Observation of a Percolation-Induced 2D Metal-Insulator Transition in a Si MOSFET

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Motivation—The exact nature of the ground state of a two-dimensional electron gas (2DEG) at low temperatures is still not well understood. This is due to the complicated many-body physics involved, which is especially difficult when one tries to incorporate disorder, which is necessary in order to describe actual experimental systems. One aspect of this problem many have focused on is the temperature dependence of the 2DEG conductivity as a function of density. Varying the electron density changes the strength of electron-electron interactions relative to the kinetic energy and also varies both of these energy scales relative to the strength of the disorder. Experimentally and theoretically, there is some evidence suggesting a transition from metallic to insulating behavior upon varying the density. However, controversy exists over whether this transition is better described as an exotic, interaction-driven phase transition or by more straightforward physics of disordered conductors.

Accomplishment—We measured the temperature and density dependence of the resistivity of two MOSFET structures. In Fig. 1 we show our measured and calculated temperature and density dependent resistivity (P(T)) for sample A. The results for sample B are similar. The classic 2D metal-insulator transition (MIT) behavior is apparent in Fig. 1(a) where $\rho(T)$ for various densities shows a clear distinction between metallic $d\rho/dT > 0$ and insulating $d\rho/dT < 0$ behavior separated by a critical density $n_c \sim 1.4 \times 10^{11}$ cm^{-2}. In Fig. 1(c) and (d) we show our theoretically calculated $\rho(T)$ where the Boltzmann transport is calculated using the screened charged impurity scattering as the only resistive scattering mechanism [1]. Although the ratio of the Coulomb to Fermi energy can be as large as ~ 15 near the MIT for this sample, suggesting that Coulomb interactions could play an important role, we note that the basic features of the experimental metallic phase are well-captured by the screening theory.

In Fig. 2 we plot our measured conductivity as a function of n to see if a percolation behavior, $\sigma \propto (n - n_p)^p$, where n_p and p are the percolation transition density and exponent, respectively, is manifested. Our fit yields $p \sim 1.20$, $n_p \sim 1.2 \times 10^{11}$ cm^{-2} for sample A and $p \sim 1.24$, $n_p \sim 2.0 \times 10^{11}$ cm^{-2} for sample B. Our values for the exponent p are fairly close to the expected theoretical value of 1.31.

Significance—Our work provides the first experimental data together with theoretical calculations that show that the 2D MIT in a Si MOSFET can be explained by percolation physics. Our data and theoretical analysis show that the temperature dependence of the observed metallic state can be described by a finite-temperature semi-classical Boltzmann screening theory and that the density dependence of our resistivity data is consistent with a percolation model.

[1] S. Das Sarma and E. H. Hwang, *Phys. Rev. Lett.* **83**, 164 (1999).

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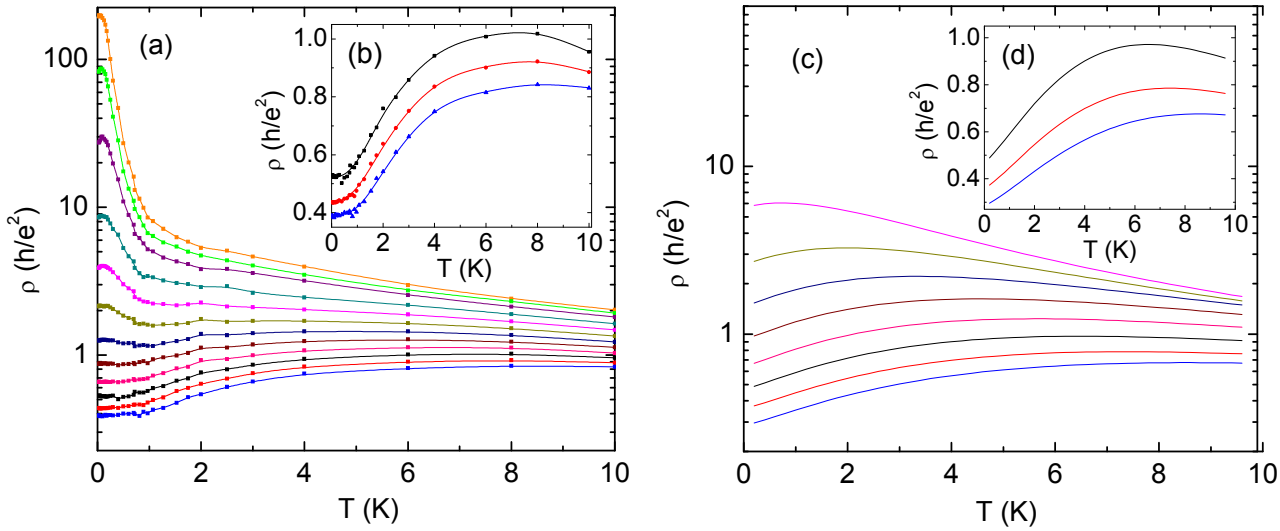

Figure 1. (a) Experimental resistivity ρ in units of h/e^2 as a function of temperature for sample A at 2D electron densities (from top to bottom) n = 1.07, 1.10, 1.13, 1.20, 1.26, 1.32, 1.38, 1.44, 1.50, 1.56, 1.62, and 1.68 × 10^{11} cm^{-2}. Inset (b) Enlarged view of data in the effective metallic regime at n = 1.56, 1.62, and 1.68 × 10^{11} cm^{-2}. Solid lines are guides to the eye. (c) Theoretically calculated temperature and density dependent resistivity for densities n = 1.26, 1.32, 1.38, 1.44, 1.50, 1.56, 1.62, and 1.68 × 10^{11} cm^{-2} (from top to bottom). Inset shows the resistivities for n = 1.56, 1.62, and 1.68 × 10^{11} cm^{-2}.

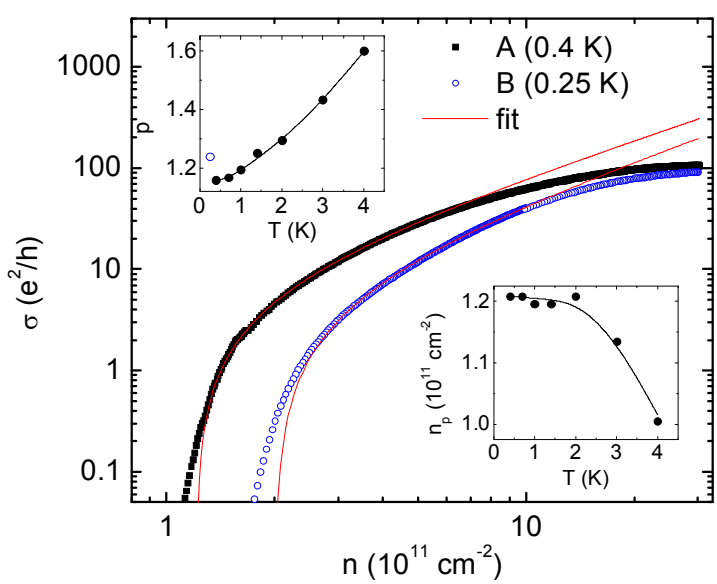

Figure 2. (a) Main plot: Points show experimental conductivity σ in units of e^2/h versus electron density n for sample A at T = 0.4 K (closed symbols) and B at T = 0.25 K (open symbols). The solid lines are fits to the data of the form $\sigma = A(n - n_p)^p$. The upper and lower insets show the exponent p and critical density n_p, respectively, as a function of temperature for sample A. Solid lines are a guide to the eye. The open symbol in the upper inset shows p for sample B at T = 0.25 K.