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HALL RESISTANCE AND QUANTIZED HALL EFFECT TO INSULATOR TRANSITIONS IN A 2*D* ELECTRON SYSTEM

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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 $\rho_{xx} = 4 \times 10^6$ Ω/□. The insulating phase was found to develop directly from at least three QHE phases at $\nu = 1$, 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 to the band insulator or magnetic freeze-out. Recently Kivelson et al. [2] suggested a global behaviour 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 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 done at above-threshold electric field and around $\nu = 1.5$ only. Recent data [7,8], on GaAs-AlGaAs confirmed the classical value of R_{xy}, despite ρ_{xx} reaching $\sim 10\rho_{xy}$ around fractional filling factors.

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

We used a high mobility (100) Si-MOSFET ($\mu^{peak} = 4.3\times10^4$ cm^2/Vs) patterned as a Hall bar (5×0.8 mm^2). The 4-terminal *dc*-transport measurements were done with a differential electrometer. At $T < 300$ mK and at electron density $n_s <$ 9.5×10^{10} and below 8.5×10^{10} cm^{-2}, the sample exhibited well pronounced reentrant

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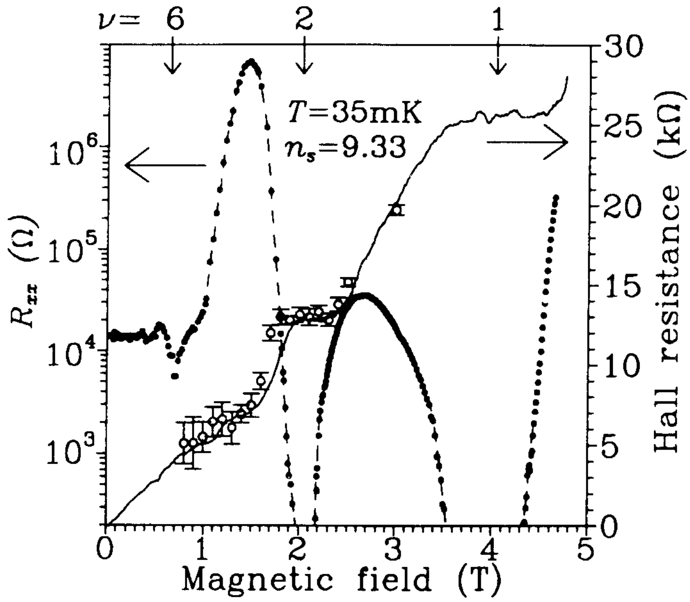

Fig.1. R_{xx} and R_{xy} vs magnetic field in the vicinity of QHE/I transition around ν=2.5. Full curve – R_{xy} measured at 10 nA (far above the threshold), open circles with error bars – at 0.25 nA (half the threshold electric field); dots – R_{xx} measured at 0.25nA. Arrows indicate filling factor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

insulating phases [4,5] centred at filling factors $\nu \approx 2.5$ 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} rises to $\approx 100h/\nu e^2$.

The theory by Kivelson et al. [2] suggests a global phase diagram to describe the QHE/I transitions in a 2DES at zero temperature (see Fig.2(a)). 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 towards 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 labelled 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 m-th 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 $s_{xy} = 1 \leftrightarrow 0$ are forbidden.

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 at the interface per electron, n_i/n_s as a more appropriate measure of the disorder [9]. Experimental points in Fig.2(b) are obtained from the critical density n_{sc}, below which activated transport appears [4], and $n_i = 3.05 \times 10^{10}$ cm^{-2} calculated from

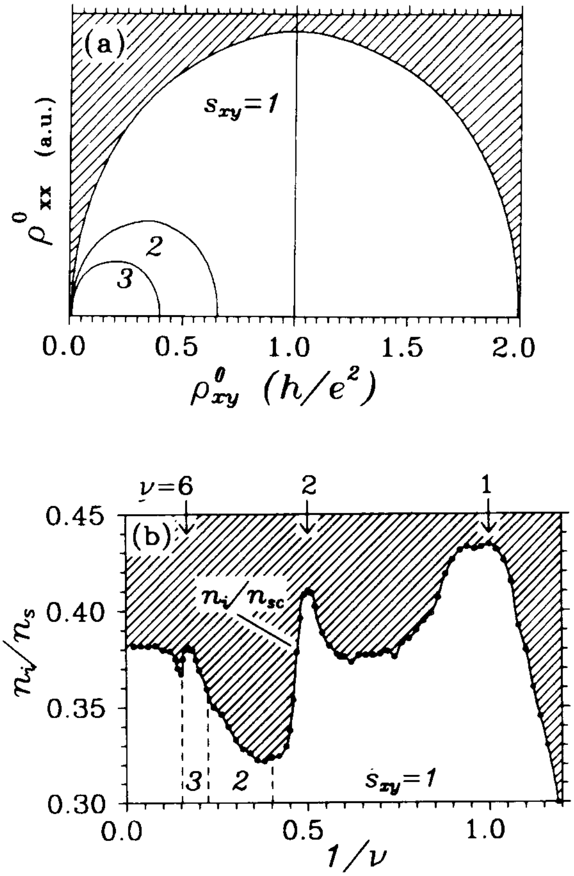

Fig.2.Phase diagrams for the QHE/I transition. (a) Theoretical [2] phase diagram at $T=0$ as the strength of the disorder vs normalized magnetic field (courtesy of D.-H. Lee); (b) the experimental data taken at T=35 mK, as the normalized inverse critical density vs normalized magnetic field $1/\nu=(He/hc)/n_s$.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

the sample's mobility [9]. The shadowed region designates the insulating state, while the regular metallic phases, characterized by the QHE at ν = 1, 2,... lie below the curve. The 2DES is driven to the insulator state at weaker disorder when $1/\nu$ exceeds ≈ 1.1, consistent with Fig.2(a). For (100) Si, we may choose to neglect e-e–interactions and consider the two-valley system as a pair of stacked independent 2DE systems. With this assumption (which is not too realistic), the entire region from $1/\nu$ = 1/0.5 to 1/2.5 can be attributed to s_{xy} =1, $1/\nu$ = 1/2.5 - 1/4.5 to s_{xy} =2,...(see Fig.2(b)). The reentrant QHE/I transitions around filling factors ν = 1 and 2, and their absence at $s_{xy}=2$ ($\nu=3$ and 4) agrees then with Ref. [2].

There are, however, a few caveats: the experimental data show the emergence of a reentrant QHE/I transition around ν = 6 [10]. The existence of such a transition with s_{xy} = 3 is not consistent with Ref. [2] and is the subject of further study. According to the scaling theory [11, 12] the energy of delocalized states should rise upon 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 whenever the boundary between phases with different s_{xy} is crossed (see Fig. 2(a)). This is not seen experimentally, in particular around $\nu = 6$, 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. 2(*b*). The other possible reason for this discrepancy, could be the non-zero 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 $\omega \to 0$, while experiments are performed at $\omega = 0$ and $T \to 0$.

The distinct behaviour of ρ_{xx} and R_{xy} during 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 towards the insulator by decreasing 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, measured at either above or below the threshold electric field, even when ρ_{xx} rises to 4×10^6 $\Omega/\Box$. While ρ_{xx} is temperature activated, R_{xy} is not. These results agree with the predictions for both 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.

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1. O.Viehweger and K.B.Efetov, J.Phys.: Condens. Matter **2**, 7049 (1990); Phys. Rev. B **44**, 1168 (1991).
2. S.Kivelson, D.-H.Lee, and S.-C.Zhang, Phys. Rev. B **46**, 2223 (1992); S.-C. Zhang, S.Kivelson, and D.-H.Lee, Phys. Rev. Lett. **69**, 1252 (1992).
3. S.T.Chui, preprint BA 92-53, Bartol Res. Inst. (1992)
4. M.D'Iorio, V.M.Pudalov, and S.G.Semenchinsky, Phys. Rev. B **46**, 15992 (1992).
5. M.D'Iorio, V.M.Pudalov, and S.G.Semenchinsky, Phys. Lett. A **150**, 422 (1990).
6. S.V.Kravchenko, J.A.A.J.Perenboom, and V.M.Pudalov, Phys. Rev. B **44**, 13513 (1991).
7. V.J.Goldman, J.K.Wang, Bo Su, and M.Shayegan, Phys. Rev. Lett. **70**, 647 (1993).
8. T.Sajoto, Y.P.Li, L.W.Engel, D.C.Tsui, and M.Shayegan, report J27.1, APS March Meeting, Seattle (1993).
9. V.M.Pudalov, M.D'Iorio, S.V.Kravchenko, and J.W.Campbell, Phys. Rev. Lett. **70**, 1866 (1993).
10. V.M.Pudalov, M.D'Iorio, and J.W.Campbell, report J27.2, APS March meeting, Seattle (1993).
11. B.I.Halperin, Phys. Rev. B **25**, 2185 (1982).
12. R.B.Laughlin, Phys. Rev. Lett. **52**, 2304 (1984).