# Electric Field Scaling at a $B = 0$ Metal-Insulator Transition in Two Dimensions

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The nonlinear (electric field-dependent) resistivity of the 2D electron system in silicon exhibits scaling as a function of electric field and electron density in both the metallic and insulating phases, providing further evidence for a true metal-insulator transition in this 2D system at $B = 0$. Comparison with the temperature scaling yields separate determinations of the correlation length exponent, $\nu \approx 1.5$, and the dynamical exponent, $z \approx 0.8$, close to the theoretical value $z = 1$. [S0031-9007(96)01867-4]

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Conventional wisdom holds that a two-dimensional (2D) system of noninteracting electrons is always localized in zero magnetic field at zero temperature no matter how weak the disorder [1]. If so, there should be no metal-insulator phase transition at $B = 0$ in an infinite sample in 2D. However, recent experiments [2,3] have shown clear signatures of a metal-insulator transition in a high-quality two-dimensional electron system (2DES) in silicon in zero magnetic field. The resistivity, $\rho$, was found to scale with temperature, so that

$$\rho(T, n_s) = f_1(|\delta_n|/T^b), \quad \text{with } b = 1/z\nu. \tag{1}$$

Here $n_s$ is the electron density, $\delta_n \equiv (n_s - n_c)/n_c$, $n_c$ is the critical electron density at the metal-insulator transition, $z$ is the dynamical exponent, and $\nu$ is the correlation length exponent. On the insulating side of the transition, the resistivity was found to have a temperature dependence characteristic of hopping in the presence of a Coulomb gap in the density of states [4] due to strong electron-electron interactions. Such scaling behavior is characteristic of a true phase transition and implies that there is a diverging correlation length, $\xi \sim |\delta_n|^{-\nu}$, at the transition. The behavior strongly resembles the superconductor-insulator phase transition in thin disordered films [5,6], as well as the phase transition between quantum Hall liquid and insulator [7–9]. These results are in apparent contradiction with the scaling theory [1] which, however, ignores electron-electron interactions. In the 2DES in silicon, electron-electron interactions provide the dominant energy, $E_{ee}$, at low electron densities: At $n_s \sim 10^{11}$ cm$^{-2}$, $E_{ee} \sim 5$ meV while the Fermi energy is only ~0.6 meV. For comparison, in GaAs/AlGaAs heterostructures these energies are approximately equal to each other at the same electron density: $E_{ee} \approx E_F \approx 3.5$ meV. We note that recent theoretical studies [10,11] have shown that strong electron-electron interactions can cause delocalization.

The resistivities reported in Refs. [2,3] were obtained in the linear regime, i.e., in the limit of zero electric field, $E \to 0$. When the electric field is strong, however, the effective temperature of the electrons becomes different from the lattice temperature. A general scaling analysis of the Coulomb interacting quantum critical point [12] shows that the resistivity should also scale with the electric field, but the scaling exponent in this case will be $1/[(z + 1)\nu]$ (instead of $1/z\nu$ in the case of temperature scaling) so that

$$\rho(E, n_s) = f_2(|\delta_n|/E^a), \quad \text{with } a = 1/[(z + 1)\nu]. \tag{2}$$

Knowing both $z\nu$ and $(z + 1)\nu$, one should be able to determine the exponents $z$ and $\nu$ separately. It is worth noting that this was done recently for the superconductor-insulator transition in thin disordered films [6].

In this Letter we report measurements of the nonlinear resistivity of a two-dimensional electron system as a function of electric field at $B = 0$. Scaling is observed as a function of electric field and electron density about a critical point which corresponds to the same critical density about which *temperature* scaling was reported earlier [2,3]. By comparing the electric field scaling with the temperature scaling, separate determinations (rather than their product) were obtained for the correlation length exponent, $\nu \approx 1.5$, and the dynamical exponent, $z \approx 0.8$, close to the theoretical value $z = 1$ for strongly interacting Coulomb systems. At the transition ($n_s = n_c$), the resistivity is independent of electric field and close to $3h/e^2$. These data provide additional strong evidence for a true metal-insulator transition in high-mobility 2DES in silicon in the absence of a magnetic field.

The samples used in this work were high-mobility silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) with maximum electron mobility $\mu^{\max} \approx 35\,000$–$40\,000$ cm$^2$/V s similar to those used in Refs. [2,3]. The resistivity was determined as a function of electric field by measuring current versus voltage ($I$-$V$ curves) for many values of $n_s$ using a standard

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four-terminal dc technique. Typical curves are shown in Fig. 1. The middle, solid curve is close to linear and separates all $I$-$V$ curves into two groups exhibiting different types of nonlinear behavior. Note that there is a remarkable symmetry about the middle curve. This symmetry is reminiscent of that observed for the $I$-$V$ curves in the vicinity of the quantum Hall effect- (QHE)-insulator phase transition [8] and is consistent with the existence of a critical point at a critical electron density $n_c$. The physical origin of this symmetry in our system is unclear and merits theoretical study.

Curves of resistivity $\rho$ vs electric field $E$ for different electron densities are shown in Fig. 2 (not all curves measured are shown in order to avoid a too high density of points). Here, the resistivity is determined from $\rho = (V/I)(W/L)$ ($W$ is the sample width and $L$ is the distance between potential contacts) and the electric field $E = V/L$. Again, there is clearly a critical electron density which separates two distinct density regions characterized by different types of resistivity behavior as a function of electric field. At the critical point, the resistivity (solid curve in Fig. 1, closed circles in Fig. 2) is virtually independent of the electric field and close to $3h/e^2$. All curves below this line are characterized by $d\rho/dE > 0$ while all curves above are characterized by $d\rho/dE < 0$. The observed critical behavior of $\rho$ as a function of $E$ is very similar to the critical behavior of the resistivity with *temperature* observed near the metal-insulator transition in 2DES in silicon [2,3] (with the only difference being that the resistivity at the critical point is $E$ independent but *not* $T$ independent at $T \gtrsim 2$ K). It also resembles the behavior found near the superconductor-insulator phase transition in thin metallic films [5] and the quantum Hall effect-insulator (QHE-I) transition in GaAs/AlGaAs heterostructures [7–9].

A remarkable property is that plotting the resistivity against the scaling variable, $|\delta_n|/E^a$, causes all the curves to collapse onto two distinct branches, as shown in Fig. 3(a). Note that points for $E \to 0$, where $\rho$ saturates due to finite temperature, have been omitted. As expected, the scaling fails at electron densities far from the critical point, where the system is no longer in the critical regime, as seen on the lower curve in Fig. 3(a). The upper branch corresponds to $n_s < n_c$ and the lower one to $n_s > n_c$. At the transition ($n_s = n_c$), the resistivity is close to $3h/e^2$. It is interesting to note that almost the same value was reported recently in Ref. [13] for a transition between weak and strong localization in disordered metallic films. The exponent $a$ was varied to obtain the best visual collapse, yielding $a = 0.37 \pm 0.01$.

Repeating the procedure reported in Refs. [2,3], the temperature dependence of the resistivity measured in the linear regime ($E \to 0$) was used to obtain scaled curves of the resistivity as a function of the *temperature*-dependent scaling variable, $|\delta_n|/T^b$. This is shown in Fig. 3(b), where it is evident that all curves again collapse onto two distinct branches, confirming the earlier results. We note that the data scale well only at temperatures below 1 K, presumably because at higher temperatures the system

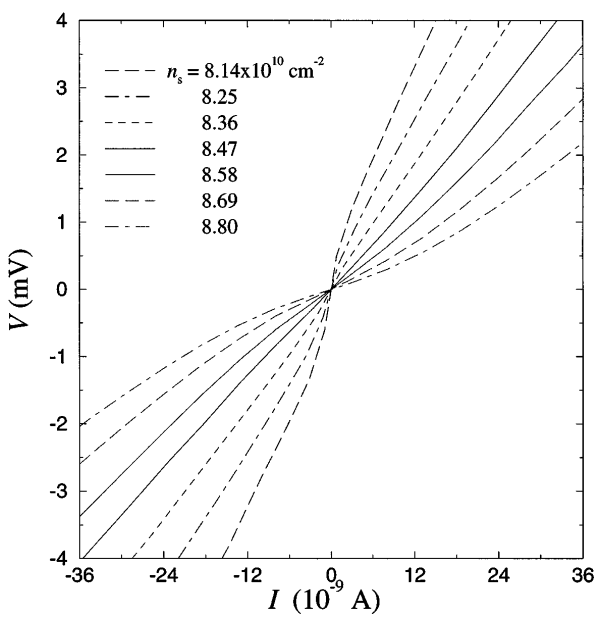


FIG. 1. Nonlinear current-voltage curves at several electron densities around the metal-insulator transition. $T = 0.22$ K.

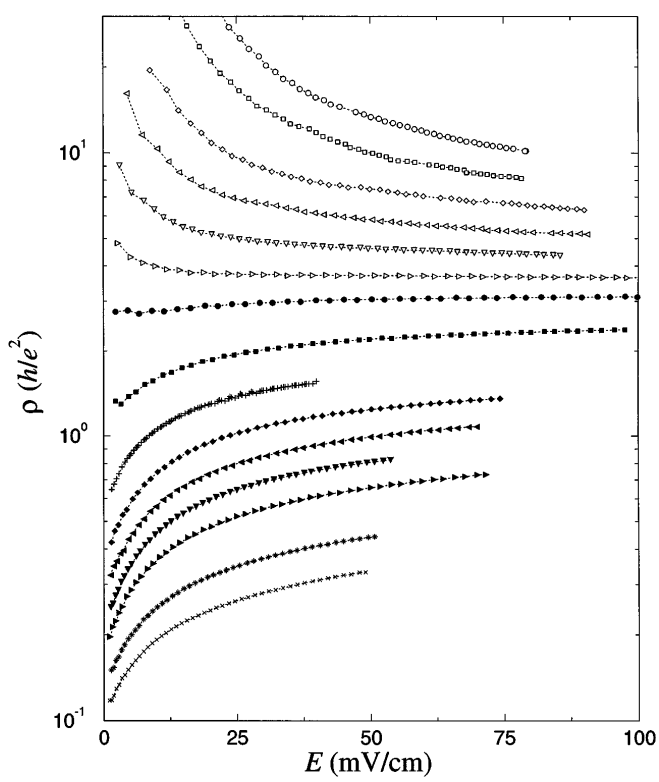


FIG. 2. Resistivity as a function of electric field at $n_s = 7.81$, 7.92, 8.03, 8.14, 8.25, 8.36, 8.47, 8.70, 8.91, 9.13, 9.35, 9.57, 9.79, 10.34, and $10.78 \times 10^{10}$ cm$^{-2}$ at $T = 0.22$ K.

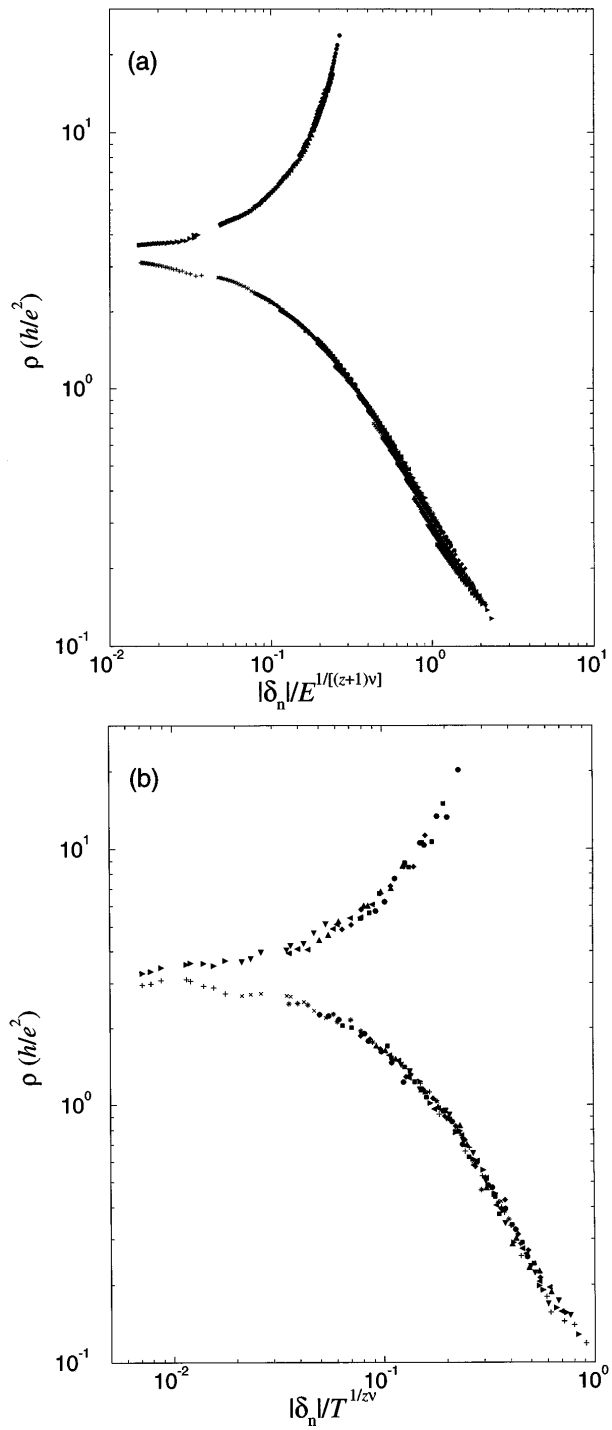


FIG. 3. (a) Demonstrating scaling with electric field, the resistivity at 0.22 K is plotted as a function of $|\delta_n|/E^a$ for $a = 1/[(z+1)\nu] = 0.37$. (b) Demonstrating scaling with temperature in the temperature interval 0.3 to 1 K, the linear resistivity ($E \rightarrow 0$) is shown as a function of $|\delta_n|/T^b$ for $b = 1/z\nu = 0.83$. Electron densities are in the range $7.81-10.78 \times 10^{10}$ cm$^{-2}$.

is outside the critical regime. The best collapse was achieved for $b = 0.83 \pm 0.08$.

As mentioned earlier, these two scaling analyses allow one to determine both the dynamical exponent and the correlation length exponent. The values obtained in our experiments are $z = 0.8 \pm 0.1$ and $\nu = 1.5 \pm 0.1$. While the correlation length exponent has not been theoretically predicted for this system, the value of the dynamical exponent in a strongly interacting 2D system was predicted to be $z = 1$ [12], close to what we observe. In the majority of interacting 2D systems where it has been determined, the exponent $z$ has also been found to be close to 1 (see, e.g., Ref. [6] for the case of a superconductor-insulator transition and Ref. [14] for the transition between two neighboring QHE plateaus). The same result for the case of hopping conductance follows from the theory of Polyakov and Shklovskii [15] who found the ratio of scaling exponents $a/b = 1/2$ [see Eqs. (1) and (2)] which is equivalent to $z = 1$.

We note that the above considerations were based on the assumption that there is a diverging correlation time at the critical point which controls the dynamics [12]. An alternative picture involving hydrodynamic heating was developed in Ref. [16] which assumes that the electron temperature is governed by phonon emission. In the case of silicon, this model gives $a/b = 1/3$ rather than $a/b = 1/2$. Some influence of phonons may be responsible for the ratio $a/b$ somewhat less than $1/2$ ($a/b \approx 0.45$) found in the present work. A crossover between the two regimes will be reported elsewhere [17].

In summary, we have shown that, in the absence of a magnetic field, the resistivity of the 2DES in high-quality silicon MOSFET's scales as a function of electric field and electron density, exhibiting critical behavior about the same point as the temperature scaling. At the critical point the resistivity is independent of electric field and close to $3h/e^2$. Comparison of scaling of the resistivity with temperature and scaling with electric field yields separate determinations of the correlation length exponent, $\nu \approx 1.5$, and the dynamical exponent, $z \approx 0.8$, close to the theoretical value $z = 1$. These results provide additional strong evidence of a true metal-insulator phase transition in a high-quality 2DES in silicon in zero magnetic field.

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