Conductivity increase of a 2*D* electron gas with decreasing temperature in Si (100) metal-insulator-semiconductor structures

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A linear temperature dependence has been found for the conductivity σ of a 2*D* electron gas on a Si (100) surface at liquid-helium temperatures ($1.3\ \mathrm{K} \leqslant T \leqslant 4.2\ \mathrm{K}$): $\sigma(N_S, T) = \sigma_0(N_S) - \alpha T$. Under these particular experimental conditions the coefficient α depends only weakly on the electron density (N_S) in the inversion layer. At $N_S \approx 2\times 10^{11}\ \mathrm{cm}^{-2}$ the conductivity increases severalfold as the temperature is reduced from 4.2 to 1.3 K.

The temperature dependence of the conductivity of a 2*D* electron gas in a metal-insulator-semiconductor structure at low temperatures may be determined by several factors[1]: 1) localization effects, 2) scattering of electrons by phonons, and 3) a temperature dependence of the screening of charged static defects.[2,3] Strong-localization effects cause an exponential decrease in the conductivity with decreasing temperature and are seen at $\sigma \lesssim 10^{-5}$ S. We will not discuss this range of conductivities in the present letter. At higher conductivities, the weak localization of electrons gives rise to logarithmic corrections to the conductivity, $\Delta\sigma(T) \sim (e^2/2\pi^2\hbar) \ln T/T_0$, with a typical value $e^2/2\pi^2\hbar \approx 1.2\times 10^{-5}$ S. Two other mechanisms lead to an increase in the conductivity with decreasing temperature. It should be noted that there has been essentially no study of how the temperature dependence of the screening affects the conductivity of a

2D electron gas. All that we have on this topic is a single theoretical study,[2] based on numerical calculations.

Extensive measurements[1] carried out with samples with a comparatively low carrier mobility, $\mu < 10^4$ cm^2/(V s), have shown that the conductivity of such samples decreases with decreasing temperature in the liquid helium range, because of electron localization effects. More recent studies,[3,4] however, have revealed a decrease in the resistance with decreasing temperature in samples with a higher mobility.

In the experiments reported here we measured the temperature dependence of the conductivity of electron inversion channels on four silicon field-effect transistors. Two of the samples have a Corbino configuration (the field electrode is a ring); the maximum carrier mobility in these samples is $\mu_{\max} \approx 12\,000$ cm^2/(V s) at $T = 4.2$ K. Samples 3 and 4 have a long ($L = 2.5$ mm), narrow ($W = 0.28$ mm) field electrode and have potential contacts, so that the Hall constant can be measured. The carrier mobility at $N_S = 6\times 10^{11}$ cm^{-2} and $T = 4.2$ K in sample 3 is 21 000 cm^2/(V s), while that of sample 4 is 25 000 cm^2/(V s). All the samples studied exhibit a conductivity increase as the temperature is lowered from 4.2 to 1.3 K. Quantitative results were obtained for samples 3 and 4 in a four-point measurement arrangement. The temperature dependence is measured at a current frequency of 21 Hz and at an electric field $E < 10^{-2}$ V/cm in the sample. To determine the charge carrier density in the layer we measure the Hall constant R_H in a magnetic field $H = 160$ Oe at 4.2 and 1.3 K. These results show (Fig. 1) that the electron density $N_S = (ecR_H)^{-1}$ is independent of the temperature within the accuracy of these measurements.

It is easy to see from the experimental results in Figs. 2 and 3 that the conductivity can be described by $\sigma(N_S,T) = \sigma_0(N_S) - \alpha T$ over a significant interval of carrier densities (2.5×10^{11} cm$^{-2} \leqslant N_S \leqslant 7\times 10^{11}$ cm^{-2} in Fig. 2). For sample 3 we find a coefficient $\alpha = 1.1\times 10^{-4}$ S/deg, and for sample 4 we find $\alpha = 1.5\times 10^{-4}$ S/deg. In a

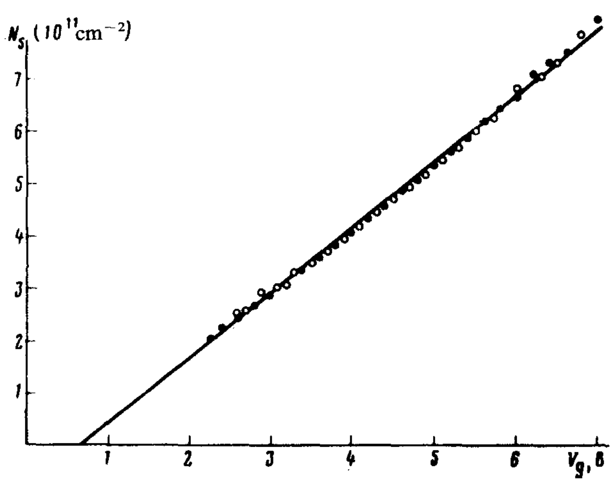

FIG. 1. Electron density in the inversion layer, N_S, as a function of the gate voltage V_g, according to calculations from the measured Hall constant: $N_S = (ecR_H)^{-1}$. Open circles—$T = 1.3$ K; filled circles—$T = 4.2$ K.

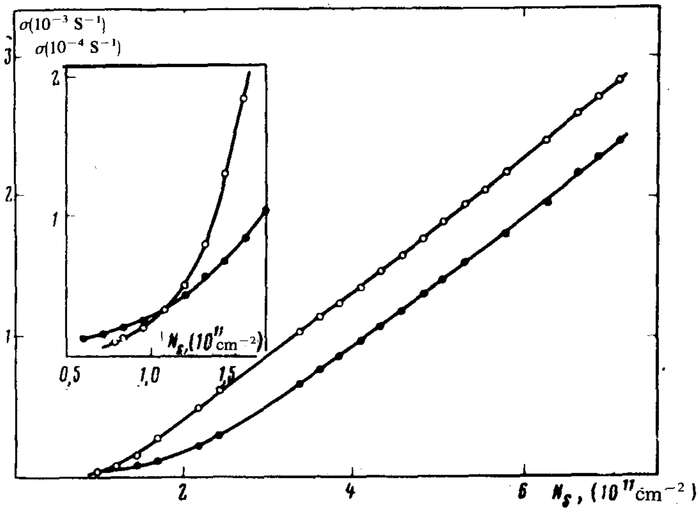

FIG. 2. The conductivity σ versus the electron density in an inversion layer N_S for sample 4. Open circles—$T=1.3$ K; filled circles—$T=4.2$ K.

special experiment with sample 4 we verified that this temperature dependence of the conductivity prevails down to 0.4 K. The coefficient α generally increases slightly with increasing N_S, and this behavior can be seen in Fig. 2 as a slight deviation from a parallel course of the solid curves; the $\alpha(N_S)$ dependence is weak, however. At $N_S < 2.5\times 10^{11}$ cm^{-2} in sample 4 the temperature-dependent part of the conductivity, $\Delta\sigma(T)$, falls off rapidly, and at $N_S \lesssim 1\times 10^{11}$ cm^{-2} strong-localization effects become

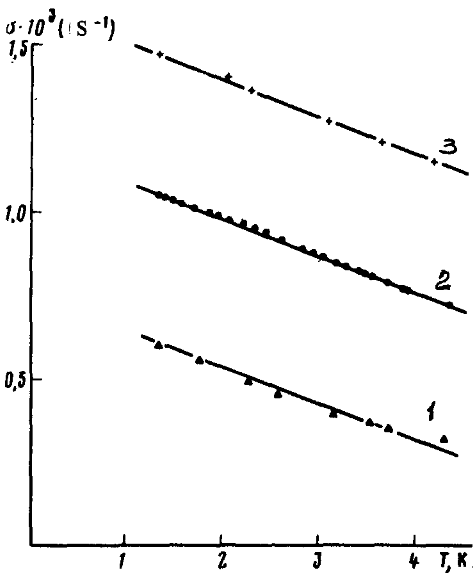

FIG. 3. Temperature dependence of the conductivity for sample 3. 1—$N_S=2.7\times 10^{11}$ cm^{-2}; 2—$N_S=3.9\times 10^{11}$ cm^{-2}; 3—$N_S=5.1\times 10^{11}$ cm^{-2}. Lines 1 and 3 are drawn parallel to line 2.

dominant (see the inset in Fig. 2). The decrease in $\Delta\sigma(T)$ in the interval 1×10^{11} $\text{cm}^{-2} < N_S < 2.5\times10^{11}$ cm^{-2} may be due to either localization effects or a possible dependence of $\Delta\sigma(T)$ on the mobility μ and a sharp decrease in the mobility in this region.

To evaluate the effect of the scattering of electrons by phonons on the temperature dependence of the conductivity, we measured the nonlinearities in the I-V characteristics of the inversion channel. Significant deviations from linearity arise in electric fields $E \gtrsim 10^{-1}$ V/cm. Using the $\sigma(T)$ dependence measured in the linear regime as a calibration curve, we determined the temperature of electron system, T_e, as a function of the power dissipated in the sample, $P = \sigma E^2$. At the power levels used, the electron system is heated,[5] but the lattice temperature T_0 remains essentially constant. We can easily determine the energy relaxation time τ_ϵ by equating the power introduced into the electron system to the rate at which energy is removed: $P = C_e(T_e - T_0)/\tau_\epsilon$ (C_e is the electron specific heat per unit area of the sample). For sample 3 with $N_S = 3.9\times10^{11}$ cm^{-2} and at $T = 1.3$ K we have $\tau_\epsilon = 3\times10^{-8}$ s. In our case the thermal-phonon momentum is on the order of the Fermi electron momentum, so that the momentum relaxation time of the electron system is on the order of the energy relaxation time. The observed temperature dependence of the conductivity cannot be explained in terms of scattering of electrons by phonons, since this explanation would require a momentum relaxation time three or four orders of magnitude shorter than the measured time τ_ϵ. Furthermore, the logarithmic quantum corrections to the conductivity play no role of any sort in our case, as is clear from the linear temperature dependence of the conductivity and the circumstance that the change in the conductivity is roughly 30 times the typical value of the quantum corrections.

Stern[2] took the temperature dependence of screening effects into account and carried out numerical calculations which predict a linear increase in the resistance (R) of a $2D$ electron gas with the temperature. When only scattering by Coulomb centers is taken into account, the coefficient of the term linear in the temperature turns out to be proportional to $N_S^{-2.9}$. Since these calculations were carried out for specific values of the experimental parameters—values greatly different from those in the present experiments—we cannot make a quantitative comparison with our own results. All that we can do is compare the functional dependence of the resistance on the temperature and on the electron density N_S. In our experiments the temperature dependence of the resistance is nonlinear, while the conductivity changes linearly.[1)] The $N_S^{-2.9}$ law gives a satisfactory description of the measured dependence of the quantity R(4.2 K) $-$ R(1.3 K) on N_S over a rather broad interval of electron densities (2.5×10^{-11} $\text{cm}^{-2} \leqslant N_S \leqslant 7\times10^{11}$ cm^{-2} for sample 4).

The observed temperature dependence of the conductivity is actually related to a change in the screening, since this effect gives a qualitatively correct description of all our results. The magnitude of the effect can be explained on the basis that the electron gas is not strongly degenerate. In fact, the Fermi temperature for electrons on the silicon (100) surface is $T_F = \pi\hbar^2 N_S/2m^*k = 7.3[N_S(\text{cm}^{-2})/10^{11}](\text{K})$. Here $m^* = 0.19m_e$ is the effective mass of the electron, and k is Boltzmann's constant. The appearance of corrections to the mobility linear in T/T_F could therefore explain the observed effect, both its functional dependences and its order of magnitude:

$$\sigma = N_S e\mu\left(1 - \frac{T}{T_F}\right) = N_S e\mu - \left(\frac{e^2}{2\pi^2\hbar}\right)\frac{4\pi kT\tau}{\hbar},$$

where τ is the momentum relaxation time at $T=0$, and $\mu = e\tau/m^*$. Under our experimental conditions we have $4\pi kT\tau/\hbar \approx 18$ at $T=4$ K. Whether the temperature-dependent part of the conductivity is proportional to the mobility remains an open question, however, requiring further experiments.

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[1)]A nonlinear temperature dependence of the resistance was also noted in Refs. 3 and 4.

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