

Structure of two-dimensional subbands on (111) Ge in MIS structures

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The Shubnikov–de Haas oscillations in the curves $(\partial\sigma_{xx}/\partial V_g)(H)$ for (111) Ge in MIS structures were measured up to electron densities of $N_s = 5.4 \times 10^{12} \text{ cm}^{-2}$ in the two-dimensional layer. It is shown that the curves of the electron-density dependence of the positions of the peaks in the oscillations with respect to the magnetic field have a break at $N_s = 2.8 \pm 0.4 \times 10^{12} \text{ cm}^{-2}$. It is suggested that the break is caused by the filling of the subbands S'_0 .

The two-dimensional electron gas on the (111) surface of germanium in MIS structures is to a large extent analogous to the well-studied layer of two-dimensional electrons on the (100) surface of silicon. Two series of subbands S_0, S_1, \dots and S'_0, S'_1, \dots are formed by electrons in different valleys with different masses in a direction perpendicular to the surface of the sample. As the electron density in the layer is increased, several subbands corresponding to the valley with the heavy mass along the normal to the surface are filled first. The subbands with the light mass in this direction are filled next. The main difference between germanium and silicon is that several electronic subbands are already filled at comparatively low electron densities attainable in practice.

The measurements of the structure of the two-dimensional electronic subbands in silicon were performed on (111) Ge in MIS structures using either Mylar foil¹ or a layer of lacquer^{2,3} as the insulator. In the first case, Shubnikov–de Haas oscillations from the S_1 subband were observed, while in the second case it was shown that for electron densities of $N_s < 2.3 \times 10^{12} \text{ cm}^{-2}$ three two-dimensional subbands are filled. Quantum oscillations of the electrons in the two subbands, S_0 and S_1 , were observed in the experiment. The fact that a third subband was filled was deduced from measurements of the electron densities in the subbands S_0 and S_1 on the basis of the quantum-oscillation period and by comparing the sum of these densities with the total electron density in the two-dimensional layer. For electron densities $N_s > 10^{12} \text{ cm}^{-2}$ the sum of the densities turned out to be $N_{S_0} + N_{S_1} < N_s$.

The third filled subband could be either the subband S_2 (which would be in complete agreement with calculations⁷) or the subband S'_0 . Binder *et al.*^{2,3} concluded that in order to explain all of their results it would be convenient to assume that the subband S'_0 is filled.

In our experiment we measured the Shubnikov–de Haas oscillations in *n*-germanium in an MIS structure. The insulator was a sandwich consisting of layers of SiO_2 , Si_3N_4 , and SiO . The measurements were performed in the Corbino geometry by using a contactless method^{4,5} in the radio frequency range ($\omega/2\pi = 30 \times 10^6 \text{ Hz}$). The maximum electron density was $5.4 \times 10^{12} \text{ cm}^{-2}$. It should be specially noted that at helium

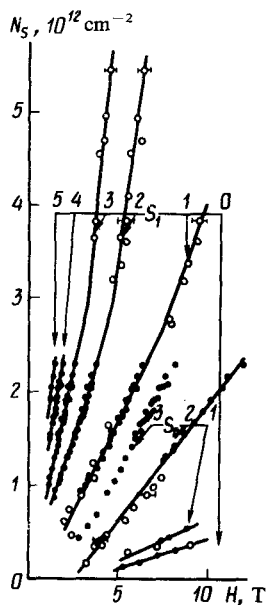


FIG. 1.

temperatures the tested sample exhibited virtually no hysteresis due to a change in the gate voltage. The measurements were performed at a temperature of 2 K.

The experimental results are shown in Fig. 1 in the form of plots of the positions of the peaks in the curves of $(\partial\sigma_{xx}/\partial V_g)(H)$ for different electron densities N_s in the two-dimensional layer. The filled circles represent the results of Refs. 2 and 3; the open circles correspond to the results of this work. (We note that for the dopant concentrations used in Refs. 2 and 3 identical results were obtained for the inversion and accumulation layers).

As is evident from this figure, at low densities the positions of the observed peaks coincide, to within the limits of error, with the previously determined positions. At high electron densities, $N_s > 3 \times 10^{12} \text{ cm}^{-2}$, however, the slope of the curves showing the N_s -dependent change in the value of the magnetic field at which the peak is observed differs markedly from that in the low-density regions. The change in slope occurs at electron densities of $(2.8 \pm 0.4) \times 10^{12} \text{ cm}^{-2}$.

The population density of the corresponding subband can be determined from the oscillation period in the inverse magnetic field $\Delta(1/H)$:

$$N_{Sn} = g_s g_v \frac{e}{2\pi\hbar} \frac{1}{\Delta_n(1/H)}.$$

For the (111) surface of germanium and electrons with heavy mass perpendicular to the sample surface we have $g_v = 1$ and $g_s = 2$. The dependence of the electron density in the subband S_1 on the total electron density in the two-dimensional layer is shown in Fig. 2. The filled circles correspond to the results of Refs. 2 and 3, the crosses represent the results of Ref. 1, and the open circles are the results of our measure-

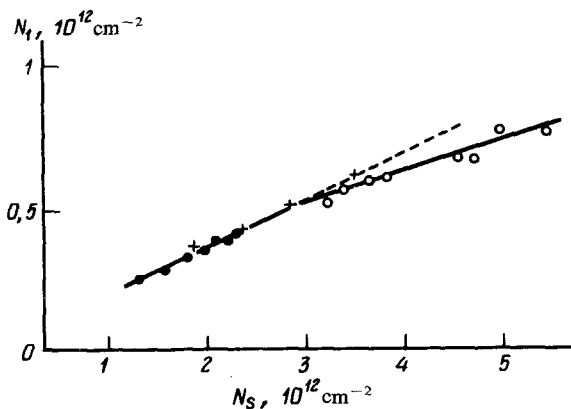


FIG. 2.

ments. The dashed curve is an extrapolation of the results of previous measurements to high densities.^{3,6} The break at an electron density of $N_S \approx 2.8 \times 10^{12} \text{ cm}^{-2}$ is also clearly seen in this figure.

The numbering of the peaks for large values of N_S does not follow the results of the preceding studies. Since the number of a peak l is related to the value of the magnetic field H in which the peak is observed by the relation

$$l = \frac{H^{-1}}{\Delta(1/H)} - \gamma,$$

[where $\Delta(1/H)$ is the oscillation period, and $\gamma < 1$], the numbering can easily be established at densities ($3.6 \times 10^{12} \text{ cm}^{-2} < N_S < 3.9 \times 10^{12} \text{ cm}^{-2}$) for which three peaks, which are associated with the same two-dimensional subband, are observed in the curves $(\partial\sigma_{xx}/\partial V_g)(H)$. The coefficient γ turned out to be equal to 0.33.

The experimental results obtained by us, in our view, indicate that for an electron density of $N_S \approx 1.0 \times 10^{12} \text{ cm}^{-2}$, it is not the subband S'_0 that is filled, as previously proposed, but rather the subband S_2 . The subband S'_0 begins to fill up at a density of $N_S \approx 2.8 \times 10^{12} \text{ cm}^{-2}$. This picture agrees very well with the calculations of Ref. 7. Figure 3 shows the calculation⁷ of the dependences of $E_n - E_0$ on the electron density. The dashed lines indicate the range of densities in which, according to the results of

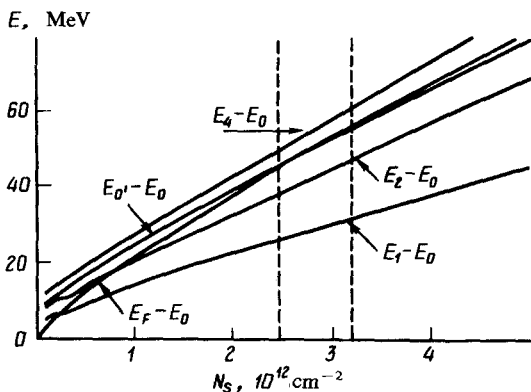


FIG. 3.

our experiments, the subband S'_0 is filled. As is evident from this figure, the curves $E'_0 - E_0$ and $E_F - E_0$ intersect precisely in this region of densities. An additional argument supporting the fact that the observed break corresponds to the filling of the subband S'_0 is that this break is much more pronounced than the previously observed break at $1.0 \times 10^{12} \text{ cm}^{-2}$. This means that it corresponds to filling of the subband with a higher state density.

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¹W. Weber, G. Abstreiter, and F. Koch, Solid State Commun. **18**, 1397 (1976).

²J. Binder, K. Germanova, A. Huber, and F. Koch, Phys. Rev. B **20**, 2382 (1979).

³J. Binder, Dissertation, Technische Univ., München, 1979.

⁴V. T. Dologopolov, A. Zrenner, C. Mazure, and F. Koch, J. Appl. Phys. (1984).

⁵V. T. Dologopolov, S. I. Dorozhkin, and A. A. Shashkin, Solid State Commun. **50**, 273 (1984).

⁶T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

⁷B. Vinter, Phys. Rev. B **20**, 2395 (1979).