Hall resistance and quantized Hall effect to insulator transitions in a 2D electron system

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(Submitted 12 April 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **57**, No. 9, 592–595 (10 May 1993)

The Hall resistance R_{xy} was studied deep in the insulating phase at the quantized Hall effect to insulator transitions in a dilute 2D electron system. While the diagonal resistivity ρ_{xx} diverges, R_{xy} remains close to its classical value, H/nec, at least up to $\rho_{xx}=4\times 10^6\ \Omega/\square$. The insulating phase was found to develop directly from at least three QHE phases at $v=1$, 2 and 6, in contrast to recent theoretical predictions.

The low-temperature transition in a 2D electron system (2DES) between the metallic phase in the quantized Hall effect (QHE) regime and the insulating phase (QHE/I transitions) has become recently the focus of theoretical and experimental interest. Considering the disorder-induced insulating transition for noninteracting electrons at the lowest Landau level, Viehweger and Efetov[1] have found that $\sigma_{xy}\propto(\sigma_{xx})^2$. The Hall resistance R_{xy} therefore remains constant when $\rho_{xx}\to\infty$, in contrast with the band insulator or magnetic freeze-out. Recently, Kivelson *et al.*[2] suggested a global behavior for the QHE/I transitions. The existence of the "Hall insulator" has been proven again for noninteracting electrons, and it has been argued that this phase is generic for interacting electrons as well. In the Hall insulator phase $\rho_{xx}\to\infty$, $\sigma_{xx}\to 0$, $\sigma_{xy}\to 0$, while $\rho_{xy}=H/nec$ at $T=0$. For the ordered insulating phase (pinned Wigner crystal), Chui[3] argued that R_{xy} should not diverge as $T\to 0$ but be very close to the classical value $R_{xy}=H/nec$ if transport is due to the dislocation motion.

Experimentally, since magnetotransport in the insulator phase is nonlinear and depends on the electric field,[4] the R_{xy} measurements must be carried out at electric fields below and above its threshold value; this has not been done yet. In the first measurements of the Hall resistance through the QHE/I transition,[5,6] no deviation of R_{xy} from its classical value was found in Si MOSFET's . These measurements, however, were carried out at above-threshold electric field and near $v=1.5$ only. Recent data[7,8] on GaAs–AlGaAs confirmed the classical value of R_{xy}, despite ρ_{xx} reaching $\sim 10\rho_{xy}$ near the fractional filling factors.

In the present study we extend measurements of the Hall resistance (i) deeper into the insulating phase, up to $\rho_{xx}=4\times 10^6\ \Omega/\square$, (ii) for filling factors near $v\sim 1.5$ and $v\sim 2.5$, and (iii) we analyze the topology of the boundary for the QHE/I transition.

We used a high mobility (100) Si-MOSFET ($\mu^{\text{peak}}=4.3\times 10^4$ cm^2/V·s) pat-

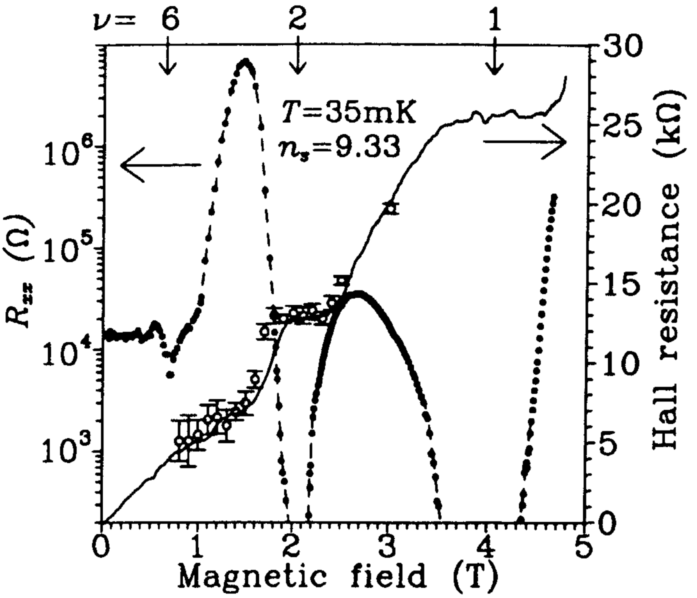

FIG. 1. R_{xx} and R_{xy} vs magnetic field in the vicinity of QHE/I transition near $\nu=2.5$. Full curve—R_{xy} measured at 10 nA (far above the threshold); open circles with error bars—at 0.25 nA (half the threshold electric field); dots—R_{xx} measured at 0.25 nA. Arrows indicate filling factor positions for the principal extrema in R_{xx}. The value n_s is in units of 10^{10} cm^{-2}; the aspect ratio for potential contacts is 0.64.

terned as a Hall bar (5×0.8 mm^2). The four-terminal dc transport measurements were carried out with a differential electrometer. At $T<300$ mK and at electron density $n_s<9.5\times10^{10}$ and below 8.5×10^{10} cm^{-2}, the sample exhibited pronounced reentrant insulating phases[4,5] centered at filling factors $\nu\approx2.5$ and 1.5, respectively (see Fig. 1). To eliminate the admixture of the longitudinal voltage into the Hall voltage, we subtracted measurements taken in two opposite magnetic field directions. As shown in Fig. 1, the R_{xy} values are rather close to the classical dependence $R_{xy}=H/(n_s ec)$ both far above and below the threshold electric field, even when ρ_{xx} increases to $\approx100h/\nu e^2$.

The theory by Kivelson *et al.*[2] suggests a global/phase diagram to describe the QHE/I transitions in a 2DES at zero temperature (Fig. 2a). The y axis, ρ^0_{xx}, is a measure of the disorder, while the x axis, ρ^0_{xy}, is a measure of the magnetic field. The dashed region represents the insulating phase which spreads toward zero disorder at zero field ($\rho^0_{xy}=0$) and at the half-filled lowest Landau level ($\rho^0_{xy}=2h/e^2$). The nested curves separate regions labeled by the index s_{xy}, denoting the number of delocalized levels below the Fermi energy E_F. The transition from the initial QHE state with $s_{xy}=m$ (i.e., from mth plateau) to the insulator (where $s_{xy}=0$) would occur in this picture only through a sequence of transitions to lower-order QHE states $s_{xy}=m-1$, $m-2$, ... Transitions to and from the insulating phase beyond $s_{xy}=1\leftrightarrow0$ are forbidden.

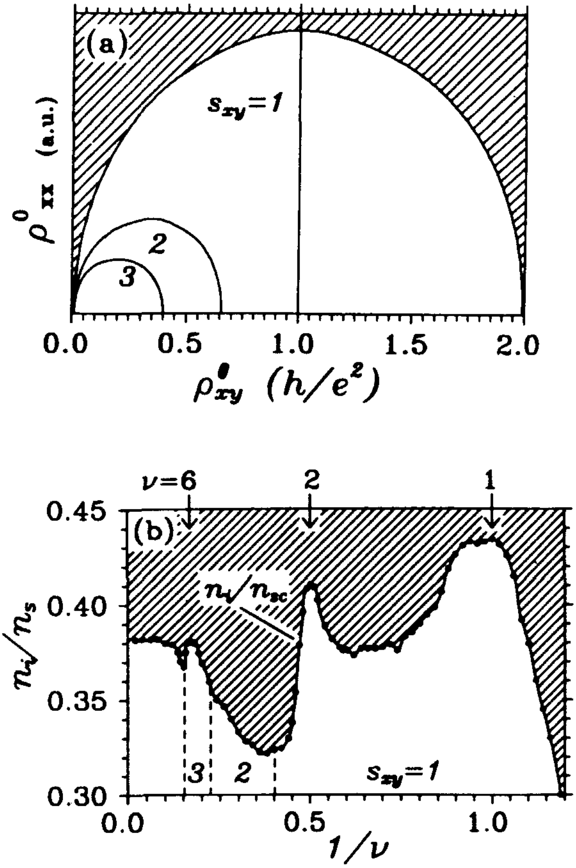

FIG. 2. Phase diagrams for the QHE/I transition. (a) Theoretical[2] phase diagram at $T=0$ as the strength of the disorder vs normalized magnetic field (courtesy of D.-H. Lee); (b) the experimental data taken at $T=35$ mK, as the normalized inverse critical density vs normalized magnetic field $1/\upsilon=(He/hc)/n_s$. Hatched regions designate the insulating phase.

Although the experimental data in Fig. 1 are shown as R_{xx} vs H, R_{xx} is not an obvious measure of the disorder since its magnitude also indicates the onset of the insulating phase. We have chosen the number of impurities per electron at the interface, n_i/n_s, as a more appropriate measure of the disorder.[9] Experimental points in Fig. 2b are obtained from the critical density n_{sc}, below which activated transport appears,[4] and $n_i=3.05\times10^{10}$ cm^{-2}, calculated from the sample's mobility.[9] The hatched region designates the insulating state, while the regular metallic phases, characterized by the QHE at $\upsilon=1, 2,\ldots$, lie below the curve. The 2DES is driven to the insulator state at weaker disorder when $1/\upsilon$ exceeds ≈ 1.1, consistent with Fig. 2a. For (100) Si, we may choose to ignore the e–e-interactions and consider the two-valley system as a pair of stacked independent 2DE systems. Under this assumption (which is not too realistic), the entire region from $1/\upsilon=1/0.5$ to $1/2.5$ can be attributed to

$s_{xy}=1$, $1/\upsilon=1/2.5$-$1/4.5$ to $s_{xy}=2$,... (see Fig. 2b). The reentrant QHE/I transitions near the filling factors $\upsilon=1$ and 2, and their absence at $s_{xy}=2$ ($\upsilon=3$ and 4) then agree with Ref. 2.

There are, however, a few caveats: The experimental data show the emergence of a reentrant QHE/I transition near $\upsilon=6$ (Ref. 10). The existence of such a transition with $s_{xy}=3$, inconsistent with the result of Ref. 2, is the subject of further study. According to the scaling theory,[11,12] the energy of delocalized states should increase with increasing disorder; the delocalized states would then "float up" and "exit through the Fermi energy"[12] during the QHE/I transition. Anomalies in ρ_{xx} (and possibly in R_{xy}) would then be observed when the boundary between phases with different s_{xy} is crossed (see Fig. 2a). This is not seen experimentally, in particular, near $\upsilon=6$, and it appears that the QHE/I transitions develop directly from any liquid phase to the insulator. The same follows from the topology of the boundary in Fig. 2b. The other possible reason for this discrepancy could be the nonzero temperature (30 mK) which may smear the expected features in ρ_{xx}, since theoretical predictions[1,2] have been made for $T=0$ and in the limit of low frequencies $\omega\rightarrow 0$, while experiments were performed at $\omega=0$ and $T\rightarrow 0$.

The distinct behavior of ρ_{xx} and R_{xy} during the QHE/I transition, and the absence of any signature of the "exit" of delocalized states through the Fermi energy may have an alternative explanation, based upon the collective nature of the reentrant insulating state.[4,9] When the 2DES is pushed toward the insulator by decreasing the density, rather than by increasing disorder, this is accompanied by an increase in the ratio of the *e–e* interaction energy to the Fermi energy, which is $E_{ee}/E_F\approx 6$ at $n_s=8\times 10^{10}$ cm^{-2}. It is possible that the delocalized states form a collective solid phase (e.g., an electron lattice) which becomes insulating due to pinning by the existing disorder.

In summary, our measurements in the vicinity of the QHE/I transitions show that (i) the Hall resistance does not diverge when measured at either above or below the threshold electric field, even if ρ_{xx} increases to 4×10^6 $\Omega/\square$. While ρ_{xx} is temperature activated, R_{xy} is not. These results agree with the predictions for the Hall insulator[1,2] and the pinned Wigner lattice with transport provided by extended defects.[3] (ii) The disorder–magnetic field diagram for the QHE/I transitions suggests that the insulating state develops directly from the QHE phases at different indices.

We wish to thank D.-H. Lee, S. Kivelson, and K. Efetov for valuable discussions. We also thank D. Brown for expert technical assistance.

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Submitted in English by the authors