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Reflection symmetry at a $B=0$ metal-insulator transition in two dimensions

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We report a remarkable symmetry between the resistivity and conductivity on opposite sides of the $B=0$ metal-insulator transition in a two-dimensional electron gas in high-mobility silicon metal-oxide-semiconductor field-effect transistors. This symmetry implies that the transport mechanisms on the two sides are related. [S0163-1829(97)52620-8]

Within the scaling theory of localization[1] developed for noninteracting electrons, no metallic phase exists in two dimensions in the absence of a magnetic field and no metal-insulator transition is therefore possible. Contrary to this expectation, several recent experiments[2–4] have given clear indication of a metal-insulator transition in zero magnetic field in a two-dimensional (2D) electron gas in high-mobility silicon metal-oxide-semiconductor field-effect transistors (MOSFET's). Measurements in samples equipped both with aluminum[2,4] and polysilicon[3] gates have demonstrated that the 2D gas of electrons exhibits behavior that is characteristic of a true phase transition: the resistivity scales with temperature[2,3] and electric field[4] with a single parameter that approaches zero at a critical electron density n_c. The nature of this unexpected transition and the physical mechanism that drives it are not understood.

In GaAs/Al_xGa_{1-x}As heterostructures, Shahar *et al.*[5] have recently found a direct and simple relation between the longitudinal resistivity in the magnetic field-induced insulating phase and the neighboring quantum Hall liquid (QHL) phase: $\rho_{xx}(\Delta\nu)=1/\rho_{xx}(-\Delta\nu)$. Here $\Delta\nu=\nu-\nu_c$, and ν_c is the critical filling factor for the $\nu=1$ QHL-insulator transition; the relation also holds for the fractional $\nu=1/3$ QHL-insulator transition when mapped[6] onto the $\nu=1$ QHL-insulator transition of composite fermions. Shahar *et al.*[5] point out that this remarkable symmetry indicates a close relation between the conduction mechanisms in the two phases.

In this paper, we report a similar symmetry near the critical electron density for the $B=0$ metal-insulator transition in the 2D electron gas in high-mobility silicon MOSFET's. Over a range of temperature $0.3\text{K}<T<1\text{K}$, the (normalized) linear conductivity on either side of the transition is equal to its inverse on the other side:

$$\rho^*(\delta_n,T)=\sigma^*(-\delta_n,T). \tag{1}$$

Here $\delta_n\equiv(n_s-n_c)/n_c$, n_s is the electron density, n_c is the critical electron density, $\rho^*\equiv\rho/\rho_c$ is the resistivity normalized by its value, $\rho_c\approx 3h/e^2$, at the transition, and $\sigma^*\equiv 1/\rho^*$. In the case of the magnetic field-induced QHL-insulator transition, the symmetry was attributed to charge-flux duality.[7] The observation of similar behavior in a 2D electron gas in the absence of a magnetic field implies that flux does not play a role in this case. Although the observed duality may have different underlying causes, our results suggest that it may originate with some fundamental feature that is common to both.

Four terminal dc resistivity measurements were performed on high quality silicon MOSFET's with maximum electron mobilities $\mu^{max}\approx 35\,000-40\,000$ cm^2/Vs similar to the samples used in Refs. 2 and 4. Different electron densities were obtained in the usual manner by controlling the gate voltage V_g. I-V curves were recorded at each temperature and electron density, and the resistivity was determined from the slope of the linear portion of the curve.

Figure 1 shows the resistivity as a function of gate voltage (electron density) at several different temperatures between 0.3 K and 0.9 K. The curves all intersect at a single value of the gate voltage, $V_g=1.348$ V, corresponding to a critical electron density, $n_c=8.45\times10^{10}$ cm^{-2}. The resistivity decreases (increases) with increasing temperature for $n_s<n_c$ ($n_s>n_c$), as expected for insulating (metallic) behavior. In

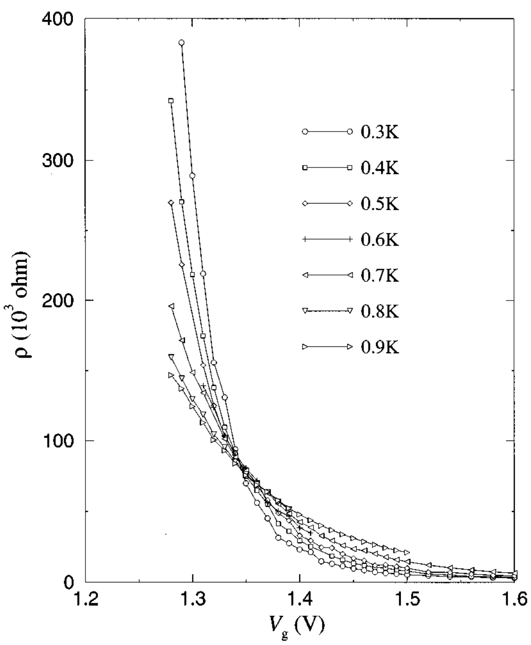

FIG. 1. Resistivity as a function of gate voltage V_g for temperatures between 0.3 K and 0.9 K, obtained from the linear portion of the $I-V$ curves using the appropriate dimensionless geometric factor.

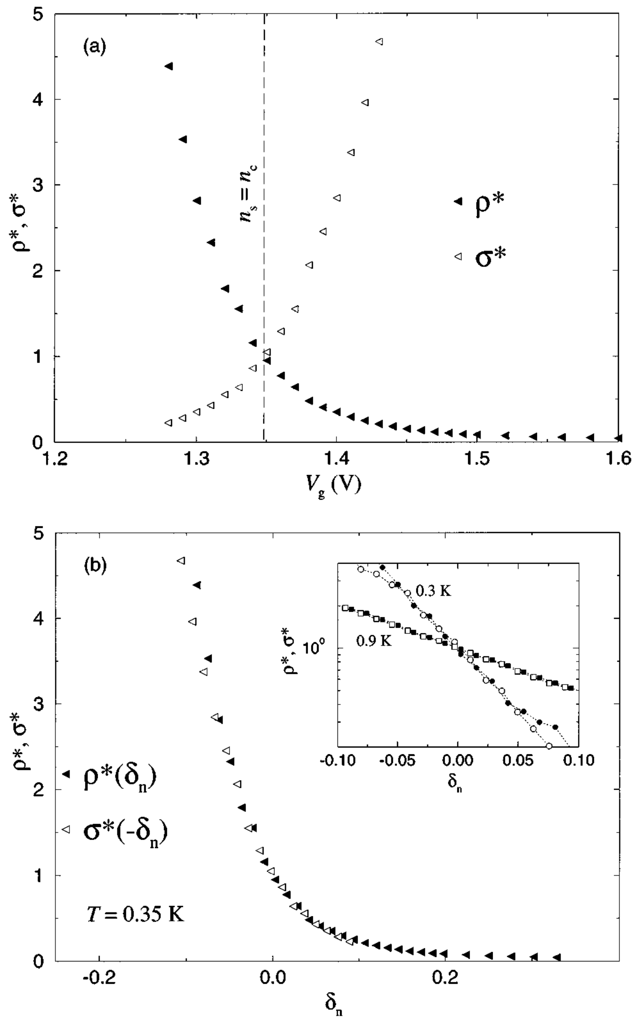

FIG. 2. (a) Normalized resistivity ρ^*, and normalized conductivity σ^*, as functions of the gate voltage V_g, at $T=0.35$ K. Note the symmetry about the line $n_s=n_c$. The electron density is given by $n_s=(V_g-0.58\ \text{V})\times 1.1\times 10^{11}\ \text{cm}^{-2}$. (b) To demonstrate this symmetry explicitly, $\rho^*(\delta_n)$ (closed symbols) and $\sigma^*(-\delta_n)$ (open symbols) are plotted versus $\delta_n\equiv(n_s-n_c)/n_c$. Inset: $\rho^*(\delta_n)$ (closed symbols) and $\sigma^*(-\delta_n)$ (open symbols) versus δ_n at $T=0.3$ K and $T=0.9$ K, the lowest and highest measured temperatures.

agreement with earlier measurements,[2–4] the resistivity at the critical point is close to $3h/e^2$.

The normalized resistivity $\rho^*(V_g)$ and the normalized conductivity $\sigma^*(V_g)$ at $T=0.35$ K are shown as functions of the gate voltage in Fig. 2(a). Note the apparent symmetry about the vertical line corresponding to the critical electron density. Figure 2(b) demonstrates that the curves can be mapped onto each other by reflection, i.e., $\rho^*(\delta_n)$ is virtually identical to $\sigma^*(-\delta_n)$. Our data indicate that this mapping holds over a range of temperature from 0.3 K to 0.9 K. The range $|\delta_n|$ over which it holds decreases continuously as the temperature is decreased: for example, at $T=0.9$ K, ρ^* and σ^* are symmetric for $|\delta_n|\lesssim 0.1$, while at $T=0.3$ K, they are symmetric only for $|\delta_n|\lesssim 0.05$ [see inset to Fig. 2(b)]. On the other hand, the overall change in resistivity for which the mapping is valid remains approximately the same.

The resistivity of the 2D electron gas in Si MOSFET's was shown[2] to scale near the transition according to

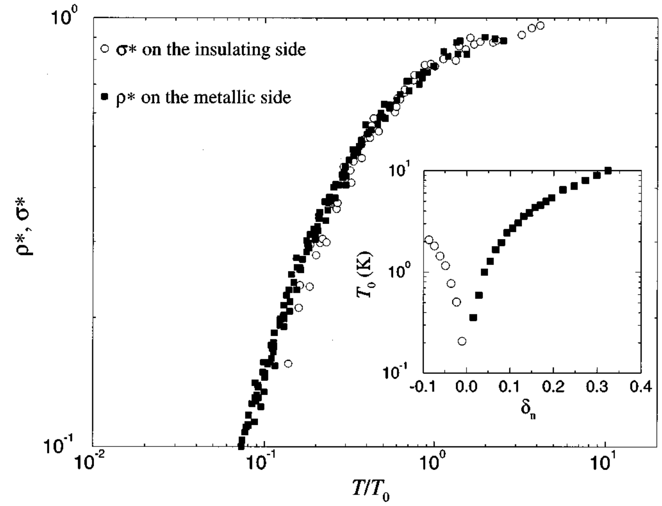

FIG. 3. Normalized resistivity ρ^* on the metallic side of the transition (closed symbols) and normalized conductivity σ^* on the insulating side (open symbols) versus scaled temperature, T/T_0. The scaling parameter T_0 is shown as a function of δ_n in the inset.

$$\rho(T,\delta_n)=f(|\delta_n|/T^b)=\rho(T/T_0), \tag{2}$$

with a single parameter T_0 that is the same function of $|\delta_n|$ on both the metallic and the insulating side of the transition, $T_0\propto|\delta_n|^{1/b}$. Combined with the scaling of Eq. (2), the duality expressed in Eq. (1) takes the form

$$\rho^*_{\text{met,ins}}(T/T_0)=\sigma^*_{\text{ins,met}}(T/T_0). \tag{3}$$

The scaled curves $\rho^*(T/T_0)$ for the metallic side and $\sigma^*(T/T_0)$ for the insulating side should thus be equivalent. This is demonstrated in Fig. 3, which shows that $\rho^*(T/T_0)$ and $\sigma^*(T/T_0)$ are indeed virtually identical for a given sample in a range where the resistivity (conductivity) changes by an order of magnitude. Remarkably, this indicates that the temperature dependence of the resistivity in either phase is similar to the temperature dependence of the conductivity in the other phase, implying that the mechanisms responsible for electrical transport in the insulating and metallic phases are related.

We note that since $\sigma\rightarrow 0$ at $T=0$ in the insulating phase, full symmetry requires that $\rho\rightarrow 0$ at $T=0$ in the ''metallic'' phase. This would in turn imply that the transition in silicon MOSFET's is to a superconducting or other phase in which the resistivity goes to zero. Experiments to much lower temperatures are required to determine whether Eq. (3) remains valid as $T\rightarrow 0$.

The symmetry shown in Fig. 2 bears a strong resemblance to the behavior found for the resistivity near the quantum Hall liquid (QHL)-to-insulator transition in high-mobility GaAs/$\text{Al}_x\text{Ga}_{1-x}$As heterostructures, where it has been attributed to charge-flux duality in the composite boson description.[8] The symmetry was shown in this case to hold for the entire nonlinear I-V curve.[7] Approximate reflection symmetry of the I-V curves was also noted by van der Zant *et al.*[9] at the magnetic-field-induced superconductor-insulator transition in aluminum Josephson junction arrays; it has been suggested that this duality can be traced to the symmetry between single charges in the superconducting phase and vortices in the insulating phase.[10] On the other hand, there is no evident symmetry of the superconducting and insulating branches at the superconductor-insulator transition in thin films driven by varying thickness[11] or a magnetic field,[12] nor do the I-V curves show a reflection symmetry about the critical point in the former case.[13]

To summarize, we have presented evidence for a reflection symmetry about the critical point of the resistivity on one side and its inverse on the other side of the metal-insulator transition in the 2D electron gas in high-mobility silicon MOSFET's in the absence of a magnetic field. This implies there is a simple relation between the conduction mechanisms in the two phases. The behavior near this $B=0$ transition is remarkably similar to that found at the quantum Hall liquid-to-insulator transition. This suggests that some feature common to both transitions may be responsible for the observed duality. A $B=0$ metal-insulator transition is unexpected in two dimensions, and its nature in high-mobility silicon MOSFET's is not currently understood. The symmetry reported here may provide an additional clue that could lead to a theoretical understanding of the anomalous metal-insulator transition in 2D in the absence of a magnetic field.

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[1] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979).

[2] S. V. Kravchenko, G. V. Kravchenko, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, Phys. Rev. B **50**, 8039 (1994); S. V. Kravchenko, W. E. Mason, G. E. Bowker, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, *ibid.* **51**, 7038 (1995).

[3] J. E. Furneaux, S. V. Kravchenko, W. Mason, V. M. Pudalov, and M. D'Iorio, Surf. Sci. **361/362**, 949 (1996).

[4] S. V. Kravchenko, D. Simonian, M. P. Sarachik, W. Mason, and J. E. Furneaux, Phys. Rev. Lett. **77**, 4938 (1996).

[5] D. Shahar, D. C. Tsui, M. Shayegan, J. E. Cunningham, E. Shimshoni, and S. L. Sondhi, cond-mat 19607127 (unpublished).

[6] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989); Phys. Rev. B **40**, 8079 (1989).

[7] D. Shahar, D. C. Tsui, M. Shayegan, E. Shimshoni, and S. L. Sondhi, Science **274**, 591 (1996).

[8] S. A. Kivelson, D. H. Lee, and S. C. Zhang, Phys. Rev. B **46**, 2223 (1992).

[9] H. S. J. van der Zant, F. C. Fritschy, W. J. Elion, L. J. Geerligs, and J. E. Mooij, Phys. Rev. Lett. **69**, 2971 (1992), and references therein.

[10] See, for example, S. M. Girvin, Science **274**, 524 (1996).

[11] Y. Liu, K. A. McGreer, B. Nease, D. B. Haviland, G. Martinez, J. W. Halley, and A. M. Goldman, Phys. Rev. Lett. **67**, 2068 (1991).

[12] A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. **74**, 3037 (1995).

[13] A. M. Goldman (private communication).