The role of Coulomb interaction in the Mott hopping conductivity of crystalline Si⟨P⟩

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The effect of long-range Coulomb interaction on the hopping conductivity of crystalline Si⟨P⟩ is proved.

The effect of electron-electron interaction on the electrical conductivity of silicon on the insulator side of the metal-insulator transition at low temperatures is currently an unresolved problem.

Efros and Shklovskiĭ[1] have shown that incorporating long-range Coulomb interaction results in the appearance of a parabolic gap in the state density $g(\epsilon)$, with $g(\epsilon_F) = 0$, where ϵ_F is the energy at the Fermi level. In this case the law governing the hopping conductivity with a variable hopping length is

$$\sigma(T) = \sigma(0)\exp\left[-(T_1/T)^x\right], \tag{1}$$

where $T_1 = \beta e^2|\kappa a$, $\beta = 2.7$ (Ref. 2), and $x = 1/2$. Here κ is the dielectric constant, and a is the electron localization length.

This conductivity law applies to crystalline germanium,[3–5] amorphous Si, implanted P near the metal-insulator transition,[6] and also amorphous Ge_xCr_{1-x} films obtained by electron sputtering.[7]

The data[8] on low-temperature conductivity of crystalline Si⟨P⟩ (Ref. 8) found in the literature are, however, interpreted in terms of Mott's model, which ignores the long-range Coulomb interaction. As a result, the state density $g(\epsilon)$ is constant near the Fermi level. In this case, the functional dependence $\sigma(T)$ satisfies (1), but[9] with $x = 1/4$ and $T_1 = 16/g(\epsilon_F)a^3$. At the same time, analysis of the behavior of κ near the metal-insulator transition[10] shows that the long-range Coulomb interaction must be taken into account.

Our purpose in this letter is to determine the conductivity of the crystalline silicon on the insulator side of the metal-insulator transition. The test samples were doped with phosphorus without any special compensation. The charge-carrier density n was determined from the Hall constant, R_H, as $n = 1/R_He$ and was varied around the

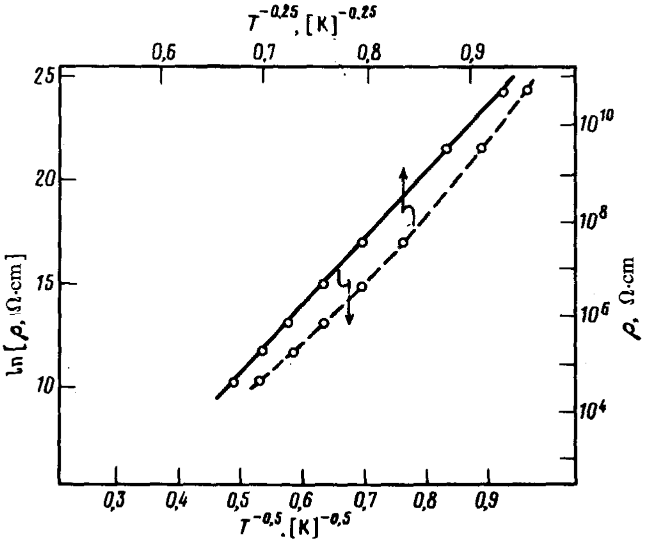

FIG. 1. Temperature dependence of the resistivity of one of the samples studied.

value 2.5×10^{18} cm^{-3} ($\rho^{(4.2\text{ K})}/\rho^{(293\text{ K})}=1.5\times10^{6}$). For the impurity P in Si, the critical density corresponding to the metal-insulator transition[10] is $n_c=3.74\times10^{18}$ cm^{-3}, so that from the ratio $n_c^{1/3}\,a=0.25$ we find $a=17$ Å. The contacts for the samples were fabricated from Au⟨Sb⟩ by alloy technology. To eliminate surface conductivity, the samples were etched in CP-4 for at least 4 min. A further etching (as in Ref. 11) did not change the temperature dependence of the conductivity of the samples. The functional dependence $\sigma(T)$ was measured with a dc current in the resistive region. A digital V7-30 electrometer was used for the measurements. The temperature dependence of the magnetoresistance was also measured.

Figure 1 shows typical $\rho(T)$ curves for the test samples on the scales of $T^{1/2}$ and $T^{1/4}$. We see that over the range of six orders of magnitude of the variation of ρ, the conductivity satisfies (1) with $x=1/2$, rather than $x=1/4$. Analysis of the dependence $\log\rho=f(1/T)$ on the basis of a procedure used in Ref. 12 shows that $x=0.55\pm0.10$. We now determine the characteristic temperature T_1 from (1) and compare it with the temperature observed experimentally. If we assume that the values for a and κ are for an isolated impurity P, i.e., if they are assumed to be 17 and 12 Å, respectively, then the value for T_1 will be 1500 K. Analysis of experimental data yields a value of 1000 K for T_1. It is reasonable to attribute the discrepancy (by a factor of 1.5) between these values to an increase in a and κ, since the samples studied are, in terms of concentration, near the metal-insulator transition.

Additional proof of the necessity of taking into account the electron–electron interaction on the insulator side near the hopping conductivity with a variable hopping length can be inferred from the behavior of the temperature dependence of the magnetoresistance of the samples. Shlimak *et al.*[13] found the theoretical dependence of $\rho(T,H)$ near the hopping conductivity with a variable hopping length in the presence of Coulomb interaction:

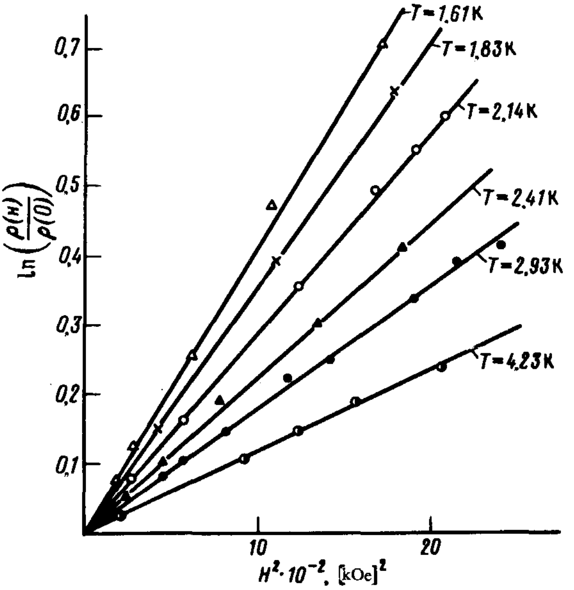

FIG. 2. Magnetoresistance at various temperatures of the sample.

$$\ln \frac{\rho(H)}{\rho(0)} = t \frac{e^2 H^2 a^4}{c^2 \hbar^2} \left(\frac{T_1}{T}\right)^y . \tag{2}$$

Here $t =$ const, and $y = 3/2$. In the absence of Coulomb interaction the exponent is[1] $y = 3/4$. It follows, therefore, that a comparison with the predictions of these models can be made by experimentally determining the value of y in (2).

Figure 2 is a plot of $\ln^{\rho(H)}/\rho(0)$ versus H^2 at various temperatures. We see that the experimental points lie satisfactorily on the straight line which emerges from the coordinate origin. Figure 3 is a plot of $\log[\ln^{\rho(H)}/\rho(0)]$ versus $\log T$ for a constant

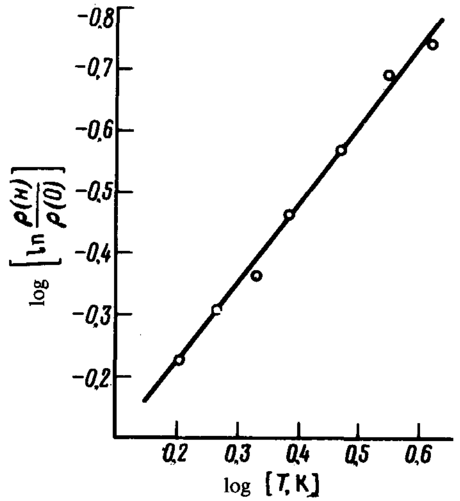

FIG. 3. The plot of $\log[\ln^{\rho(H)}/\rho(0)]$ versus $\log T$ in a constant magnetic field $H^2 = 1500$ kOe^2 for the same sample.

value of H^2. The value of y found from the slope of the line is 1.3. A similar value was also found in germanium.[4] The value obtained by us is closer to 1.5 than to 0.75, which confirms, in our view, that the Shklovskiĭ-Efros law [Eq. (1)] is correct.

The results of our studies show, therefore, that the low-temperature hopping conductivity with a variable hopping length of crystalline silicon satisfies Eq. (1) with $x = 0.5$. Analysis of the behavior of magnetoresistance also shows that long-range Coulomb interaction must be taken into account.

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