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Fractional quantum Hall effect of two-dimensional electrons in high-mobility Si/SiGe field-effect transistors

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The fractional quantum Hall (FQH) regime of the Si two-dimensional electron system (2DES) in enhancement-mode field-effect transistors of Si/SiGe heterostructures was probed via electrical transport measurements. At $n \sim 2.6 \times 10^{11}$ cm^2 with $\mu = 1.6 \times 10^6$ cm^2/V s, signatures of FQH states at filling factors $\nu = 4/5$, $6/5$, and $10/7$ were observed, in addition to the FQH states reported in previous studies. The temperature dependence of the FQH states is investigated and comparison is made with previous work done on modulation-doped samples. Results indicate that robustness of the FQH states is dependent on the nature of disorder in the 2DES.

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The discoveries of the integer quantum Hall (IQH) effect[1] and the fractional quantum Hall (FQH) effect[2] have spurred much research on the ground states of two-dimensional (2D) electrons in the presence of strong magnetic fields over the past 30 years. Thanks to the constantly refined III-V epitaxial technology, the quality of GaAs/AlGaAs heterostructures has been continually improving, leading to the observation of a few tens of FQH states in GaAs.[3] While large in number, most of the FQH states can be understood within the theoretical framework of composite fermions (CFs).[4] In the CF model, the FQH effect, originally arising from electron-electron interaction, is mapped to the IQH effect arising from Landau quantization of the orbital motion of CFs.

Soon after the discoveries of the IQH and FQH effects, it was realized that additional degrees of freedom of 2DESs such as spins, layers, subbands, and valleys, may produce new correlated states which do not exist in a one-component 2DES.[5] Celebrated examples include Skyrmions in systems with small Zeeman splitting,[6,7] even-denominator FQH states,[8,9] and the excitonic superfluid in bilayer systems.[10] While much effort toward the understanding of the roles of spins, layers, and subbands in the FQH regime has been made using high-quality GaAs quantum wells, experimental studies on the effects of valleys have been relatively sparse; only a few reports on 2D electrons in Si[11,12] and AlAs[13–16] are available, partly due to the less impressive material quality of multivalley semiconductors. Indeed, the electron mobilities of the devices used in these studies were smaller than that of GaAs by almost two orders of magnitude.[3,17] Nevertheless, looking back at the history of discoveries of new states in GaAs, we may expect that more interesting physical phenomena in multivalley systems will emerge, once materials with higher mobility are available.

Recently, we reported a fabrication process for making undoped (100)-oriented Si/SiGe FETs and observed an electron mobility of 1.6×10^6 cm^2/V s,[18] approximately eight times higher than that of typical modulation-doped Si/SiGe quantum wells.[19] Such improvement in material quality naturally prompted us to perform magnetotransport experiments and search for new states in Si 2DESs. In this Rapid Communication, we focus on the FQH regime $\nu < 2$, where the spin degree of freedom is frozen due to the large Landé g factor in Si. We report signatures of three previously obscure or absent FQH states at $\nu = 4/5$, $6/5$, and $10/7$. Temperature dependence of the FQH states is investigated and compared with previous work on modulation-doped samples. Results indicate that the existence of the FQH states and their robustness is dependent on the nature of disorder in the 2DES.

The Hall-bar-shaped devices used in this study were enhancement-mode Si/SiGe FETs with 15-nm-thick Si quantum wells. All of the data were obtained at $n \sim 2.6 \times 10^{11}$ cm^2 with a low-temperature electron mobility of 1.6×10^6 cm^2/V s. The samples were cooled down in a dilution refrigerator to a base temperature T $\sim$ 30 mK without illumination. Magnetotransport measurements were performed using standard lock-in techniques with an excitation current of 1–10 nA at ~5 Hz.

In Fig. 1, the diagonal resistance (R_{xx}) and the Hall resistance (R_{xy}) are shown for $\nu < 2$. The series of FQH states around $\nu = 1/2$, marked by arrows at $\nu = 2/3, 4/7, 4/9$, $2/5$, and $1/3$ in Fig. 1(a), are consistent with those reported previously in modulation-doped samples with much lower mobilities[12] and can be phenomenologically understood as the IQH effect of two-flux CFs with a valley degree of freedom. As discussed above, at $\nu = 1/2$, CFs form by attaching two fictitious magnetic flux quanta to one electron. The observed FQH states at $\nu = 2/3$, $4/7$, $4/9$, $2/5$, and $1/3$ are the IQH states of the CFs at their Landau level fillings $\nu^* = 2$, 4, 4, 2, and 1 with the spin degeneracy lifted, due to the large Zeeman splitting in Si at high magnetic field. The absence of the FQH states at $\nu = 3/5$ and $3/7$ is taken as evidence that the CF model is applicable to a 2DES with a valley degree of freedom. Generally, one may argue that valley does not play a role in the FQH states at $\nu < 1$ as the valley degree of freedom is already frozen out. However, a well known counter example to this view is the spin unpolarized state at $\nu = 2/3$.[20] There it was found that the energy gap of the $\nu = 2/3$ FQH state collapses and then reopens with respect to an in-plane magnetic field, suggesting that the $\nu = 2/3$ state is

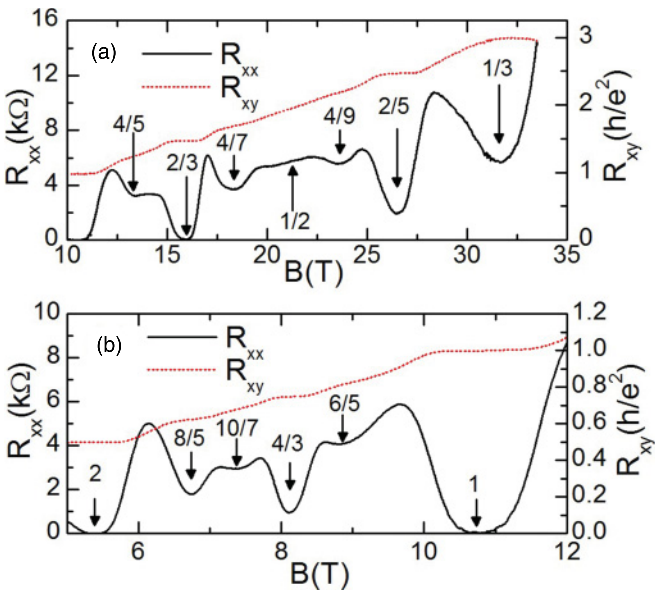

FIG. 1. (Color online) (a) R_{xx} and R_{xy} at $T = 30$ mK for $\nu < 1$. (b) R_{xx} and R_{xy} at $T = 140$ mK for $1 < \nu < 2$.

unpolarized at zero in-plane magnetic field. Even though the filling factor 2/3 is smaller than 1, the spin degree of freedom remains important. Following the same line of thought, in the previous work by Lai *et al*.[12] it was argued that the valley degree of freedom remains active and phenomenologically explains the experimental observations. Figure 1(b) shows R_{xx} and R_{xy} between $\nu = 1$ and 2. The two strong minima are the FQH states at $\nu = 8/5$ and 4/3, again consistent with previous studies.[11,12] Since the 2DES has a two-fold valley degeneracy, the states at $\nu = 8/5$ and 4/3 can be viewed as the particle-hole conjugate of the states at $\nu = 2 - 8/5 = 2/5$ and $2 - 4/3 = 2/3$, respectively. We should note that there is a rising background in R_{xx} with increasing B, which quickly turns the 2DES into an insulator at $\nu < 1/3$, similar to previous observation.[12] The rising background could signal the onset of an insulating phase[21,22] and the coexistence of FQH liquids and the insulating phase, probably a pinned Wigner crystal,[23] both of which have been observed in clean GaAs samples. Consistent with this coexistence picture, we note that the energy gap at $\nu = 1/3$ is much smaller than those at $\nu = 2/3$ and 2/5. Indeed, since the resistance of the insulating phase decreases with increasing temperature, contrary to that of a FQH liquid, the apparent temperature dependence of the resistance of the coexisting phase is hence much weakened, which in turn makes the 1/3 energy gap underestimated. In this regard, we believe that the real energy gap at $\nu = 1/3$ should in fact be much larger.

We now turn to the weaker features in the data, which are either obscure or not observed in previous work on modulation-doped samples. These are the dips clearly seen in R_{xx} at $\nu = 10/7$, 6/5, and 4/5. At $\nu = 4/5$, the R_{xy} shows a discernible inflection indicating a developing plateau at $R_{xy} = 1.25h/e^2$. The data, therefore, shows that there is a FQH state at $\nu = 4/5$. At $\nu = 6/5$ and 10/7, on the other hand, the inflections in R_{xy} are not apparent in the R_{xy} versus B trace. In Fig. 2, we plot the derivative of the R_{xy} data with respect to B together with the R_{xx} data as functions of ν. It can be seen that all the structures

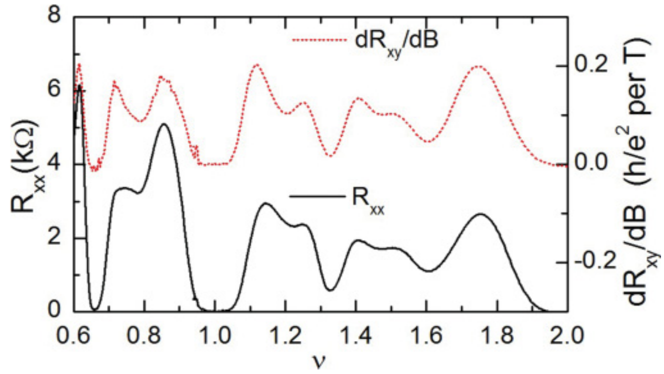

FIG. 2. (Color online) R_{xx} and the derivative of R_{xy} with respect to B vs ν at $T = 30$ mK.

in R_{xx} versus ν are reproduced in dR_{xy}/dB versus ν, showing that inflections in R_{xy} also occur at $\nu = 6/5$ and 10/7. We thus conclude that these weak features are signatures of the FQH states at these filling factors.

In Fig. 3, we display the evolution of R_{xx} versus B from $B = 5$ T to 17 T, showing that the minima at $\nu = 10/7$, 6/5, and 4/5 have weak temperature dependence while the adjacent maxima rise with decreasing temperature. In order to quantitatively analyze the temperature dependence, we employ the method used in previous studies to assign a characteristic strength to a FQH state.[24,25] We define the strength (S) of the state as the ratio of the resistance minimum to the average of the adjacent maxima, as depicted in Fig. 3(b), and extract a quasigap from the temperature dependence of S, as shown in

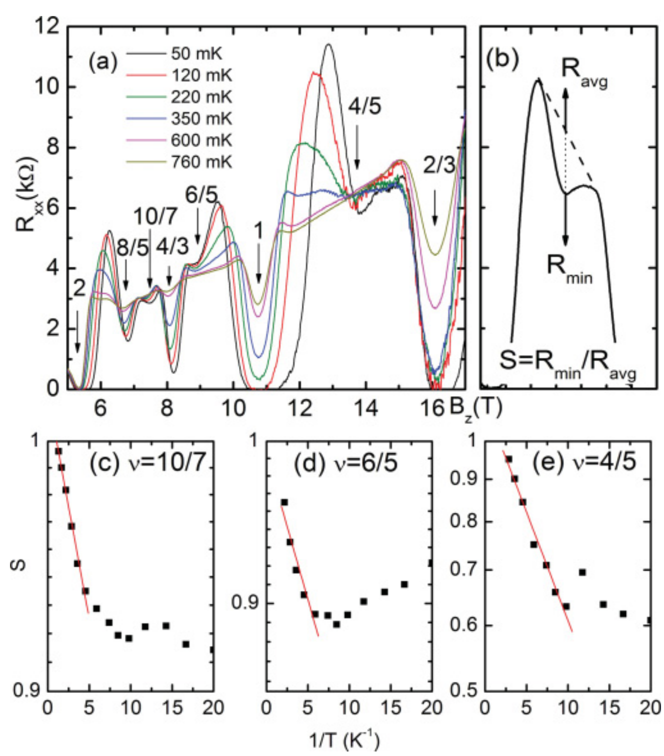

FIG. 3. (Color) (a) Evolution of R_{xx} with temperature. (b) Schematic drawing of the definition of S for a weak FQH state. Extraction of quasigaps of (c) $\nu = 10/7$, (d) $\nu = 6/5$, and (e) $\nu = 4/5$ from the temperature dependence of S.

TABLE I. Measured activation gaps of prominent FQH states.

Activation Gap (K)	$\nu = 8/5$	$\nu = 4/3$	$\nu = 2/3$	$\nu = 4/7$	$\nu = 4/9$	$\nu = 2/5$	$\nu = 1/3$
This work	0.25	0.6	2.6	0.13	0.8	0.8	0.08
Ref. 12	–	–	–	0.2	0.2	1.3	0.8

Figs. 3(c)–3(e). The extracted quasigaps are ∼40 mK, 40 mK, and 120 mK for $\nu = 10/7$, 6/5, and 4/5, respectively. We note that the states remain observable even at temperatures a few times higher than the extracted quasigaps, suggesting that the extracted values significantly underestimate the real energy gaps, due to competition from nearby stronger quantum Hall states. Similar behavior has been observed in GaAs when new FQH states are on the verge of emerging and compete with nearby stronger states.[24,26,27] The evolution of R_{xx} with temperature at $\nu = 6/5$ clearly shows such behavior. The minimum actually rises and shifts to lower magnetic field with decreasing temperature, as the quantum Hall state at $\nu = 1$ rapidly widens. In Fig. 3(d), S of the $\nu = 6/5$ state also shows an upturn as the temperature drops below ∼120 mK. Although such upturns are not observed at $\nu = 10/7$ and 4/5, these states may suffer from similar effects as well.

The $\nu = 10/7$ state is again consistent with the two-flux CF model, and can be viewed as the particle-hole conjugate of the state at $\nu = 2 - 10/7 = 4/7$, which indeed is one of the observed FQH states below $\nu = 1$. The $\nu = 6/5$ and $\nu = 4/5$ states, however, do not fall into this category. The $\nu = 4/5$ state may be viewed as the particle-hole conjugate of the state at $\nu = 1/5$ in the first level; the $\nu = 6/5$ state is the FQH state at 1/5 filling of the second level. This observation implies that the two-fold valley degeneracy of the 2D electrons is lifted in the high magnetic fields at which the two states are observed, consistent with the well known fact that the valley-splitting gap in (100) Si 2D electrons is dependent on the host device structure[28] and on the external magnetic field.[29,30] These two states can be seen as the IQH states of CFs at $\nu = 1/4$, formed by attaching four magnetic flux quanta to one electron. To the best of our knowledge, except for high-mobility 2D electrons in GaAs, four-flux CF FQH states have not previously been observed in other 2D electron material systems.

Finally, we compare this study to the previous work on modulation-doped samples reported in Ref. 12. The electron densities at which the measurements were performed in the two experiments are comparable, $n \sim 2.6 - 2.7 \times 10^{11}$ cm^2, while the zero-field electron mobility of the device used in this study is more than a factor of six higher. Since the electron densities are almost the same, analysis of the energy scales yields an energy diagram similar to what is shown in Ref. 12. We note that in spite of the much improved zero-field mobility, the extracted CF mobility using the resistivity at $\nu = 1/2$ is only $\sim 8.2 \times 10^3$ cm^2/V s, which leads to a disorder broadening similar to what is found in Ref. 12. The energy gaps obtained in this study except for $\nu = 4/9$ are in general smaller than those observed in Ref. 12, as shown in Table I. The R_{xx} at $\nu = 2/5$ and 1/3 does not vanish at the lowest temperatures. The weak FQH state at $\nu = 3/5$, observable in Ref. 12, was not seen in our experiments. On the other hand, the FQH states at $\nu = 10/7$, 6/5, and 4/5, either obscure or absent in Ref. 12, are much better developed. These seemingly contradictory facts indicate that the nature of disorder may play an important role. Indeed, recent measurement of the energy gaps at $\nu = 5/2$ in enhancement-mode and modulation-doped GaAs samples has clearly highlighted such effects.[31] In our undoped enhancement-mode FET, the mobility saturates at $n = 1.5 \times 10^{11}$ cm^2 and even shows a slight decrease with increasing n,[18] indicating that interface roughness scattering becomes important at high densities.[32] This is different from modulation-doped heterostructures where disorder is dominated by remote charge scattering. In fact, a recent theoretical work by Gold shows that interface roughness indeed is important.[33] Our results thus show that the nature of disorder is as important as the strength of disorder in determining the existence and the robustness of the FQH states.

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