field-driven destruction of $\Delta_{SAS}$ in this double-layer system similar to what Boebinger *et al.* have reported for DQW's.[8] Comparison

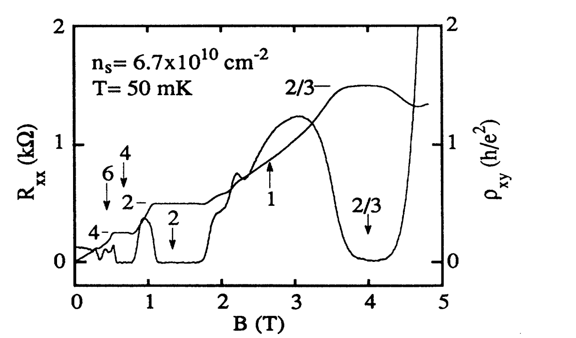


FIG. 4. The $R_{xx}$ and $\rho_{xy}$ data for $n_s = 6.7\times 10^{10}$ cm$^{-2}$ in a 1200-Å-wide well. There is no evidence for the IQHE states at odd $\nu$.

of our data points with the $d/l_B$ vs $\Delta_{SAS}/(e^2/\epsilon l_B)$ "phase diagram" proposed by MacDonald, Platzman, and Boebinger[9] for the presence or absence of the IQHE at odd $\nu$ provides additional evidence for this interpretation[14] [$l_B = (\hbar/eB)^{1/2}$ is the magnetic length and $\epsilon$ is the dielectric constant]. We find that all the experimental data points lie above the theoretical phase boundary (at least for the first two Landau levels, i.e., for $\nu = 1$, 3, 5, and 7) and in the "NO QHE" regime. Our results are, therefore, consistent with this theory.

To examine the possibility of the disorder potential smearing out $\Delta_{SAS}$ and thus causing the absence of the IQHE states at odd $\nu$, we can scrutinize the low-field transport data. For example, in the inset to Figs. 3 and 4, respectively, the states with $\nu = 14$ and 18 for $n_s = 1.7 \times 10^{11}$ cm$^{-2}$ and with $\nu = 6$ for $n_s = 6.7 \times 10^{10}$ cm$^{-2}$ are observed at $B \sim 0.5$ T. In a single electron picture, when $\hbar\omega_c \gg \Delta_{spin} \sim \Delta_{SAS}$, these states result from either $\Delta_{spin}$ or $\Delta_{SAS}$ (or $|\Delta_{spin}-\Delta_{SAS}|$) gap. In our experiments (not shown here), we find that these three states become stronger in tilted fields, providing an unambiguous evidence that they originate from the Zeeman gap and not $\Delta_{SAS}$. At $B = 0.5$ T, assuming a bare effective $g$ factor of 0.4, $\Delta_{spin} \simeq 120$ mK and is smaller than the calculated $\Delta_{SAS}$ which ranges from 185 mK to 1.9 K in the experimental density range. There is no reason why disorder should destroy only the $\Delta_{SAS}$ gap but not $\Delta_{spin}$ which is even smaller. Therefore, we conclude that the missing of IQHE states at odd $\nu$ is not a result of the sample disorder.

We next studied the magnetotransport coefficients of the 800-Å-wide well. The narrower width of this well leads to a larger $\Delta_{SAS}$ compared to the wider well, making the observation of the IQHE at odd $\nu$ possible. Figure 5 shows the $R_{xx}$ and $\rho_{xy}$ data for the 800-Å-wide well at $n_s = 1.6 \times 10^{11}$ cm$^{-2}$.[15] A very strong IQHE state at $\nu = 3$ and a weaker one at $\nu = 1$ can be seen in Fig. 5(a). Figure 5(b) shows that both $\nu = 1$ and 3 states are destroyed when an in-plane magnetic field is applied, evincing that both states result from $\Delta_{SAS}$.[8] More specifically, the $\nu = 1$ state disappears at $\theta \sim 20°$ ($B_{\parallel} \sim 2.4$ T) and the $\nu = 3$ state at $\theta \sim 45°$ ($B_{\parallel} \sim 2.2$ T).[16]

For the 800-Å-wide well with $n_s = 1.6 \times 10^{11}$ cm$^{-2}$, our calculated $\Delta_{SAS}$ is about 5.7 K. On the "phase diagram" of Ref. 9, our observed IQHE at $\nu = 1$ and 3 lie near the theoretical boundary, but still in the "NO QHE" region. If the finite thickness of the electron layers in the 2DES's in our system is incorporated in the calculation, it is likely that the modified boundary will agree better with the experimental data. We mention here that our observation of a *weak* $\nu = 1$ state *near* the phase boundary of Ref. 9 already points to the semiquantitative agreement between the calculations and the experimental data.

Finally, we wish to emphasize that in double-layer systems in wide quantum wells, it is possible to tune $d/l_B$ and $\Delta_{SAS}/(e^2/\epsilon l_B)$ by changing the carrier density in the well. In principle, therefore, one may be able to map out the experimental phase boundary for the presence or absence of IQHE at odd $\nu$ in a *single* sample.[17]

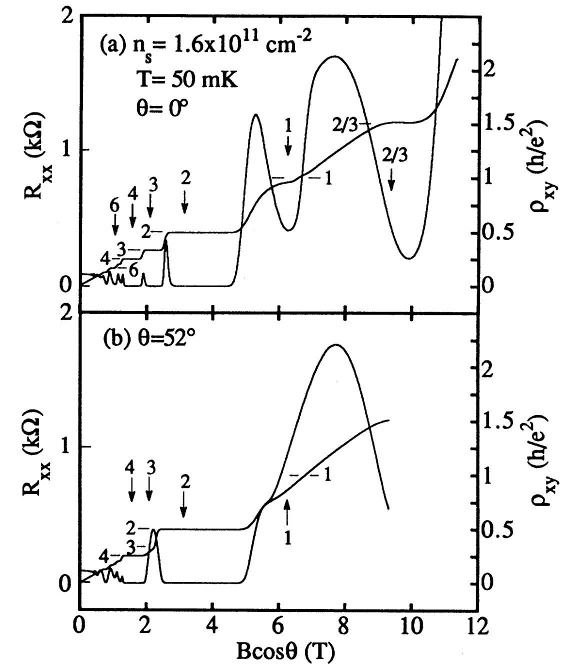


FIG. 5. The magnetotransport data for $n_s = 1.6 \times 10^{11}$ cm$^{-2}$ in an 800-Å-wide well. The magnetic field is perpendicular to the sample plane ($\theta = 0$) for (a), and is 52° off the sample plane normal for (b). The IQHE states at $\nu = 1$ and 3 which are present at $\theta = 0$ are destroyed in the tilted field.

In summary, we report the observation of the IQHE and FQHE states in weakly coupled double-layer electron systems in wide single quantum wells. We observe the absence of the IQHE at odd $\nu$ in a 1200-Å-wide well in which $\Delta_{SAS}$ is sufficiently small. We attribute this absence to the destruction of $\Delta_{SAS}$ by the applied magnetic field. Our experimental data are qualitatively consistent with the results of recent calculations which were done for DQW's;[9] however, more theoretical as well as experimental work is needed to understand the origin of the missing IQHE state in double-layer systems.

We thank D. C. Tsui for advice and encouragement. Support of this work by the National Science Foundation Grants No. ECS-8553110 and No. DMR-8921073, the Army Research Office Grant No. DAAL03-89-K-0036, and the New Jersey Commission on Science and Technology is acknowledged. M.S. also acknowledges support by the Alfred P. Sloan Foundation.

[1]K. von Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).

[2]D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).

[3]H. C. A. Oji, A. H. MacDonald, and S. M. Girvin, Phys. Rev. Lett. **58**, 824 (1987); A. H. MacDonald, Phys. Rev. B **37**, 4792 (1988); D. Yoshioka, A. H. MacDonald, and S. M. Girvin, *ibid.* **39**, 1932 (1989).

[4]H. A. Fertig, Phys. Rev. B **40**, 1087 (1989).

[5]T. Chakraborty and P. Pietiläinen, Phys. Rev. Lett. **59**, 2784

(1987).

[6]H. L. Stormer, J. P. Eisenstein, A. C. Gossard, W. Wiegmann, and K. Baldwin, Phys. Rev. Lett. **56**, 85 (1986).

[7]J. Jo, M. B. Santos, M. Shayegan, Y. W. Suen, L. W. Engel, and A. M. Lanzillotto, Appl. Phys. Lett. **57**, 2130 (1990).

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

[9]A. H. MacDonald, P. M. Platzman, and G. S. Boebinger, Phys. Rev. Lett. **65**, 775 (1990).

[10]L. Brey, Phys. Rev. Lett. **65**, 903 (1990).

[11]F. Stern and S. Das Sarma, Phys. Rev. B **30**, 840 (1984).

[12]Y. W. Suen, M. B. Santos, J. Jo, L. W. Engel, and M. Shayegan (unpublished).

[13]T. Sajoto, Y. W. Suen, L. W. Engel, M. B. Santos, and M. Shayegan, Phys. Rev. B **41**, 8449 (1990).

[14]However, it is important to note that $\Delta_{SAS}$ in our system is very sensitive to the electron distribution which can be modified by the increasing electron correlations in the presence of the magnetic field. Because of this difference between our system and the DQW's for which the calculations in Ref. 9 is performed, a quantitative comparison between our data and the results of Ref. 9 may not be justified.

[15]Comparison of the data in Figs. 5 and 3 indicates that the quality of the 800-Å-wide well is poorer. The measured mobility for the 800-Å-wide well ($\mu \simeq 6.4\times10^4$ cm$^2$/V s for $n_s = 1.6\times10^{11}$ cm$^{-2}$) is much lower than the mobility for the wider well ($\mu \simeq 3.6\times10^5$ cm$^2$/V s for $n_s = 1.7\times10^{11}$ cm$^{-2}$). Also the observed QHE plateaus are wider for the narrower well. We do not know the origin for this difference in quality at present.

[16]In our experiments the sample can be rotated around only one axis. There is, therefore, a possibility that even at $\theta = 0°$ the sample is slightly tilted ($< 5°$) with respect to $B$. The disappearance of the $\nu = 1$ state at $\theta$ as large as 20° implies that such slight tilt is not responsible for the weakness of this state at $\theta = 0°$.

[17]An 800-Å-wide well is nearly ideal for such an experiment. Unfortunately, we were not able to change the density in our 800-Å-wide well.