Quantum oscillations of the width of the Landau levels in a two-dimensional electronic layer

S. G. Semenchinskiĭ

All-Union Scientific-Research Institute of Metrological Service, Institute of Physics Problems, Academy of Sciences of the USSR

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Experiments have shown that the width of the Landau levels of the inversion electron layer in an MIS structure oscillates at the (001) surface of silicon due to a variation of the magnetic field and carrier density.

We know that the properties of two-dimensional (2D) inversion layers of electrons in silicon MIS structures are strongly affected by fluctuations of the electric potential of the layer. These fluctuations are caused by the random distribution of bound charges in the semiconductor and at the semiconductor-insulator interface, by the fluctuations in thickness of the insulator layer, and by other factors. These fluctuations must obviously be screened to some extent by the 2D-layer electrons, since the regions in which the external potential is smaller have a local electron density higher than the average density and hence a higher potential energy which is associated with the Coulomb interaction of electrons. Such an effect reduces the fluctuations of the potential by several orders of magnitude at an adequately high density of electrons in the 2D layer.[1]

The screening can be altered by placing the MIS structure in a strong magnetic field directed perpendicular to its surface. The electrons belonging to completely filled Landau levels are not involved in the screening, since they are distributed uniformly along the surface—the density of these electrons at each point is determined solely by the magnetic field strength. The number of electrons involved in the screening evidently oscillates in this case upon variation of the magnetic field (or the electron density). This effect causes the width of the Landau levels to oscillate. The maximum width of the level corresponding to the position of the Fermi level E_F halfway between the two Landau levels is determined by the number of thermally activated electrons in the higher-lying levels or by the overlap of the levels. In an electronic layer, the energy

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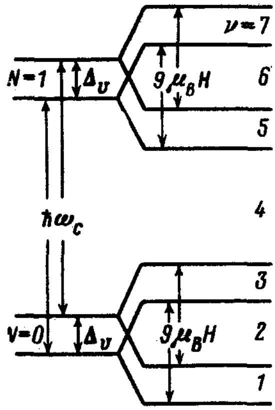

FIG. 1. Level scheme of the inversion-layer electrons at the (001) surface of silicon in a magnetic field.

levels at the (001) surface of silicon are not spaced uniformly—each Landau level is split into four sublevels in accordance with the two spins and the two different valleys (Fig. 1), and the magnitude of the energy splitting Δ_ν depends on the spacing index ν. For this reason, the width of the Landau levels must also change with the position of the Fermi level in the different energy-level spacings.

The smallest splitting in the spectrum is the intervalley splitting with $\nu = 3, 5, \ldots$, and the largest splitting, the splitting with $\nu = 4, 8, \ldots$, corresponds to the transition between the Landau levels with different indices N. The level splitting with $\nu = 2, 6, 10 \ldots$, corresponds to the transitions involving a change in the spin and in the valley without a change in the number of the Landau level.

The dependence of the width of the Landau levels on ν was detected experimentally in analyzing the oscillations of the voltage across an MIS gate, caused by the oscillations of the chemical potential of a 2D layer.[2] In the experiments we used MIS

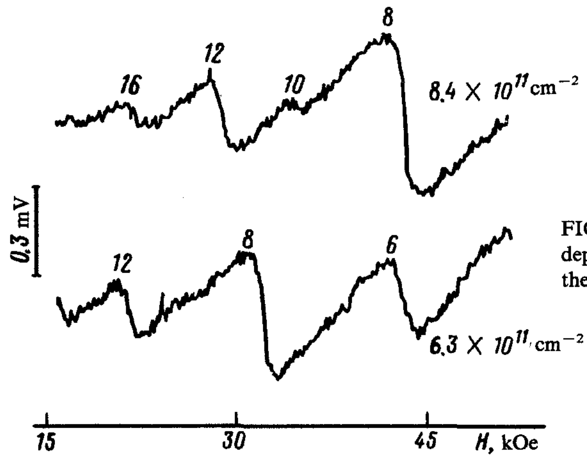

FIG. 2. Experimental traces of the functional dependence $U_3(H)$ for two electron densities in the 2M layer. The scale is shown at the left.

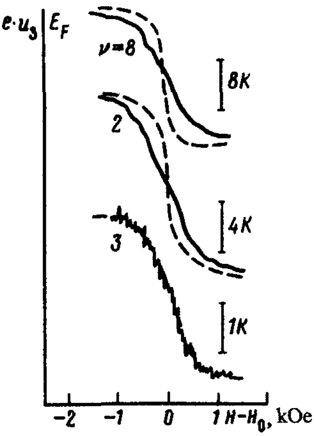

FIG. 3. A comparison of the experimentally observed functional dependence $U_3(H)$, multiplied by the electron charge e (solid curve), and the calculated $E_F(H)$ curve for uniformly narrow levels (dashed curve). The vertical bars at the right give the scale for each curve. $H_0 \approx 80$ kOe; $T = 1.34$ K for $\nu = 2$ and $T = 8$ and 0.8 K for $\nu = 3$.

structures to study the (001) surface of a silicon crystal with a p-type conductivity in magnetic fields $\leqslant 85$ kOe. The measurements were carried out using an electrometer with an input current of $< 10^{-14}$ A, after the gate power supply was turned off. Figure 2 shows typical $U_3(H)$ curves. The parts of the curves where U_3 increases with increasing H correspond to the position of the Fermi level near the center of the Landau level. The parts of the curves where U_3 decreases sharply or the "potential jumps" correspond to the transitions of the Fermi level from one energy level to another via a regular energy interval. This part of the $U_3(H)$ curve is most sensitive to the width of the energy levels and to the temperature.

The shape of the potential drops for odd ν (see the lower curve in Fig. 3) is in good agreement with the calculations in which the width of the Landau levels is assumed to be zero; i.e., it is in good agreement with the $E_F(H)$ curve plotted from the equation

$$(eH/ch) \sum_i f(\epsilon_i, E_F, T) = n_s .$$

Here f is the Fermi function, ϵ_i is the energy of the i-th energy level, and n_s is the surface density of the carriers in the 2D layer, which does not depend on H (as shown in Ref. 3). If the width of the Landau level did not depend on ν, we could expect a similar agreement for a greater energy splitting corresponding to even ν. The experiment, however, gives the opposite result. For even ν the slope of the experimental curve differs markedly from the slope of the calculated curve near the center of the potential jump. This difference for $\nu = 2$ and 8 is illustrated in Fig. 3. We see that the width of the energy levels must be taken into account for potential jumps with even ν. The experiment thus shows that the width of the Landau levels depends on ν nonmonotonically (it oscillates), taking on finite values for even ν and values of nearly zero for odd ν. The level width can be quantitatively estimated by assuming that the state density distribution with respect to energy at the Landau level is nearly Gaussian, $D(\epsilon, \Gamma) = (\Gamma\sqrt{\pi})^{-1} \exp[-(\epsilon/\Gamma)^2]$, and is the same for all levels. Using the experimentally known derivative $dE_F/dH = dU_3/dH$ at the center of the jump, we can thus deter-

TABLE I.

ν	2	3	4	5	6	8	10
Γ, K	4 ± 1	< 1.5	8 ± 1.5	< 2	3 ± 1	7 ± 1	2 ± 1.5
Δ_ν, K	20 ± 2	7.5 ± 1	30 ± 3	6 ± 1	15 ± 2	28 ± 3	13 ± 2
T, K	1.34	0.8	1.34	0.8	0.8	1.34	0.8

mine the value of Γ from the equation

$$d\left\{(eH/ch)\sum_i\int_0^\infty D(\epsilon-\epsilon_i,\Gamma)f(\epsilon,F_F,T)d\epsilon\right\}/dH=0\ .$$

These values are given in Table I for various ν at $H\approx 80$ kOe, along with the temperatures at which the measurement was carried out and the corresponding energy splitting Δ_ν.

In studying the jumps with $\nu = 2$, 4, and 8 we had to raise the temperature to 1.34 K in order to reduce the time required to establish an equilibrium distribution of the carriers in the 2D layer and to eliminate the transient effects that were described in Ref. 4.

We wish to point out that a theory in which screening is ignored predicts a nearly Gaussian distribution of the state density at the Landau level.[5] The shape of a jump determined experimentally corresponds, however, to a much slower decrease in the state density near the Fermi level as it moves farther away from the center of the Landau level. A dependence of this sort may stem from an increase in the width of the Landau levels upon completion of the filling of a regular level; i.e., it may be another manifestation of the screening.

In summary, the functional dependence $U_3(H)$ measured experimentally by us suggests that screening must be taken into account in analyzing the experimental data and in formulating the theory of 2D electron systems in strong magnetic fields.

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