Valley effects on the fractions in ultra-high mobility SiGe/Si/SiGe 2D electron system

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We observe minima of the longitudinal resistance corresponding to the quantum Hall effect of composite fermions at quantum numbers \( p = 1, 2, 3, 4, \) and 6 in an ultra-clean strongly interacting bivalence SiGe/Si/SiGe 2D electron system. The minima at \( p = 3 \) disappear below a certain electron density, although the surrounding minima at \( p = 2 \) and \( p = 4 \) survive at significantly lower densities. Furthermore, the onset for the resistance minimum at filling factor \( \nu = 3/5 \) is found to be independent of the tilt angle of the magnetic field. These results indicate the intersection or merging of the quantum levels of composite fermions with different valley indices, which reveals the valley effect on fractions.

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The concept of composite fermions [1–5] can successfully describe the fractional quantum Hall effect with odd denominators by reducing it to the ordinary integer quantum Hall effect for composite particles. In the simplest case, the composite fermion consists of an electron and two magnetic flux quanta and moves in an effective magnetic field, \( B^* \), given by the difference between the external magnetic field, \( B \), and the field corresponding to the filling factor for electrons, \( \nu = n_e \hbar c/\epsilon B \), equal to \( \nu = 1/2 \), where \( n_e \) is the electron density. The filling factor for composite fermions, \( p \), is connected to \( \nu \) according to the expression \( \nu = p/(2p \pm 1) \). The fractional energy gap, which is predicted to be determined by the Coulomb interaction in the form \( \epsilon^2/\epsilon l_B \), corresponds to the cyclotron energy of composite fermions \( \hbar \omega^*_{c} = \hbar e B^*/m_{CF} c \), where \( \epsilon \) is the dielectric constant, \( l_B = (\hbar c/eB)^{1/2} \) is the magnetic length, and \( m_{CF} \) is the effective composite fermion mass. The electron-electron interactions enter the theory [1–5] implicitly because a mean-field approximation is employed, assuming that the electron density fluctuations are small. The theory is confirmed by the experimental observation of a scale corresponding to the Fermi momentum of composite fermions in zero effective magnetic field at \( \nu = 1/2 \).

The majority of the experiments on the fractional quantum Hall effect have been performed on single-valley GaAs-based heterostructures [6]. There are only a few experiments on other 2D electron systems in which electrons occupy two valleys, e.g., in (001) SiGe heterostructures [6, 8] and (001) AlAs quantum wells [6, 12]. A significant advantage of the ultra-clean bivalence 2D electron system in SiGe heterostructures (as well as the 2D hole system in GaAs/AlGaAs heterostructures) compared to the 2D electron system in GaAs/AlGaAs heterostructures is that at accessible low electron densities/weak magnetic fields, the limit can be reached where the electron interaction energy \( \epsilon^2/\epsilon l_B \) becomes much greater than the cyclotron energy \( \hbar e B/m_{CF} c \), where \( m \) is the effective electron mass. In this case, the fractional gap can exceed some of the other spectral gaps, e.g., the spin or valley gaps, leading to a change in the gap systematics in the spectrum. In the bivalence 2D electron system in SiGe quantum wells, an unusual behavior has been observed in the longitudinal resistance at low densities: the dominance of the \( \nu = 2/5 \) fraction over the \( \nu = 1/3 \) fraction [8], which is in contrast to the results obtained on GaAs-based heterostructures and in disagreement with the hierarchy of fractions, as inferred from the concept of composite fermions. The origin of the discrepancy has not yet been explained. Notably, two additional minima in the magnetoresistance at \( \nu = 4/5 \) and \( \nu = 4/11 \) that are symmetric relative to \( \nu = 1/2 \) have been recently observed in 2D electron systems in both GaAs/AlGaAs quantum wells [12] and SiGe quantum wells [14]. Both minima correspond to the fractional filling factor of composite fermions, \( p = 4/3 \), which suggests a formation of the second generation of composite fermions on the basis of already existing ones, as described by the double attachment of two magnetic flux quanta [14, 15].

Here, we observe minima of the longitudinal resistance corresponding to the quantum Hall effect of composite fermions at quantum numbers \( p = 1, 2, 3, 4, \) and 6 in ultra-clean strongly interacting bivalence SiGe/Si/SiGe 2D electron system. The minima at \( p = 3 \) disappear below a certain electron density, although the surrounding minima at \( p = 2 \) and \( p = 4 \) persist to significantly lower...
layers. After that, the contact gate was fabricated, of SiO. In addition, a 20 nm thick layer of NiCr was and a 60 nm thick aluminum gate was deposited on top on the surface of the wafer in a thermal evaporator, to minimize the contact resistance at low electron densities. Furthermore, the onset for the resistance minimum at filling factor $\nu = 3/5$ is found to be independent of the tilt angle of the magnetic field. The results point out to the intersection or merging of the quantum levels of composite fermions with different valley indices, which reveals the valley effect on the fractions. The dominance of the $\nu = 2/5$ fraction over the $\nu = 1/3$ fraction, observed earlier in the magnetoresistance at low densities in this electron system, may also be related to valley effects.

The samples used were ultra-high mobility SiGe/Si/SiGe quantum wells similar to those described in Ref. [16]. The peak electron mobility in these samples reaches $\approx 2 \times 10^6$ cm$^2$/Vs. The approximately 15 nm wide silicon (001) quantum well is sandwiched between Si$_{0.8}$Ge$_{0.2}$ potential barriers. Contacts to the 2D layer consisted of $\approx 300$ nm Au$_{0.99}$Sb$_{0.01}$ alloy deposited in a thermal evaporator and annealed for 3-5 minutes at 440$^\circ$C in N$_2$ atmosphere. A 200-300 nm thick layer of SiO was deposited on the surface of the wafer in a thermal evaporator, and a $> 20$ nm thick aluminum gate was deposited on top of SiO. The samples were patterned in Hall-bar shapes with the distance between the potential probes of 150 $\mu$m and width of 50 $\mu$m using standard photo-lithography. The long side of the Hall bar corresponded to the direction of current parallel to the [110] or [−110] crystallographic axis. In addition to single-gate samples, double-gate samples with a NiCr/Al Hall-bar gate and an Al contact gate were used to minimize the contact resistance at low electron densities in the main part of the sample (Fig. 1). For making the Hall-bar gate, a 240 nm thick SiO layer was deposited on the surface of the wafer in a thermal evaporator, and a 60 nm thick aluminum gate was deposited on top of SiO. In addition, a 20 nm thick layer of NiCr was deposited on top of Al for better adhesion of subsequent layers. After that, the contact gate was fabricated, for which the whole structure was covered by a 60 nm thick SiO layer, and a 30 nm thick aluminum gate was deposited on top of SiO. The contact gate allows for maintaining high electron density $\approx 2 \times 10^{11}$ cm$^{-2}$ near the contacts regardless of its value in the main part of the sample. The electron density was controlled by applying a positive dc voltage to the gate relative to the contacts. To improve the quality of contacts and increase the electron mobility, a saturating infra-red illumination of the samples was used. The range of accessible electron densities was restricted because of a tunneling of the electrons through the SiGe barrier at high gate voltages [17], whereas the contact resistance increased drastically at very low electron densities/high magnetic fields. Measurements were carried out in an Oxford TLM-400 dilution refrigerator at a temperature $T \approx 0.03$ K. Magnetoresistance was measured with a standard four-terminal lock-in technique in a frequency range $0.2 - 11$ Hz in the linear response regime (the measuring current was in the range between 0.05 and 2 nA). In tilted magnetic fields, the parallel field

![FIG. 1: (a) Schematic top view on the sample with two independent gates. The Hall bar-shaped gate is hidden and is shown by the dotted line in the central part of the sample. (b) Schematics of the layer growth sequence and the cross section of the double-gate sample.](image)

![FIG. 2: Magnetoresistance of single-gate sample 1 in perpendicular magnetic fields at electron densities (from top to bottom) 3.19, 3.81, 4.42, 5.03, 5.65, 6.26, 6.88, 7.49, 8.10, 8.72, 9.33, 9.95, 10.6, 11.2, 11.8, 12.4, 13.0, 13.6, 14.9, 16.1, 17.3, and 18.5 $\times 10^{10}$ cm$^{-2}$. Curves are vertically shifted by 500 $\Omega$. Dashed vertical lines mark the expected positions of the observed minima of the resistance, and solid vertical lines correspond to the minima that are expected, but not observed at low densities.](image)
component was always perpendicular to the current in order to exclude the influence of ridges on the quantum well surface [18]. Similar results were obtained on three samples of the same wafer.

The longitudinal resistance $\rho_{xx}$ as a function of the inverse filling factor is shown for different electron densities in sample 1 in Fig. 2. The resistance minima are seen at composite fermion quantum numbers $p = 1, 2, 3, 4,$ and $6$ near $\nu = 1/2$ in positive and negative effective field $B^*$, revealing the high quality of the sample. This is confirmed by the presence of the $\nu = 4/5$ and $\nu = 4/11$ fractions, corresponding to $p = 4/3$, which can be described in terms of the second generation of composite fermions. The behavior of the minima at $p = 3$ is unusual in that they disappear below a certain electron density, $n^*_s$, although the surrounding minima at $p = 2$ and $p = 4$ persist to significantly lower densities. Such a behavior is observed in all samples studied, see, e.g., the data for $\rho_{xx}$ versus $1/\nu$ in sample 2 in Fig. 3(a). Clearly, the prominence of the minima at $p = 3$ at low electron densities cannot be explained by level broadening. On the other hand, this finding is very similar to the effect of the disappearance of the cyclotron minima in the magnetoresistance at low electron densities in Si metal-oxide-semiconductor field-effect transistors (MOSFETs) while the spin minima survive down to appreciably lower densities, which signifies that the cyclotron and spin splittings become equal to each other and the corresponding levels cross or merge [19, 20]. Thus, crossing or merging of both spin and valley sublevels of composite fermions are possible for our case.

We make measurements in tilted magnetic fields in order to distinguish between the spin or valley origin of the effect. The magnetoresistance as a function of the inverse filling factor is shown for the tilt angle $\Theta \approx 61^\circ$ at different electron densities in sample 2 in Fig. 3(b). Here we focus on the resistance minimum at $\nu = 3/5$. The behavior observed for the $\nu = 3/5$ minimum is very similar to that in perpendicular magnetic fields, which holds for all samples and tilt angles. We determine the onset $n^*_s$ for the $\nu = 3/5$ minimum and plot it versus the tilt angle, as shown in Fig. 4. The value $n^*_s$ turns out to be independent, within the experimental uncertainty, of the tilt angle of the magnetic field. Since the spin splitting is determined by total magnetic field, $\Delta_s = g\mu_B B_{\text{tot}}$ (where $g$ is the Lande $g$ factor and $\mu_B$ is the Bohr magneton), one expects that the onset $n^*_s$ should decrease with the tilt angle (the inset to Fig. 4), which is in contradic-
survive at significantly lower densities, and the onset for the resistance minimum at filling factor $\nu = 3/5$ is found to be independent of the tilt angle of the magnetic field. These results point out to the intersection or merging of the quantum levels of composite fermions with different valley indices, which reveals the valley effect on the fractions. The observed dominance of the $\nu = 2/5$ fraction over the $\nu = 1/3$ fraction warrants further theoretical consideration.

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