Metal-insulator transition in inversion channels of silicon MOS structures

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The electrical conductivity of silicon inversion channels with a high carrier mobility has been studied over the temperature interval $0.5 \leqslant T \leqslant 15$ K. The results of the measurements agree with Mott's idea [N. F. Mott, Phil. Mag. **19**, 835 (1969)] of the existence of a limiting value $\sigma_{\min} \simeq e^2/h$, which divides 2D conductors into insulators and metals.

The metal-insulator transition is a central question in research on disordered conductors. Of particular interest are two-dimensional (2D) media, because of contradictory predictions regarding the nature of the electron states of the carriers in such media. According to Mott,[1] there is a sharp boundary, $\sigma_{\min} \simeq e^2/h$, which divides 2D conductors into insulators and metals. On the other hand, the scaling approach to the Anderson problem[2] leads to the assertion that there is no genuine metallic conductivity at all in the 2D case and that the value of σ decreases monotonically (logarithmically) with increasing size of the conductor (or with decreasing temperature[4]) until, at $\sigma_\square \approx \sigma_{\min}$, there is a "turn" to a sharper decay of this quantity.

A logarithmic decay of a quasimetallic conductivity, amounting to a small correction to $\sigma_\square$, has been observed in many 2D conductors[2] which meet the qualifications for a "dirty metal." In this letter we report a study of electron and hole transport in 2D conductors with the highest charge-carrier mobilities.

In the experiments we use metal-oxide-semiconductor structures (metal-SiO_2-Si) with *n*- and *p*-type conducting channels, which were fabricated at the Institute of Semiconductors, Siberian Branch, Academy of Sciences of the USSR. Each of the structures studied has, in addition to current contacts to the conducting channel ($400 \times 1200\ \mu m^2$), four symmetrically positioned potential contacts ($\sim 20\ \mu$m), separated from each other by a distance $\sim 400\ \mu$m. The charge-carrier density N_s is varied over the range $(0.5\text{–}15) \times 10^{11}$ cm^{-2} by varying the voltage on the "gate," which controls the band curvature at the Si–SiO_2 interface. The thickness of the SiO_2 layer is ~ 1000 Å. The electrical conductivity is measured by a dc potentiometric method. The measurement circuit allows the use of currents from 10^{-5} to 10^{-9} A, and it allows measurements of resistances from 10^2 to 10^7 Ω within an error as low as 10^{-4}. The measurements of $\sigma_\square$ are carried out over the temperature interval $0.5 \leqslant T \leqslant 15$ K under conditions of a linear dependence of the current on the "extracting" voltage. The error of the temperature measurements is 0.005 K.

Figure 1 shows the results of the measurements of $\sigma_\square$ in *n*- and *p*-type inversion channels (for several fixed values of N_s) versus the reciprocal temperature. At low

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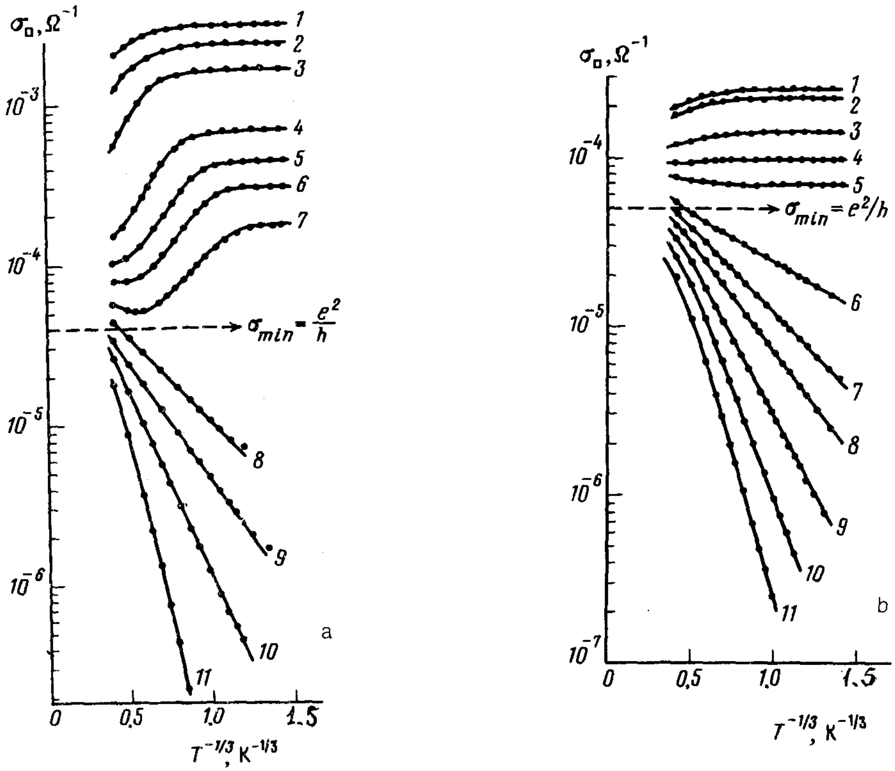

FIG. 1. The electrical conductivity $\sigma_\square$ versus the reciprocal temperature in silicon inversion channels with various carrier densities N_s (in units of 10^{11} cm^{-2}). a: Electrons. 1—10; 2—6; 3—3.8; 4—2.1; 5—1.6; 6—1.25; 7—1.05; 8–11—less than 1. b: Holes. 1—12; 2—8; 3—6; 4—5; 5—4.5; 6–11—less than 4.

carrier densities ($N_s \lesssim N_c^{(1)} \cong 1 \times 10^{11}$ cm^{-2} for electrons in n-type channels and $N_s \lesssim N_c^{(2)} = 3.5 \times 10^{11}$ cm^{-2} for holes in p-channels), the conductivity of the MOS structures falls off with decreasing temperature in accordance with the exponential law

$$\sigma = \sigma_0 \exp[-(T_0/T)^{1/3}], \qquad (1)$$

where T_0 is a fixed temperature. This expression, known as "Mott's law,"[6] is typical of a 2D hopping conductivity with a variable hopping length under conditions such that the carrier state density near the Fermi level does not depend on the carrier energy. This situation prevails in inversion layers because the metal gate in the MOS structures lies near the conducting channel, causing an effective screening[7] of the Coulomb interaction.[8]

At electron (or hole) densities slightly above $N_c^{(1)}$ (or $N_c^{(2)}$) the conductivity $\sigma_\square$ in the inversion channels of either type increases significantly, and its T dependence is no longer described by (1). These changes in the nature of the electronic processes in the region $\sigma_\square > (e^2/h)$ are manifested particularly vividly in the n-type channels. As can be seen from Fig. 1a, $\sigma_\Box$ increases substantially1) in n-type channels with a high conductivity and decreases in poorly conducting channels. Even in those cases in which the samples have nearly the same parameter values (we are talking about parameters such as the depth of the potential well and the extent to which the levels are filled by electrons), the curves of $\sigma(T)$ take off in different directions, as can be seen from curves 7 and 8 in Fig. 1a, if the initial values of the conductivity $\sigma_\Box$ are just a bit higher (or lower) than the critical value e^2/h.

At the very lowest temperatures, something in the way of a "gap" arises between the values of $\sigma_\Box$ in these samples: The conductivity in some of them remains high, while that in others becomes vanishingly low at low T. The role played by the value of e^2/h, as the boundary between these two regions of values, can be seen clearly from the data in Fig. 2, which compares the results of measurements of $\sigma_\Box$ of two temperatures: one quite low ($T_1 = 0.5$ K) and one ten times higher ($T_2 = 5$ K).

It can be seen from Fig. 2 that over the entire conductivity region, in which the condition $\sigma_\Box < (e^2/h)$ holds, the function $A = \sigma(0.5\ \text{K})/\sigma(5\ \text{K})$ is substantially less than unity. This result means that the low-temperature conductivity $\sigma(0.5\ \text{K})$ constitutes only a small fraction of the total conductivity of the sample at high T. This

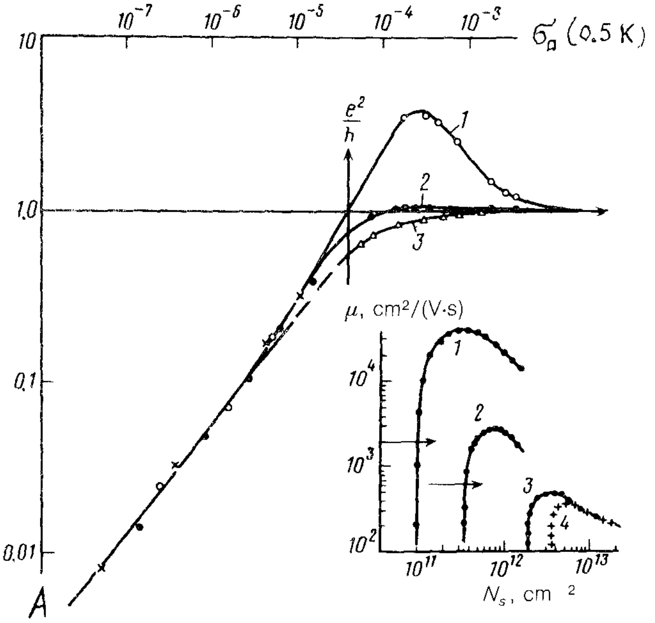

FIG. 2. The quantity $A = \sigma(0.5\ \text{K})/\sigma(5\ \text{K})$ versus the conductivity $\sigma_\Box$ at $T = 0.5$ K. 1—In an n-type inversion channel; 2—in a p-type inversion channel; 3—Ge bicrystals, according to the data of Ref. 12; $\times$—in an n-type inversion channel, according to the data of Ref. 11. The arrows show the values of μ corresponding to the condition $\mu_{\min} = \sigma_{\min}/eN_c$. Inset: the mobility μ (at $T = 1$ K) versus the carrier density in 2D systems. 1—Electrons (in an n-type inversion channel); 2—holes (in a p-type inversion channel); 3—holes (near cleaved surfaces of Ge, according to the data of Ref. 12); 4—holes (in Ge bicrystals, according to the data of Ref. 12).

behavior is typical of a thermally activated conductivity for which the mechanism hops between localized states. This region of $\sigma_\square$ corresponds to the conditions of a "strong" localization; it has universality features and is described by a common curve for all of the samples that we studied, as can be seen from Fig. 2 (this comment also applies to the other samples which have been reported in the literature; see Ref. 11, for example). It can confidently be asserted that in the region $\sigma_\square < (e^2/h)$ the behavior of the 2D systems which we have studied agrees well with the predictions of the scaling theory.[3]

At conductivities $\sigma_\square > (e^2/h)$ we see a different situation. As can be seen from Fig. 2, the function $A = \sigma(0.5\ \mathrm{K})/\sigma(5\ \mathrm{K})$ is not a universal function under these conditions. It apparently depends on the degree of disorder in the 2D system. This possibility is suggested by a comparison of the data found for the MOS structures (curves 1 and 2 in Fig. 2) with data obtained previously[12] for Ge bicrystals, shown by curve 3 in Fig. 2.

The electrical conductivities of various 2D systems reach identically high values $\sigma_\square$, but this quantity does not by itself exhaust all the properties of 2D systems in the region of a quasimetallic conductivity. As can be seen from the inset in Fig. 2, other parameters are also important, e.g., the "peak" value of the mobility and the "minimum" density N_c, near the localization threshold. The upper energy level of the localized states is directly related to the latter quantity: $E_c \sim (\pi\hbar^2/m)\cdot N_c \simeq 8\times 10^{-11} N_c$. If we also note that the localization boundary E_c shifts up the energy scale with increasing degree of disorder, we easily see that Ge bicrystals (with $E_c \simeq 300$ K) constitute the least ordered system (among those considered). The p-type channels of the MOS structures (with $E_c \simeq 30$ K) represent a system with an intermediate degree of disorder, while the n-type inversion channels (with $E_c \simeq 8$ K) may be thought of as a fairly ordered 2D system.

On the basis of these features of the systems (looking at Fig. 2) one might argue that in a disordered system (such as Ge bicrystals) the 2D quasimetallic conductivity decreases slightly with decreasing temperature, in agreement with the ideas of a "weak" localization.[3] In more-ordered systems (such as the n- and p-type channels of MOS structures), however, the conductivity does not decrease with decreasing temperature in the region $\sigma_\square > (e^2/h)$ (in fact, it increases in a certain region). This behavior of the 2D systems supports Mott's idea that a 2D metal exists and that the quantity $\sigma_{\min} \simeq (e^2/h)$ plays the role of a boundary dividing two-dimensional conductors into insulators and metals.

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[1)] The increase in $\sigma_\square$ with decreasing T was studied previously in Refs. 9 and 10.

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