Observation of a Fractional Quantum Hall State at $\nu=1/4$ in a Wide GaAs Quantum Well

D.R. Luhman, W. Pan, D.C. Tsui, L.N. Pfeiffer, K.W. Baldwin and K.W. West

Department of Electrical Engineering, Princeton University, Princeton, NJ 08544
Sandia National Laboratories, Albuquerque, NM, 87195
Bell Labs, Lucent Technologies, 700 Mountain Avenue, Murray Hill, New Jersey 07974

(Dated: October 13, 2008)

We report the observation of an even-denominator fractional quantum Hall (FQH) state at $\nu=1/4$ in a high quality, wide GaAs quantum well. The sample has a quantum well width of 50 nm and an electron density of $n_e = 2.55 \times 10^{11}$ cm$^{-2}$. We have performed transport measurements at $T \sim 35$ mK in magnetic fields up to 45 T. When the sample is perpendicular to the applied magnetic field, the diagonal resistance displays a kink at $\nu = 1/4$. Upon tilting the sample to an angle of $\theta = 20.3^\circ$, a clear FQH state at emerges at $\nu = 1/4$ with a plateau in the Hall resistance and a strong minimum in the diagonal resistance.

Interest in the even-denominator fractional quantum Hall (FQH) state at $\nu = 1/4$ in the first excited Landau level continues to remain high over twenty years after its discovery[1]. Generally believed to be due to the $p$–wave pairing of composite fermions[2, 4, 5], the quasi-particle excitations of this state are thought to obey nonabelian statistics and thus may be relevant to fault-tolerant, topological quantum computing schemes[6, 7].

To date, observations of even-denominator FQH states have been rare beyond the $\nu = 5/2$ state in single-layer systems[8]. In particular, experimental evidence for a FQH state at $\nu = 1/2$, the lowest Landau level counterpart of the $\nu = 5/2$ state, does not exist, although previous theoretical work has suggested that it may form in thick two-dimensional electrons systems (2DES)[9].

In bilayer systems, however, the situation is different. The presence of two nearby interacting electron layers introduces an additional degree of freedom which can allow the formation of a FQH state at $\nu = 1/2$. Observations of such a state at $\nu = 1/2$ have been made in both double quantum wells[10] and wide single quantum wells (WSQWs)[11, 12]. In both of these cases the $\nu = 1/2$ state has been shown to have a large overlap with the so-called $\{331\}$ wave function[13]. Originally proposed by Halperin[14] to describe two-component FQH states, the $\{331\}$ wave function can also be characterized as a $p$–wave pairing state, although with albelian statistics[13, 15]. A crude way to interpret the $\{331\}$ wave function, or in general any $\{nm\}$ wave function, is to consider two electron layers each with a filling factor of $\nu^* = 1/n$. The electrons in each layer are bound to correlation holes in the other, represented by a filling factor of $1/m$. Together the filling factor of the entire system is $\nu = 2/(n + m)$[13].

Beyond the $\{331\}$ state the model should generalize to other even-denominator states. For example, both the $\{771\}$ and $\{553\}$ wave functions would be possible candidates to describe a FQH state at $\nu = 1/4$. In contrast to $\nu = 1/2$, relatively little theoretical work has been done concerning a FQH state $\nu = 1/4$ and an experimental observation of this state has yet to be reported. On the one hand, an observation of the $\nu = 1/4$ state would be demanding experimentally, including a high mobility 2DES and ultra high magnetic fields for high density samples. On the other hand, an observation of the a FQH state at $\nu = 1/4$ would not only be of interest by itself, but may also further elucidate the still enigmatic $\nu = 1/2$ state in WSQWs.

In this Letter, we report the observation a FQH state at $\nu = 1/4$ in a high quality GaAs quantum well of width $L = 50$ nm at $T \sim 35$ mK using a 45 T magnet. When the quantum well is oriented perpendicular to the applied magnetic field, a small kink is seen in the diagonal resistance ($R_{xx}$). When the sample is tilted to an angle of $\theta = 20.3^\circ$, the kink in $R_{xx}$ develops into a strong minimum and a plateau appears in $R_{xy}$, clearly demonstrating a FQH state at $\nu = 1/4$.

Our sample is a Al$_{0.24}$Ga$_{0.76}$As/GaAs/Al$_{0.24}$Ga$_{0.76}$As modulation doped quantum well. The width of the well is $L = 50$ nm and the two doping layers are symmetrically positioned at a distance of 80 nm from each side of the quantum well. The specific piece used for the measurement was a 5 mm $\times$ 5 mm square with eight equally spaced ohmic contacts positioned around the perimeter. The sample was cooled from room temperature to 4 K over the course of 90 minutes while being exposed to light from a red light-emitting-diode. The sample was then cooled further to a base temperature of $T \sim 35$ mK in the mixing chamber of a dilution refrigerator. The electron density of the sample was $n_e = 2.55 \times 10^{11}$ cm$^{-2}$ and the mobility was $\mu \sim 10^7$ cm$^2$/Vs. The density of the 2DES varied slightly ($\sim 5\%$) depending on the cooling and illumination conditions. Transport measurements were performed using standard lock-in amplifier techniques with a low frequency ($\sim 7$ Hz) excitation current of 50 nA and negligible heating effects. All the measurements were car-
very subtle deviation from the classical Hall slope in odd denominator FQH states at \( \nu \). With the sample tilted to \( \theta \) for \( \nu \), a kink is noticeable in \( R_{xx} \) perpendicular to the plane of the sample. Many of the odd-denominator FQH states are labeled. The filling factors \( \nu = 1/2 \) and \( \nu = 1/4 \) are also marked. The horizontal lines at \( R_{xy} = 2h/e^2, 3h/e^2 \) and \( 3.9h/e^2 \) highlight the plateaus at those values. In the inset in the upper left corner we show the zero-field, self-consistently calculated results of the electronic potential (solid line) and the electron distribution across the well (dashed line).

Tilt measurements were done with an in situ rotator and the angle (\( \theta \)) was determined by aligning well developed quantum Hall states using \( B_{\perp} = B \times \cos \theta \) where \( B \) is the total applied magnetic field and \( B_{\perp} \) is the component perpendicular to the plane of the sample.

In Fig. 1 we display \( R_{xx} \) and \( R_{xy} \) as a function of \( B_{\perp} \) for \( \theta = 0^\circ \) and \( \theta = 20.3^\circ \). The high quality of the sample is evident from the large number of FQH states surrounding \( \nu = 1/2 \); clear minima are seen to \( \nu = 7/13 \) and \( 6/13 \) on the low field and high field side of \( \nu = 1/2 \) respectively. Furthermore, a FQH state is present at \( \nu = 1/2 \) with both a minimum in \( R_{xx} \) and a weak plateau in \( R_{xy} \). This FQH state becomes fully developed at \( \theta = 20.3^\circ \) with \( R_{xx} \) vanishingly small and \( R_{xy} \) precisely quantized at \( 2h/e^2 \). Moving beyond \( \nu = 1/3 \), FQH states are visible at \( \nu = 2/7, 3/11, 4/15, \) and \( 5/19 \), their strength weakening as \( \nu = 1/4 \) is approached. In the absence of tilt, a kink is noticeable in \( R_{xx} \) at \( \nu = 1/4 \) along with a very subtle deviation from the classical Hall slope in \( R_{xy} \). With the sample tilted to \( \theta = 20.3^\circ \) the strength of the odd denominator FQH states at \( \nu = 1/3 \) and \( 2/7 \) varied little, while the states at \( \nu = 3/11, 4/15, \) and \( 5/19 \) weakened slightly. In contrast, at \( \nu = 1/4 \) the kink in \( R_{xx} \) has developed into a well defined minimum on top of the rising background and a plateau has emerged in \( R_{xy} \), indicating a FQH state at \( \nu = 1/4 \). The measured value of the plateau, \( R_{xy} = 3.9h/e^2 \), is slightly below the expected value of \( 4h/e^2 \). This is readily apparent in Fig. 2 where we have magnified the regime surrounding \( \nu = 1/4 \). We believe the reduced value of the plateau is due to the mixture of \( R_{xx} \) into \( R_{xy} \). In general, the mixing effect can be eliminated by averaging the data from both positive and negative values of \( B \), but due to the extremely high values of magnetic field (\( B \sim 45 \) T) this was not possible. However as further evidence to support our claim of mixing, we point out that the a reduced Hall resistance is also observed at other well developed FQH states approaching \( \nu = 1/4 \). At \( \nu = 2/7 \) the corresponding plateau in \( R_{xy} \) barely achieves the expected value of \( (7/2)h/e^2 \) and then dips below this value. At \( \nu = 3/11 \) the value of the plateau is \( R_{xy} = 3.64h/e^2 \), slightly below the expected value of \( (11/3)h/e^2 \). Moving to \( \nu = 4/15 \) and beyond, the discrepancy between the measured and expected values of \( R_{xy} \) continues to increase. It is also possible the observed discrepancy in
However, we also note that in measurements with a similar series with the sample. Contact resistances of \( \approx 1 \text{ M} \Omega \) would be necessary to create the observed reductions in \( R_{xy} \), which, in our experience with high mobility samples at large magnetic fields, we find unlikely.

The data presented here provide strong evidence for the existence of a FQH state at \( \nu = 1/4 \). In the following, we discuss possible origins of this state. Previous observations of the \( \nu = 1/2 \) state in wide GaAs quantum wells have been discussed\(^{[12]}\) within the context of the quantity \( \Delta_{\text{SAS}} \), which is the energy difference between the two lowest occupied subbands in the absence of magnetic field. For a given quantum well, \( \Delta_{\text{SAS}} \) decreases with increased density and is thought to decrease with the introduction of parallel magnetic field, \( B_{\parallel} \). If we assume that \( \Delta_{\text{SAS}} \) (estimated by calculation as \( \Delta_{\text{SAS}} \approx 30 \text{ K} \) in our sample at \( B = 0 \)) decreases with increased \( B_{\parallel} \) then the increase in the strength of the \( \nu = 1/2 \) state (Fig. 1) is qualitatively consistent with previous observations\(^{[12]}\). In Fig. 1(a-b) we show a similar increase in strength of the \( \nu = 1/2 \) state by increasing the density, again consistent with the decrease in \( \Delta_{\text{SAS}} \) and previous measurements. Although not definitive, this provides some evidence that our \( \nu = 1/2 \) state is similar in nature to previous observations\(^{[12]}\) which were found to have significant overlap with the \{331\} state\(^{[13]}\). However, we also note that in measurements with a similar density QW with a width of 58 nm and a smaller value of \( \Delta_{\text{SAS}} \approx 17 \text{ K} \), no features indicating a FQH state were observed at \( \nu = 1/2 \).

The concomitant emergence and strengthening of the \( \nu = 1/2 \) and \( \nu = 1/4 \) states with \( \theta \) shown in Fig. 1 make it tempting to postulate that the origin of the \( \nu = 1/4 \) state is also a two-component Halperin state such as \{553\} or \{771\}. However, unlike at \( \nu = 1/2 \), the \( \nu = 1/4 \) state does not emerge with the increase in density. As shown in Fig. 3 an increase in density from \( n_e = 2.55 \times 10^{11} \text{ cm}^{-2} \) to \( 2.65 \times 10^{11} \text{ cm}^{-2} \) causes the strength of the \( \nu = 1/2 \) state to increase significantly, similar to the behavior shown in Fig. 1 with increasing \( \theta \). In contrast the data surrounding \( \nu = 1/4 \) show very little change with the increase in density, which highlights a difference between the two states. In addition, the possibility that \( \nu = 1/4 \) state is described by \{771\} is unlikely considering the bilayer interpretation of the \{unm\} wavefunctions. For the \{771\} wavefunction the filling factor for the electrons in each layer would be \( \nu^* = 1/7 \) and typical single-layer 2DESs enter into an insulating phase beyond \( \nu = 1/5 \) at low temperatures\(^{[21]}\). A \{771\} would imply a 1/7 FQH state in each layer which seems unlikely.

Further, for the tilted case, the magnetic length due to the parallel component of magnetic field at \( \nu = 1/4 \) and \( \theta = 20.3^\circ \), given by \( \ell_{\parallel} = (h/eB_{\parallel})^{1/2} = 6.5 \text{ nm} \), is much smaller than the quantum well width \( L = 50 \text{ nm} \). Considering this, it is difficult to imagine that the wave function is not significantly altered by \( B_{\parallel} \).

An alternate possible description for the observed \( \nu = 1/4 \) state may be the pairing of composite fermions, similar to the proposal for a \( \nu = 1/2 \) FQH state in a thick 2DES\(^{[9]}\). The composite fermions in the \( \nu = 1/4 \)
case would consist of one electron with four flux quanta (4CFs). The very large value of magnetic field at the observed $\nu = 1/4$ state results in a relatively decreased value of the magnetic length $\ell_B = (\hbar/eB)^{1/2} = 3.8$ nm, which effectively increases the 2DES thickness and thus reduces the short-ranged interaction and may facilitate the pairing of 4CFs.

We also remark on the similarities in the sequences of FQH states between the traces in Fig. 1 and that from another high quality GaAs quantum well of the same FQH states between the traces in Fig. 1 and that from 4 the pairing of reduces the short-ranged interaction and may facilitate the pairing of 4CFs.

Finally we make an important point when considering WSQWs. For a given density, it is only in the limit of very wide wells where electronic behavior is purely bilayer. As the width of the well decreases the overall behavior is neither entirely consistent with bilayer nor single layer properties. In the inset of Fig. 1 we have shown the self-consistently calculated (excluding the exchange term) electronic band edge and electronic distribution function, $\rho$, for our sample in the absence of magnetic field. While $\rho$ does have two clear peaks, it is difficult to characterize it as purely a bilayer distribution.

In conclusion, we report the observation of an even-denominator fractional quantum Hall state at $\nu = 1/4$ in a high quality GaAs quantum well of width $L = 50$ nm. The strength of the state increases with increased tilt angle. Several options relating to the origin of the state are discussed.

We would like to thank G. Jones, E. Palm, T. Murphy, D. Freeman, and J. Pucci for experimental assistance. A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-0084173, by the State of Florida, and by the DOE. WP was supported by the DOE/BES at Sandia, a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin com-

[1] R. Willett, J.P. Eisenstein, H.L. Störmer, D.C. Tsui, A.C. Gossard, and J.H. English, Phys. Rev. Lett. 59, 1776 (1987);
[2] G. Moore and N. Read, Nucl. Phys. B 360, 362 (1991).
[3] M. Greiter, X.G. Wen, and F. Wilczek, Phys. Rev. Lett. 66, 3205 (1991).
[4] R.H. Morf, Phys. Rev. Lett. 80, 1505 (1998).
[5] V. W. Scarola, Kwon Park, and J. K. Jain, Nature (London) 406, 863 (2000).
[6] A. Yu. Kitaev, Ann. Phys. 303 2 (2002).
[7] S. Das Sarma, M. Freedman, C. Nayak, S. Simon, and A. Stern, cond-mat/0707.1889.
[8] W. Pan, J.S. Xia, H.L. Stormer, D.C. Tsui, C. Vicente, E.D. Adams, N.S. Sullivan, L.N. Pfeiffer, K.W. Baldwin, and K.W. West, Phys. Rev. B 77, 075307 (2008).
[9] K. Park, V. Melik-Alaverdian, N.E. Bonesteel, and J.K. Jain, Phys. Rev. B 58 R10167 (1998).
[10] J.P. Eisenstein, G.S. Boebinger, L.N. Pfeiffer, K.W. West, and Song He, Phys. Rev. Lett. 68, 1383 (1992).
[11] Y.W. Suen, L.W. Engel, M.B. Santos, M. Shayegan, and D.C. Tsui, Phys. Rev. Lett. 68, 1379 (1992).
[12] Y.W. Suen, H.C. Manoharan, X. Ying, M.B. Santos, and M. Shayegan, Phys. Rev. Lett. 72, 3405 (1994).
[13] Song He, S. Das Sarma, and X.C. Xie, Phys. Rev. B 47, 4394 (1993).
[14] B.I. Halperin, Helv. Phys. Acta 56, 75 (1983).
[15] B.I. Halperin, Surf. Sci. 305, 1 (1994).
[16] N. Read and E. Rezayi, Phys. Rev. B 54, 16864 (1996).
[17] N. Read and D. Green, Phys. Rev. B 61, 10267 (2000).
[18] Perspectives in Quantum Hall Effects, edited by S. Das Sarma and A. Pinczuck (John Wiley & Sons, New York, 1997).
[19] J. Hu and A.H. MacDonald, Phys. Rev. B 46, 12554 (1992).
[20] T.S. Lay, T. Jungwirth, L. Smrčka, and M. Shayegan, Phys. Rev. B 56, R7092 (1997).
[21] W. Pan, H.L. Stormer, D.C. Tsui, L.N. Pfeiffer, K.W. Baldwin, and K.W. West, Phys. Rev. Lett. 88, 176802 (2002).