

Experimental evidence for a Coulomb gap in two dimensions

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We have studied the resistivity of a two-dimensional electron system in silicon in the temperature range $200 \text{ mK} < T < 7.5 \text{ K}$ at zero magnetic field at low electron densities, when the electron system is in the insulating regime. Our results show that at an intermediate temperature range, $\rho = \rho_0 \exp[(T_0/T)^x]$ for at least four orders of magnitude up to $3 \times 10^9 \Omega$. This behavior is consistent with the existence of a Coulomb gap. Near the metal/insulator transition, the prefactor was found to be $\rho_0 \approx h/e^2$, and resistivity scales with temperature. For very low electron densities n_s , the prefactor diminishes with diminishing n_s . A comparison with the theory shows that a specific set of conditions are necessary to observe the behavior of resistivity consistent with the existence of the Coulomb gap.

At sufficiently low temperatures (T), in disordered systems such as semiconductors, transport occurs by phonon-assisted tunneling to states nearby in energy. The tunneling distance to a state within $k_B T$ of the Fermi energy (E_F) increases with decreasing temperature (here k_B is the Boltzmann constant). This transport process has been labeled variable-range hopping and is characterized by resistivity of the form

$$\rho(T) = \rho_0 \exp(T_0/T)^x, \quad (1)$$

where T_0 is some characteristic temperature. Mott¹ derived this law by assuming a constant density of states at the Fermi energy and found in two dimensions that $x = \frac{1}{3}$. This is a single-particle picture that ignores the Coulomb interaction. Efros and Shklovskii² have argued that the Coulomb interaction between localized electrons creates a gap, the so-called "Coulomb gap," in the density of states near the Fermi energy. This is manifested by a resistivity of the form of Eq. (1) with $x = \frac{1}{2}$, which is universal for both two- and three-dimensional [(2D) and (3D)] electronic systems.

In 1986, Timp, Fowler, Hartstein, and Butcher³ (TFHB) examined the conductivity as a function of temperature and electric field in sodium-doped silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) and found no evidence of the Coulomb gap. More recently, Coulomb gap behavior has been observed in relatively low-mobility GaAs/Al_xGa_{1-x}As heterostructures.^{4,5} In this paper, we report experimental studies of the temperature dependence of resistivity of *high-mobility* silicon MOSFET's. Our experimental data follow the form of Eq. (1) with $x = \frac{1}{2}$ for a range of parameters such as temperature and 2D electron density n_s . This behavior is consistent with the existence of the Coulomb gap. We believe differences between our results and those of TFHB are due to differences between parameter spaces examined in each case.

The samples used for the studies reported here were 2D electron systems (2DES) in silicon MOSFET's with

maximum mobility μ of $3.0 \times 10^4 \text{ cm}^2/\text{Vs}$ (sample Si-1) and $3.5 \times 10^4 \text{ cm}^2/\text{Vs}$ (Si-2). The gate oxide thickness is 200 nm. Electron density was changed by changing the voltage V_g between the 2DES and the gate. The resistance was measured with a four-terminal dc technique using cold amplifiers with a very high input impedance ($> 10^{14} \Omega$). The data discussed here are for electron densities where the samples exhibited strongly insulating behavior. In this case, the current-voltage (I - V) characteristics are strongly nonlinear.⁶ To get a "true" resistivity, we measured $V(I)$ for each n_s and T ; then the values of resistivity corresponding to $I \rightarrow 0$ were obtained as $(dV/dI)|_{I=0}$ divided by the number of squares. The measurements were taken at temperatures ranging from 200 mK to 10 K at $B = 0$.

Figure 1 shows ρ versus $T^{-\frac{1}{2}}$ for Si-1 for several electron densities.⁷ (ρ is given in units of h/e^2 .) In order to determine the value of x in Eq. (1), we fit our data to $\exp(T^x)$ assuming a temperature-independent prefactor ρ_0 , and found that for $T \gtrsim 400 \text{ mK}$, the best fit of all the data gave values of x very close to 0.5. The actual values of x for various electron densities are shown in Table I. One can see that the Coulomb gap behavior exists for up to four orders of magnitude in resistivity. At low temperature, weaker T dependence is evident, particularly at higher electron density. Notice that the data are consistent with a *temperature-independent prefactor*, unlike the data presented in Ref. 5. However, it can be seen that the prefactor is n_s dependent: the lower n_s , the lower the prefactor.

Figure 2 shows ρ as a function of $T^{-\frac{1}{2}}$ for sample Si-2 with slightly higher mobility for a narrow interval on electron densities close to the metal/insulator transition.⁸ These curves show Coulomb gap behavior for about two orders of magnitude. Perhaps the most impressive part of these data is that all curves presented in Fig. 2 can be made to collapse onto one curve by scaling them along the T axis. The resulting curve is shown in Fig. 3. Note that the curve extrapolates to the value of h/e^2 , the quantum of resistivity, although the curve deviates from the $T^{-\frac{1}{2}}$

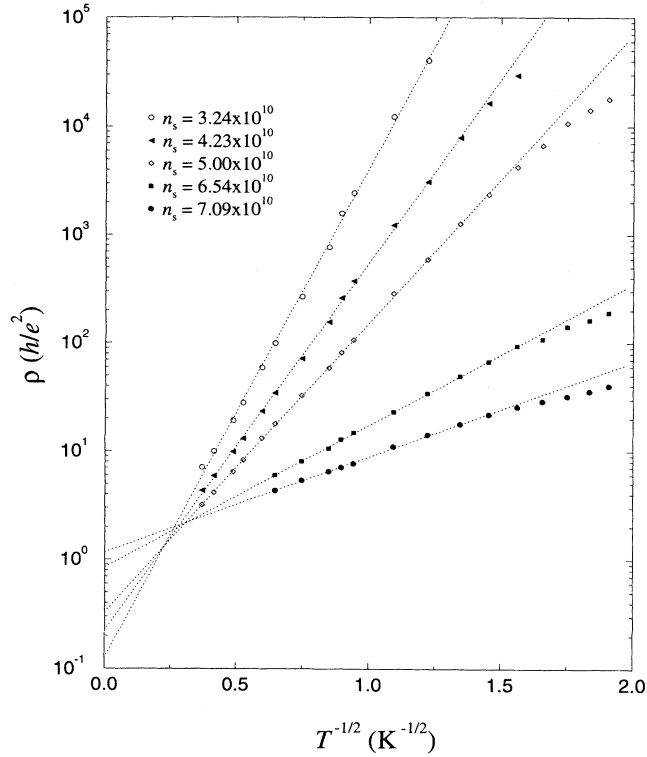


FIG. 1. Resistivity vs $T^{-1/2}$ for sample Si-1 in the insulating regime for various electron densities.

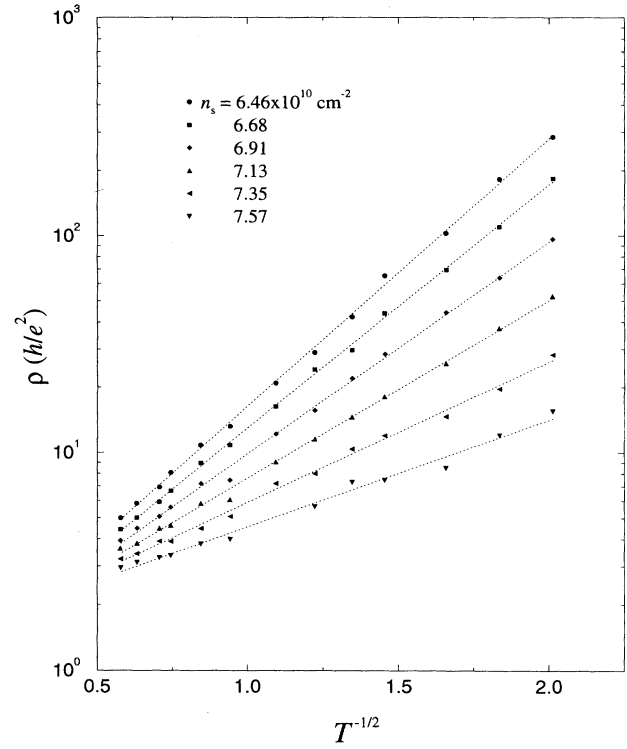


FIG. 2. Resistivity vs $T^{-1/2}$ for sample Si-2 for a narrow interval of n_s near the metal/insulator transition.

behavior when T becomes comparable with T_0 ; however, the data scale even then. Note that in the quantum Hall effect regime, where the Coulomb gap behavior has also been observed,^{9,10} the prefactor σ_0 near the critical point was found to have a form $(e^2/h)f(T/T_0)$ with $f \sim 1$ at $T \sim T_0$. The nature of this universal prefactor is unclear because the theory of phonon-assisted hopping gives much lower value.¹¹ Aleiner, Polyakov, and Shklovskii suggested¹¹ that this discrepancy might be resolved if the hopping was assisted by electron-electron scattering rather than by electron-phonon one.

In the interacting picture,² T_0 in Eq. (1) is equal to

$$T_0 = \frac{Ce^2}{k_B \epsilon \xi}, \quad (2)$$

TABLE I. Values of the best fit for x in Eq. (1) for sample Si-1 and the parameters discussed in the text for various electron densities.

n_s (10^{10} cm^{-2})	x	T_0 (K)	ξ (nm)
3.24	0.544 ± 0.007	108	120
4.23	0.487 ± 0.005	61	200
5.00	0.482 ± 0.002	38	330
6.54	0.481 ± 0.004	9.1	1400
7.09	0.474 ± 0.006	4.1	3000

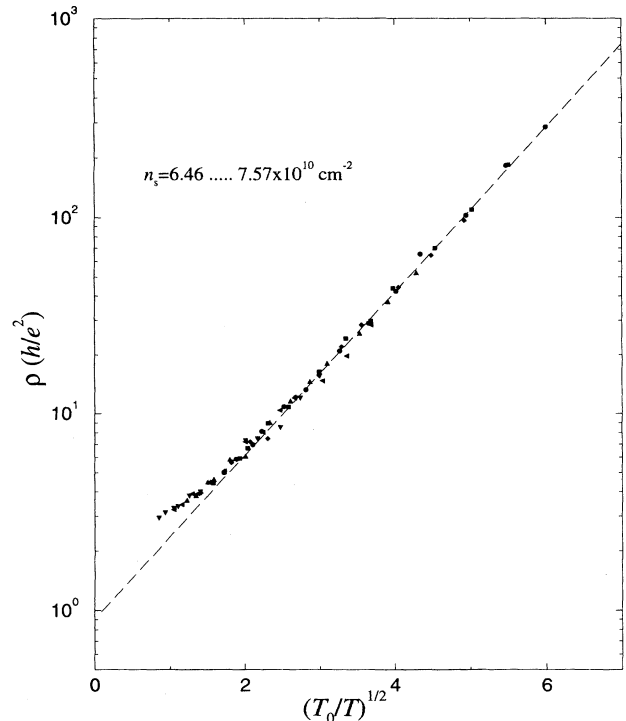


FIG. 3. Resistivity as a function of $(T_0/T)^{1/2}$ for Si-2.

where e is the electron charge, ϵ is the dielectric constant, here given an average value of 8, ξ is the localization length, and C is a constant, which has been found¹³ to be about 6.2. Therefore, it is possible to get the localization length from the slope of $\log \rho$ vs $T^{-\frac{1}{2}}$ curves. Table I gives values of the localization length for representative electron densities. Because the gate is a good metal, the effective distance to the gate d , plays the role of a screening radius.¹² In other words, the Coulomb interaction between charges separated by more than $\sim 2d$ will be effectively screened by the metal gate. Thus, the Coulomb gap should exist only when the hopping length,

$$r_h \sim \frac{1}{4} \xi (T_0/T)^{1/2}, \quad (3)$$

is shorter than $2d$, while in the opposite case, when r_h is a few times d , temperature dependence of resistivity should obey the Mott's law, $\rho(T) \propto \exp(T_0/T)^{1/3}$. If $\xi \ll d$, the crossover between the two regimes should happen at the temperature calculated by Aleiner and Shklovskii¹² to be

$$T \sim 0.013 \frac{e^2 \xi}{k_B \epsilon d^2}. \quad (4)$$

The net effect of the condition for Coulomb gap formation that $2d > \xi$ is to place an upper bound on the n_s where the Coulomb gap can form. However, for the lowest curve in Fig. 1 ($T_0 = 4.1$ K), we see a Coulomb gap behavior down to $T \approx 400$ mK which, according to Eq. (3), corresponds to $r_h \approx 2400$ nm, i.e., six times larger than $2d$. Perhaps the coefficient C in Eq. (2) has a smaller value than 6.2, which we used calculating ξ and r_h from

the data for T_0 ; however, the nature of a smaller C is not known at present. Another reason, which seems unlikely, could be that the dielectric constant ϵ is bigger than the lattice value. It is worth noting that a quantitative agreement between experiment⁵ and theory¹² was achieved after assuming that the dielectric constant is 4.8 times bigger than the lattice value.

The screening of electron-electron interactions by the gate leads to reconciliation of the results of TFHB. They found that when they could fit their data to $T^{-\frac{1}{2}}$, the data fit over some limited temperature range, but the behavior deviated to follow $T^{-\frac{1}{3}}$ as the temperature was lowered. This supports the idea of Aleiner and Shklovskii that the Coulomb gap behavior occurs in some intermediate temperature range, and that as the temperature is lowered, so that the hopping distance becomes $r_h \gg 2d$, the resistivity (conductivity) must eventually follow Mott's law.

In conclusion, the data presented here are consistent with the existence of the Coulomb gap in two dimensions. The resistivity was found to follow the Coulomb gap law, $\rho = \rho_0 \exp[(T_0/T)^{-\frac{1}{2}}]$ with temperature-independent prefactor for four orders of magnitude. In some range of n_s near the metal/insulator transition, the prefactor is close to the quantum of resistivity, h/e^2 , and resistivity scales with temperature. At lower n_s , the prefactor was found to decrease as n_s is decreased.

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⁷ The values of n_s in the low-density limit were obtained by extrapolation of the linear $n_s(V_g)$ dependence, obtained by the Shubnikov-de Haas oscillations at higher n_s , to the low- n_s region.

⁸ A two-dimensional electron gas at $B = 0$ is supposed to be in an insulating state at zero temperature regardless of the electron density. However, there is a recent evidence for a true metal/insulator phase transition in $B = 0$ [S. V. Kravchenko *et al.*, *Phys. Rev. B* **50**, 8039 (1994); **51**, 7038 (1995)].

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