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

D. Simonian, S. V. Kravchenko, and M. P. Sarachik

Physics Department, City College of the City University of New York, New York, New York 10031

(June 17, 2018)

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 MOSFET’s. This symmetry implies that the transport mechanisms on the two sides are related.

Within the scaling theory of localization [1] developed for non-interacting 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 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 [5] 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] 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/AlGaAs heterostructures, Shahar et al. [6] 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 $\nu_c$ 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. [6] 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:

$$\rho^*(\delta_n, T) = \sigma^*(-\delta_n, T).$$

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, $\rho_c \approx 3\hbar/e^2$, 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 [4]. 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 $\mu_{\text{max}} \approx 35,000 - 40,000 \, \text{cm}^2/\text{Vs}$ similar to the samples used in Refs. [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.

Fig. 1 shows the resistivity as a function of gate voltage, $V_g$, for temperatures between $0.3 \, \text{K}$ and $0.9 \, \text{K}$, obtained from the linear portion of the $I - V$ curves using the appropriate dimensionless geometric factor.
Note the symmetry about the line $s_t$. The normalized resistivity, $\rho^*$, and normalized conductivity, $\sigma^*$, 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 $n_s = (V_g - 0.58V) \times 1.1 \times 10^{11}$ cm$^{-2}$. 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 $\delta_n$ at $T = 0.3$ K and $T = 0.9$ K, the lowest and highest measured temperatures.

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. Fig. 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. However, the range $|\delta_n|$ over which it holds decreases continuously as the temperature increases.

The scaled curves $\rho^*(V_g)$ and $\sigma^*(V_g)$ are plotted versus $\delta_n \equiv (n_s - n_c)/n_c$ at $T = 0.3$ K and $T = 0.9$ K, the lowest and highest measured temperatures. The electron density is given by $n_s = (V_g - 0.58V) \times 1.1 \times 10^{11}$ cm$^{-2}$. To demonstrate this symmetry explicitly, $\rho^*(\delta_n)$ (closed symbols) and $\sigma^*(-\delta_n)$ (open symbols) are plotted versus $\delta_n$ at $T = 0.3$ K and $T = 0.9$ K, the lowest and highest measured temperatures.

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/AlGaAs heterostructures, where it has been attributed to charge-flux duality in the composite boson description [1]. The symmetry was shown in this case to hold for the entire nonlinear $I - V$ curve [2]. Approximate reflection symmetry of the $I - V$ curves was also noted by van der Zant et al. [3] 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-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.

The symmetry at the QH liquid-insulator transition provided the impetus for the present work: we are grateful to D. Shahar for sharing his data prior to publication. We would also like to thank A. M. Goldman, S. A. Kivelson, D. H. Lee, and S. L. Sondhi for helpful discussions. This work was supported by the US Department of Energy under Grant No. DE-FG02-84ER45153.

[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, Phys. Rev. B 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, to appear in Phys. Rev. Lett. 77 (1996).
[5] D. Shahar, D. C. Tsui, M. Shayegan, J. E. Cunningham, E. Shimshoni and S. L. Sondhi, to be published in Solid State Commun.
[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.