Electron delocalization in the 2D electron gas at a silicon (100) surface

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The number of localized electrons, N_l, has been studied experimentally as a function of the total concentration N_s in metal-insulator-semiconductor structures on the (100) face of silicon. The number N_l is found to decrease with increasing N_s, because of an improved screening of the potential relief by free electrons.

In an ideal 2D electron system the state density $D(E)$ would not depend on the energy. In a real system, in contrast, there are always fluctuations of the potential which result in a localization of electrons with energies below some value E_c (Ref. 1). In this case the state density has a tail which falls off exponentially at low energies

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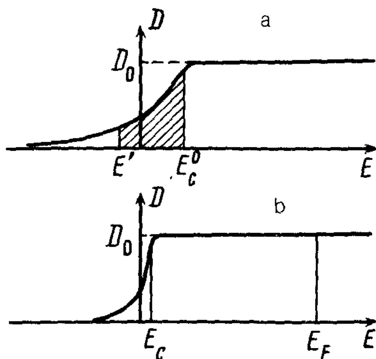

FIG. 1. Schematic diagram of the energy dependence of the state density. a—The Fermi level is the region of localized states; b—it is in the region of delocalized states. The hatching shows the region of delocalized electrons.

($E < E_c$; Fig. 1). The existence of a tail in the state density has been verified experimentally in measurements of the activation energy ($E_c - E_F$) as a function of the concentration (N_s) of 2D electrons on low densities[2,3] ($E_F < E_c$) and in optical experiments.[4] At comparatively high electron concentrations ($E_F > E_c$), no evidence of any sort for a tail on the state density has so far been found.[5]

In the present letter we report an experimental study of the number of localized electrons, $N_l = \int_{-\infty}^{E_c} D(E)dE$, as a function of the concentration N_s in the 2D electron gas near the (100) surface of silicon at $E_F > E_c$. The results show that with increasing concentration of the 2D electrons, the number of localized electrons falls off, and the $D(E)$ curve approaches the shape we would expect for an ideal system.

We measured the magnetotransport characteristics of samples with a high mobility μ at magnetic fields $\mu H \lesssim 1$. We studied the dependence $\sigma_{xx}(H)$ in a sample in the Corbino geometry. Using the Drude formula

$$\sigma_{xx} = \frac{\sigma_0}{1 + (\mu H)^2} , \qquad (1)$$

whose applicability to our sample was verified over a broad range of magnetic fields and concentrations, we found $\mu(N_s)$. Assuming $\sigma_0 = (N_s - N_l)e\mu$, we then determined $N_l(N_s)$. The total electron concentration is found independently, from measurements of the capacitance of the structure and the threshold voltage V_T, determined from the positions of the minima of Shubnikov-de Haas oscillations in magnetic fields 5–10 T. The dependence $N_l(N_s)$ found in this manner is shown in Fig. 2 for concentrations corresponding to $\sigma > 10\sigma_{\min}$.

Measurements in the Corbino geometry are carried out by a two-contact method, so that there is always the danger of finding an effect similar to that described above but resulting from a resistance of the contacts. In our case, the resistance of the contacts was apparently negligible, since the experimental curve of $\sigma_{xx}(H)$ is described well by expression (1). We also made an attempt to carry out similar measurements in a sample in the Corbino geometry, whose conductivity was measured by a capacitance-coupling technique.[6] We were not able to measure an $N_l(N_s)$ curve for this sample, since the accuracy of the method for measuring σ_{xx} falls off with increas-

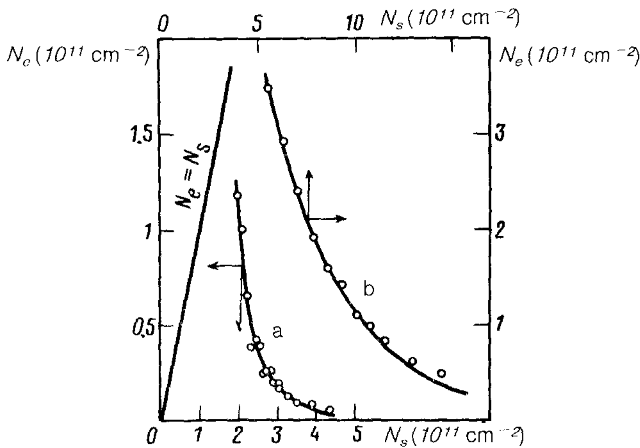

FIG. 2. Number of localized electrons, N_l, versus the total number of electrons in the inversion layer, N_s. a—Sample in the Corbino geometry [the maximum mobility $\mu_{\max}=20\,400$ cm^2/(V·s) is reached at $N_s=8.6\times10^{11}$ cm^{-2}, $T=1.46$ K, and $V_{SB}=0$]; b—Hall transistor [$\mu_{\max}=21\,000$ cm^2/(V·s) at $N_s=4.5\times10^{11}$ cm^{-2}, $T=1.42$ K, and $V_{SB}=0$].

ing conductivity. However, again in the case of this sample, the electron concentration calculated from the conductivity σ_0 turned out to be lower than N_s at $\sigma\gtrsim10\sigma_{\min}$, and the difference in concentrations was clearly greater than the experimental error.

The resistance of the contacts plays no role in measurements by a four-contact method. We used a four-contact bridge arrangement to carry out measurements with Hall transistors.[7] The results on $N_s-N_l=H(ec\rho_{xy})^{-1}$ as a function of the transistor gate voltage from these measurements are shown in Fig. 3; the corresponding curve for $N_l(N_s)$ is shown in Fig. 2.

Figure 3 also shows the positions of the minima of the quantum oscillations of ρ_{xx}

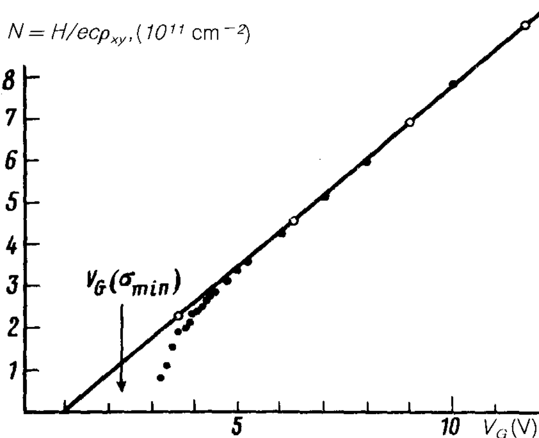

FIG. 3. Filled circles—measurements of $N=H/ec\rho_{xy}$ as a function of the gate voltage in magnetic fields $\mu H\lesssim1$; open circles—concentrations determined from the positions of the minima of the quantum oscillations in a magnetic field $H=4.77$ at $T=1.42$ K.

in a magnetic field $H=4.77$ T. We see from this figure that the positions of the minima of the Shubnikov-de Haas oscillations are determined by the total electron concentration N_s. We obtained a similar result for a sample in the Corbino geometry.

The decrease in the number of localized electrons with increasing N_s results from an improvement of the screening. The effective screening parameter $q_s(q)$ is constant at low temperatures, with $q \leqslant 2k_F$, and it falls off sharply at [8] $q>2k_F$, so that wells with different scale dimensions a are screened at different concentrations of free electrons. Let us assume that the width distribution of the wells is described by[5]

$$a = a_0\left(\frac{E_c^0}{E_c^0 - E}\right)^s \tag{1}$$

[the origin on the energy scale is chosen in such a way that we have $N_l = \int_{-\infty}^{E_c} D(E)dE = D_0 E_c, D_0 = g_v m/\pi\hbar^2$] and that the state density is $D = D_0 \exp((E-E_c)/E_c)$ if $E<E_c$. Upon the appearance of free electrons with a wave vector k_F, all the wells with $a > k_F^{-1}$ are screened. Electrons with energies $E' < E < E_c(k_F=0) = E_c^0$ become delocalized, and the energy E_c becomes dependent on the electron concentration (Fig. 1). We then have

$$E_F - E_c(N_s) = \frac{\hbar^2}{2ma_0^2}\left(\frac{E_c^0 - E'}{E_c^0}\right)^{2s}, \tag{2}$$

$$D_0(E_c^0 - E_c) = D_0 \int_{E'}^{E_c^0} dE \exp\left(\frac{E - E_c^0}{E_c^0}\right). \tag{3}$$

The first of these relations determines the Fermi energy E_F, while the second corresponds to the case in which the number of delocalized electrons is equal to the change in the number of free electrons. Eliminating E' from (2) and (3), we find

$$N_l(N_s) = D_0 E_c(N_s) = D_0 E_c^0 \exp\left[-\{\pi a_0^2 (N_s - N_l)\}^{1/2s}\right]. \tag{4}$$

For our samples, we find the best agreement with the experimental data with the values $s=0.35 \pm 0.05$ and $a_0 = 66$ Å for a sample in the Corbino geometry or with $a_0 = 130$ Å for the Hall transistor (solid lines in Fig. 2). The values found for s by Pollitt[3] range from 1 to 0.75, depending on the difference $E - E_c$. The improvement in the screening by free electrons thus makes it possible to explain the observed dependence $N_l(N_s)$ with completely reasonable values of the parameters s and a_0.

The difference between the mobilities μ and μ_H, which can be seen in Fig. 1 of Ref. 9, and which disappears with increasing N_s, can apparently be explained in terms of the presence of localized electrons. The temperature dependence of ρ_{xy} found in the 2D electron gas on [10] Si(111) is probably also due to an effect of this sort, since the corrections to ρ_{xy} for the electron-electron interaction in the dirty limit[11] vanish in the limit $k_F q_S(0) \to 0$. [The parameter $k_F q_S(0)$ in Ref. 10 was ~0.1, and even smaller in our own case.]

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