# Filling of second quantum-size subband of a 2D hole gas at a Si(110) surface

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A change in the state density of a gas of 2D carriers upon the filling of the next quantum-size subband has been observed directly by the method of capacitance spectroscopy. The carrier $g$-factor is estimated on the basis of the Shubnikov-de Haas oscillations. A "pinning" of the bottom of a subband near the Fermi level has been observed.

The energy spectrum of the system of charge carriers near the surface of the semiconductors in metal-insulator-semiconductor (MIS) structures and at heterojunctions consists of a set of subbands which correspond to a size quantization in the direction perpendicular to the surface of the semiconductor and to free motion along the surface.[1] Different numbers of subbands may be filled, depending on the type of structure and the carrier density. Essentially the only method which has been available for determining the beginning of the filling of one subband or other has been the method based on measurements of the Shubnikov-de Haas oscillations.

We have now demonstrated that capacitance spectroscopy can be used for this purpose.[2] This method is also applicable in a case in which the carriers have a low mobility, and oscillations are not observed. The method of capacitance spectroscopy and the quantum-oscillation method have been used to study the filling of the second quantum-size subband in a 2D hole gas near a Si(110) surface.[2)] We have classifed the oscillations, measured the ratio of the thermodynamic state densities in the first and second subbands, and observed a "pinning" of the bottom of the second subband near the Fermi level.

The method of capacitance spectroscopy consists of precise measurements of the capacitance of the system consisting of the 2D gas plus the insulator plus the metal gate. In this case the measured capacitance $C$ depends on the distribution of charge carriers in the semiconductor in the direction perpendicular to its surface, and through the contact potential difference it also depends on the thermodynamic state density[2] $D = dn_S/d\mu$:

$$SC^{-1} = 4\pi d/\epsilon_d + 4\pi\gamma z_0/\epsilon_S + 1/e^2D.$$

Here $d$ is the thickness of the insulating layer, $\epsilon_d$ and $\epsilon_S$ are the dielectric constants of the insulator and the semiconductor, respectively; $z_0$ is the position of the maximum of the carrier wave function, reckoned from the surface of the semiconductor; $\gamma = 0.5$–$0.7$ is a numerical factor, $n_S$ is the surface density of the 2D carriers, $\mu$ is their chemical potential, and $S$ is the area of the MIS structure. The second and third terms on the right side of this expression are usually small corrections to the first. As the next subband begins to be filled, the one-particle state density in the 2D system increases sharply (discontinuously in the ideal case). Here we can also expect sharp changes in the thermodynamic state density and thus the capacitance $C$.

Measurements carried out with two field-effect transistors with a hole gas near the Si(110) surface yielded identical results. The size of the transistor channel was $400\times1200$ $\mu m^2$; the distance between the potential contacts was 400 $\mu$m; and the thickness of the layer of the $SiO_2$ insulator was 1070 Å. In the capacitance and resistance measurements we used bridge circuits which operated at an ac frequency of 21 Hz and which provided a sensitivity and stability of about $2\times10^{-5}$ of the measured quantities. The charge-carrier density $n_S$ was determined during the filling of the lower subband from the period of the Shubnikov-de Haas oscillations in the inverse magnetic field $H^{-1}$. The linear dependence of $n_S$ on the voltage on the transistor gate, $V_g$, which we found was extrapolated into the density region corresponding to the filling of two subbands.

Figure 1 shows the change $\Delta C$ in the gate-channel capacitance of the field-effect transistor versus the hole density $n_S$, along with records of the Shubnikov-de Haas oscillations. The compensated capacitance is $C = 160$ pF. The apparent reason for the

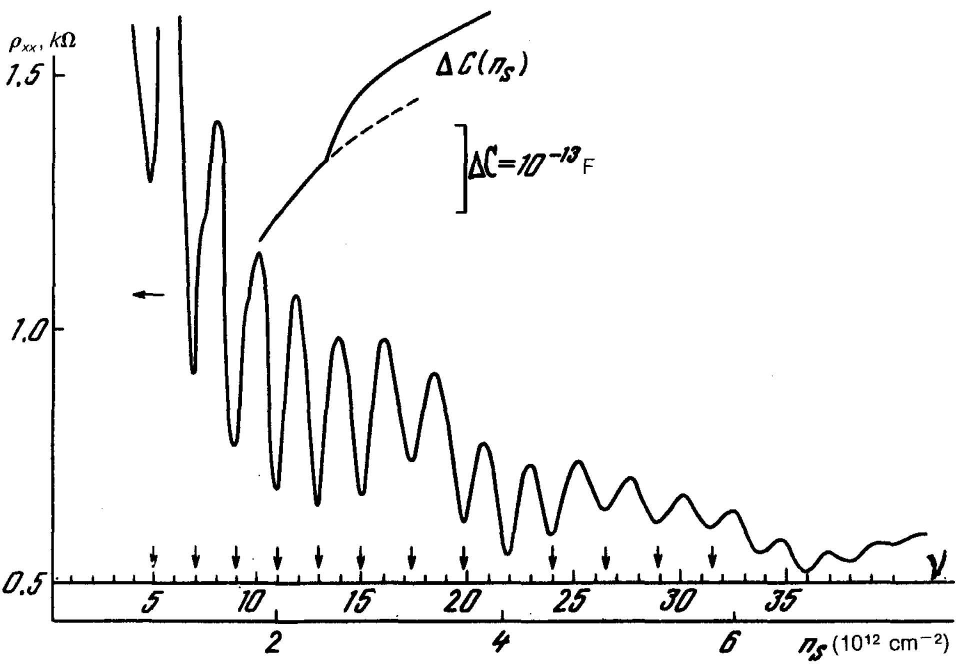


FIG. 1. The resistance ($\rho_{xx}$) of the hole channel in a field-effect transistor in a magnetic field $H = 7.7$ T versus the carrier density $n_S$ and the corresponding filling factors $\nu$. The $\Delta C(n_S)$ curve is a plot of the change in the capacitance of the transistor versus $n_S$ at $H = 0$. $T = 1.4$ K; sample No. 1. Where necessary, the positions of the minima of the high-frequency oscillations have been marked by arrows at the abscissa.

smooth dependence $\Delta C(n_S)$ is a change in the value of $z_0$. Specifically, if we work from the expressions given in Ref. 1 for $z_0$ for the case of the filling of a single subband and for an effective hole mass $m_1^* = 0.36m_e$ (more on this below), we would expect the change in the capacitance upon a change in the carrier density $n_S$ from $2\times10^{12}$ $cm^{-2}$ to $3\times10^{12}$ $cm^{-2}$ to be about $1\times10^{-13}$ F, i.e., very close to the change which is observed. We attribute the more rapid increase in the capacitance in the density interval $2.5\times10^{12}\ cm^{-2} \lesssim n_S \lesssim 2.8\times10^{12}\ cm^{-2}$ to the beginning of the filling of the second quantum-size subband. The filling of the second subband is clearly demonstrated by the pattern of Shubnikov-de Haas oscillations, whose minima correspond in our case to the filling of an integer number of magnetic-quantization levels in one of the subbands. While at $n_S < 2.4\times10^{12}\ cm^{-2}$ ($\nu < \nu_0 = 13$) the minima are equidistant along the $n_S$ scale and correspond to odd integers $\nu = n_S/n_0$ ($n_0 = eH/hc$ is the degeneracy of the Landau level), at $\nu > \nu_0$ the minima are no longer equidistant, and the envelope of the minima oscillates. It is natural to link these long-period oscillations with a filling of the magnetic-quantization levels in a second subband. The first minimum of the envelope is observed at $\nu \approx \nu_1 = 22$, and the second at $\nu \approx \nu_2 = 36$. In the interval $\nu_0 < \nu \leqslant \nu_1$ we observe four minima of short-period oscillations; i.e., eight levels are filled in the lower subband. Since the change in the density in this interval corresponds to the filling of $\nu_1 - \nu_0 = 9$ levels, only a single level is filled in the second subband. Analogously, we find that in the interval $\nu_1 < \nu \leqslant \nu_2$ respectively 12 and two levels are filled. Since the degeneracy of level $n_0$ does not depend on the energy spectrum, the ratio of the numbers of filling levels in the different subbands gives us the ratio of the thermodynamic state densities in them. Taking an average over the interval $\nu_0 \leqslant \nu \leqslant \nu_2$, we find $D_1/D_2 \approx 6.7$. Our measurements of the cyclotron masses of the carriers in the first and second subbands, based on the temperature dependence of the oscillation amplitude, yielded respective values $m_1^* = 0.36m_e$ and $m_2^* = 0.33m_e$ (the values $m_1^* = 0.35m_e$ and $m_2^* = 0.32m_e$ were reported in Ref. 3). This result means that the energy splittings of the magnetic-quantization levels in the first and second subbands are not greatly different. The large value $D_1/D_2 \gg 1$in this case could be explained only in terms of a "pinning" of the bottom of the second subband near the Fermi level—an effect which has been predicted theoretically (see Ref. 1).

It is not possible to determine $D_1$ and $D_2$ from capacitance measurements alone. If we replace $D_1$ in the expression by the one-particle state density $N_1 = m_1^*/\pi\hbar^2$ and the experimental change in the capacitance at the beginning of the filling of the second subband, $\Delta C \approx 5\times10^{-14}$ F, we find $D_1/D_2 = N_1/D_2 \approx 4$. In our opinion, the agreement of the scale values of the ratio $D_1/D_2$ found from the capacitance and oscillation measurements is evidence that the observed feature in the capacitance is being interpreted qualitatively correctly. On the other hand, the difference between these results apparently indicates that it is not correct to use the one-particle state density $N_1$ in place of the thermodynamic density $D_1$, i.e., that it is necessary to consider the motion of the bottom of the lower size-effect subband.

Minima in the oscillations from carriers in the second subband are observed as they fill an odd number (one or three) of magnetic-quantization levels. This result indicates that in this system the spin splitting exceeds half the cyclotron splitting, i.e., that we have a $g$-factor $g > 3$ ($m_2^* = 0.33m_e$). The expected effect of the spin-orbit coupling on the spectrum (see Ref. 4) is inconsequential at small filling factors.

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[2)]The fact that a second subband is filled in this system was established in Ref. 3 in a study of quantum oscillations. The cyclotron mass of the 2D holes was also measured there.

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