Manifestation of the exchange enhancement of valley splitting in the quantum Hall effect regime

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We report a "dip" effect in the Hall resistance, R_{xy}, of a Si metal-oxide-semiconductor field-effect transistor in the quantum Hall effect regime. With increasing magnetic field, the Hall resistance moves from the plateau at Landau filling factor $\nu=6$ directly to the plateau at $\nu=4$, skipping the plateau at $\nu=5$. However, when the filling factor approaches $\nu=5$, the Hall resistance sharply "dives" to the value $1/5(h/e^2)$ characteristic of the $\nu=5$ plateau, and then returns to $1/4(h/e^2)$. This is interpreted as a manifestation of the oscillating exchange enhancement of the valley splitting when the Fermi level is in the middle between two adjacent valley-split Landau bands with the asymmetric position of the extended states.

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The quantum Hall effect (QHE) was discovered in Si metal-oxide-semiconductor field-effect transistors (MOSFETs) more than 25 years ago.[1] This system is still under study, mainly because of the problem of the metal-insulator transition in two-dimensional electron systems (2DES) (see, for example, Ref. 2 and references therein). The main interest of researchers of the QHE is focused on much less disordered 2DES based on Si/SiGe and GaAs/AlGaAs structures with high electron mobility. We are aware of only a few publications in which the Hall resistivity ρ_{xy} was measured in Si-MOSFET in a narrow interval of magnetic fields B and gate voltages V_g.[3–5]

In the present work, we report the results of transport measurements in two Si-MOSFET samples in the QHE regime in a wide interval of B (up to 14 T) and electron densities n (up to 1.5×10^{16} m^{-2}), controlled by V_g.

Measurements of n and electron mobility μ at $T=0.3$ K in sample no. 1 yield a linear dependence $n(V_g)=1.41\times10^{15}(V_g-0.4\text{ V})$ m^{-2} within the interval of V_g from 5.5 to 11 V with $\mu\approx1.0$–1.5 m^2/V s. Sample no. 2 was measured in the interval V_g between 8 and 11 V, and $n(V_g)$ was approximated by a different linear dependence $n(V_g)=1.25\times10^{15}$ $(V_g+0.6\text{ V})$ m^{-2}, with very similar values for n in the measured interval of V_g. The mobility in sample no. 2 was also within the above interval, changing from $\mu=1.46$ m^2/V s at $V_g=8$ V to 1.27 m^2/V s at $V_g=11$ V. The sample resistance was measured using a standard lock-in technique with the measuring current 20 nA at a frequency of 10.6 Hz.

Figure 1 shows ρ_{xy} of sample no. 1 as a function of perpendicular magnetic field B at different V_g. One can see two features. The first one is the "overshoot" effect, which is observed at almost every plateau, being especially large at filling factor $\nu=3$ (Fig. 2). In incremental magnetic fields, when ν approaches the integer 3, ρ_{xy} overshoots the normal plateau value $1/3(h/e^2)=8.6$ kΩ. However, as B increases further, ρ_{xy} drops to its normal value. The overshoot effect has been previously observed in GaAs/AlGaAs and Si/SiGe heterostructures (see, for example, Ref. 6 and references therein).

The second feature consists of a "dip" of ρ_{xy} from the plateau at $\nu=4(6.45$ kΩ) to the plateau at $\nu=5$ (5.16 kΩ) at magnetic fields when the filling factor approaches $\nu=5$. This effect can be seen more clearly in Fig. 2, where the dimensionless Hall resistivity (in units of h/e^2) is plotted as a function of the filling factor $\nu=nh/eB$.

Figure 3 shows that the longitudinal resistivity ρ_{xx} also exhibits a "dip" at $\nu=5$ and a less pronounced "dip" at $\nu=7$.

In the present work, the "dip" effect was invariably observed in all experiments, in both samples, for different voltage probes and reversed directions of the current and magnetic field. Moreover, Figs. 1 and 2 show the development of the "dip" with variation of the gate voltage for the same sample and probes. These facts give us confidence that the observed "dip" is not connected with heterogeneity of the

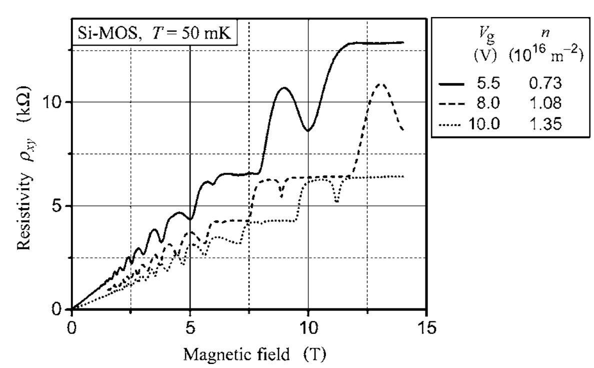

FIG. 1. Dependence of the Hall resistance ρ_{xy} on the perpendicular magnetic field B for different gate voltages V_g. The electron density is as indicated.

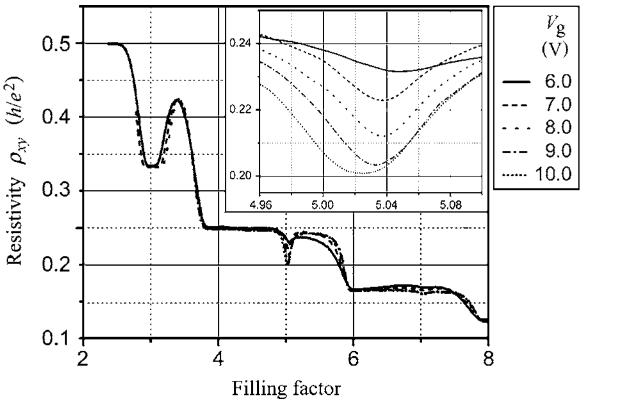

FIG. 2. Dependence of the dimensionless resistivity $\rho_{xy}/(h/e^2)$ on the filling factor $\nu=nh/eB$ for different gate voltages V_g. The inset shows the enhanced view of the "dip" effect.

2DES and possible admixture of R_{xx} into R_{xy}. Let us discuss the origin of the "dip" effect.

For Si-based 2DES, like Si/SiGe and Si-MOSFETs, the energy spectrum in a magnetic field is

$$E_n = \hbar\,\omega_c\left(N+\frac{1}{2}\right) \pm \frac{\Delta E_s}{2} \pm \frac{\Delta E_v}{2},$$

where $N=0,1,\ldots$ is the Landau level (LL) number, $\omega_c = eB_\perp/mc$ is the cyclotron frequency, $\Delta E_s = g^*\mu_B B$ is the Zeeman splitting, g^* is the effective Landé factor, $\mu_B = e\hbar/2m_e$ is the Bohr magneton, and $B=(B_\perp^2+B_\parallel^2)^{1/2}$ is the total magnetic field. $\Delta E_v[K]=\Delta_v^0+0.6B_\perp[T]$ is the valley splitting energy and Δ_v^0 is assumed[3,5] to be 2.4 K or 0.9 K. In accordance with this scheme, the odd filling factor corresponds to the Fermi level position ε_F midway between two adjacent valley-split LLs (see the inset in Fig. 4). If one takes into account the disorder in real samples, each LL is broadened into a Landau band (LB), with the width determined by the scale of the disorder energy W.

In Fig. 4, the dependences of $\rho_{xy}(\nu)$ for n-Si/SiGe (Refs. 6 and 7) and for n-Si-MOSFET with almost the same electron concentration n are shown together for comparison. In Si/SiGe, all plateaus are clearly observed, including plateaus at odd filling factor. In Si-MOSFET, plateaus at odd filling factors with $\nu > 3$ are not observed. This can be explained by the increase of disorder in Si-MOSFET, because the interface between Si and SiO_2 is much less perfect than the interface between Si and SiGe. Increase of disorder results in the broadening of LB in Si-MOSFET. If the width of LB is of order of the valley-splitting energy ΔE_v, the density of states $N(\varepsilon)$ does not have a deep minimum between valley-split adjacent Landau bands, the Fermi level does not linger between them, and the corresponding plateau is missed.

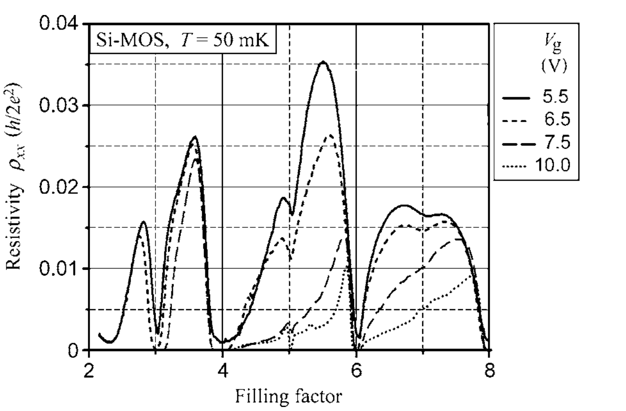

FIG. 3. Longitudinal resistivity in dimensionless units $\rho_{xx}/(h/2e^2)$ as a function of filling factor $\nu=nh/eB$ for different V_g.

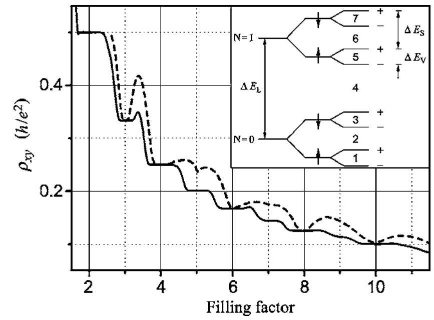

FIG. 4. Comparison of QHE in Si/SiGe ($n=8.94\times10^{15}$ m^{-2}, solid line) and in Si-MOSFET with similar electron concentration ($n=8.80\times10^{15}$ m^{-2}, dashed line).

However, when ν approaches the integer $\nu=5$, the value of ρ_{xy} starts to fall toward the missed plateau and finally reaches this plateau with increasing n (see the inset in Fig. 2). This effect can be explained by the temporary enhancement of the valley splitting. It was shown[8–10] that the occupied Landau levels undergo a self-energy shift roughly proportional to their occupation and inversely proportional to the screening of the system. Therefore, the enhancement oscillates as a function of the electron occupation of LB and has the maximum value when the filling factor approaches an integer and the Fermi level lies midway between the adjacent valley-split LB (see Fig. 5). We believe that this exchange enhancement of the valley splitting is responsible for the "dip" effect at $\nu=5$.

The model of spin-split exchange enhancement was used to explain the enhanced g factor in GaAs/AlGaAs (Ref. 11) and the bistable switching between quantum Hall conduction and dissipative conduction near $\nu=1$ in a quantum Hall system in a GaInAs quantum well.[12] Exchange enhancement was also used to explan the overshoot effect at $\nu=3$ in

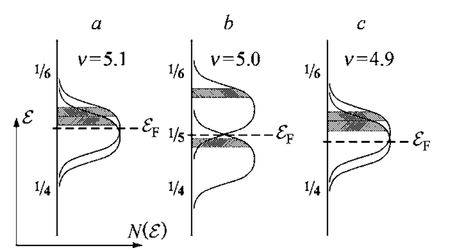

FIG. 5. Schematic sketch of the splitting enhancement between adjacent valley-split LB when the filling factor passes over $\nu=5$. Delocalized states, shown as shaded bands, are displaced from the center of LB. Fractional numbers correspond to the plateau resistance in units h/e^2. Magnetic field increases from a to c.

Si/SiGe heterostructure.[13] However, overshoot is observed at the low magnetic-field edge of the ρ_{xy} plateau when ν is far from an integer. Furthermore, after overshoot, ρ_{xy} remains at its "normal" plateau value, while the enhanced splitting due to exchange interaction oscillates and has a maximum at the integer ν. Therefore, the manifestation of the exchange enhanced splitting is expected in the close vicinity of integer ν in the form of a "dip," which is observed in our experiment (Fig. 2).

We would like to mention that nonmonotonic behavior of the Hall resistance with several reentrances of the plateau values $1/4(h/e^2)$ and $1/3(h/e^2)$ was observed in a modulation-doped GaAs quantum well at very low temperatures (15 mK) in Ref. 14 and explained by the existence of collective insulating states in the $N=1$ Landau level. Most likely, the physics behind this phenomenon and our "dip" is entirely different, although the two effects look similar.

One can see also from Fig. 2 that in Si-MOSFET, the integer values of ν do not correspond to the middle point of the plateaus, in contrast with more perfect Si/SiGe (Fig. 4). This can be considered as evidence of asymmetry of LB in Si-MOSFET, when delocalized states are displaced from the center of LB (Fig. 5). As a result of this asymmetry and considerable overlap of the adjacent valley-splt LB, the Fermi level ε_F is situated in the interval of localized states corresponding to the plateau with $\rho_{xy}=1/4$ (in units of h/e^2) even at $\nu \gtrsim 5$, Fig. 5(a). However, as ε_F approaches exactly $\nu=5$, the valley splitting increases leading to LB separation, Fig. 5(b). The localized states, which correspond to the plateau 1/5, show up, and ρ_{xy} dives to 1/5. When ν is further decreased, the exchange interaction-induced enhancement of the valley splitting disappears and ε_F finds itself again in the interval of localized states, which corresponds to the plateau $\rho_{xy}=1/4$, Fig. 5(c).

Asymmetry in the position of the delocalized states could be a consequence of the asymmetry of large potential fluctuations caused by the fact that an excess of the local electron concentration above the average value $\langle n \rangle$ is, in principle, unlimited, while the local deficit of electron density is limited by the value of $\langle n \rangle$ itself. To satisfy neutrality, the area occupied by the negatively charged fluctuations is less than the area of the positively charged fluctuations. Correspondingly, the integral number of localized states above the percolation level is less than the integral number of states below this level, which explains the asymmetry of the position of delocalized states in disorder-broadened LB. Computer simulation also shows that the increase of disorder leads to the displacement of delocalized states from the central part of LB.[15] In more perfect systems, potential fluctuations are small, and asymmetry is negligible, which explains why in Si/SiGe, the integer values of ν correspond approximately to the middle point of each plateau.

The question arises why the "dip" effect is clearly observed in Si-MOSFET at high electron densities in relatively strong magnetic fields but barely observed at low electron densities (Fig. 1); why does it not exist in Si/SiGe? We believe that the necessary condition for observation of the "dip" effect is the equality of the splitting energy ΔE and the width of the adjacent LB. The last parameter could be estimated roughly as the average energy of disorder W. In more perfect systems, $W \ll \Delta E$ and the Fermi level is fixed between the narrow adjacent LB even without enhanced splitting. As a result, the odd plateaus are clearly observed in Si/SiGe. In the opposite case, $W \gg \Delta E$ (Si-MOSFET with low electron density), the adjacent strongly broadened valley-split LB remain unresolved even in the case of enhanced splitting. The valley-splitting is small in weak magnetic fields, which explains why the "dip" effect is barely observed at $\nu=7$.

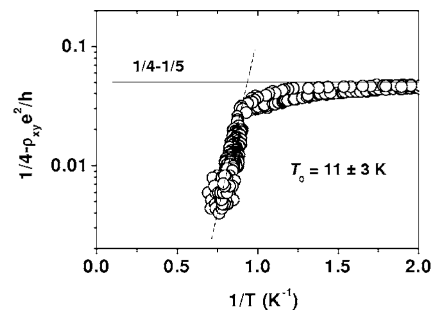

FIG. 6. Temperature dependence of the "dip" amplitude at $\nu=5$.

What follows from these considerations is that in our case, $W \approx \Delta E_v$. One can roughly estimate the average energy of disorder as $W \approx \hbar/\tau$, where τ is the time between elastic collisions which determines the mobility $\mu = e\tau/m^*$. In our sample, $\mu=1.0$–1.5 m^2/V s. Using $m^*=0.2m_0$ for strained Si layers,[10] we obtain $W \approx 7$–10 K. Figure 1 shows that the "dip" effect is clearly observed at $B \approx 10$–12 T. In these fields, $\Delta E_v \approx 8$–10 K, which is indeed equal to the above estimate of W and confirms our model.

It was also predicted[9,10] that the exchange enhancement drops drastically around a certain temperature due to a twofold positive feedback mechanism: with increasing temperature, the difference in occupation numbers of the two valleys decreases and simultaneously the screening increases.

This effect was observed in our experiment. Figure 6 shows the temperature dependence of the "dip" at $\nu=5$ measured at $V_g=11$ V and $B=12.5$ T plotted in the Arrhenius scale. The maximum amplitude of the "dip" is the difference between two plateaus at 1/4 and 1/5 in units of h/e^2 and is obtained at low temperatures. With increasing T, the amplitude of "dip" decreases first weakly but at $T>1$ K the amplitude drops drastically with the energy of activation $T_0 = 11 \pm 3$ K, which is indeed approximately equal to the valley splitting ΔE_v at $B=12.5$ T.

In summary, we have observed a "dip" effect in the Hall resistivity of Si-MOSFET measured in the quantum Hall effect regime. This effect can be considered as a manifestation of the oscillating enhancement of the valley splitting due to the exchange interactions. Observation of the "dip" effect is preferable if the width of the adjacent LB is approximately equal to the initial valley-split energy.

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