Valley splitting in the electron spectrum of a Si inversion layer

V. M. Pudalov, S. G. Semenchinskiĭ, and V. S. Édel'man

All-Union Scientific-Research Institute of the Metrological Service, State Committee on Standards, Council of Ministries of the USSR; Institute of Problems of Microelectronics Technology and Especially Pure Substances, Academy of Sciences of the USSR; Institute of Physical Problems, Academy of Sciences of the USSR

(Submitted 18 February 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 6, 265–267 (25 March 1985)

Oscillations have been observed in the gate potential of a metal-oxide-semiconductor structure on the (001) surface of p-type silicon upon a change in the magnetic field. These oscillations are associated with quantum oscillations of the chemical potential of an inversion layer. Measurements of the oscillations in fields corresponding to the condition $H = n_s ch/\nu e$ ($\nu = 3, 5, ...$) yield a value for the valley splitting of levels: $\Delta_v = 2.4 + 0.06H$ (H is in kOe, and Δ_v in K) at 20 kOe $\lesssim H \lesssim$ 80 kOe and $n_s \lesssim 10^{12}$ cm^{-2}.

The energy spectrum of a two-dimensional inversion layer on the (001) surface of a silicon single crystal in a quantizing magnetic field H directed normal to the surface is completely discrete.[1] At a relatively low surface electron density, $n_s \lesssim 10^{12}$ cm^{-2}, at which only the lower electrical-quantization subband is populated, the energy levels, reckoned from the bottom of this subband, are described by

$$E_i = \hbar\omega_c(N + 1/2) \pm g\mu_B H/2 \pm \Delta_v/2\,, \qquad (1)$$

where $\omega_c = eH/m^*c$ is the cyclotron frequency corresponding to the mass m^*, the second term on the right describes the spin splitting governed by the g-factor, Δ_v is the energy splitting of the two valleys, which are equivalent in a bulk crystal, and N is an integer. The cyclotron mass $m^* = (0.21 \pm 0.01)m_0$ can be regarded as reliably established.[1,2] The g-factor which is believed to depend on the density n_s and the magnetic field[1] is known less accurately. Its values lie between[1] 2.5 and 4.5, and the spin splitting is 0.25–0.45 of the cyclotron splitting.

The existence of valley splitting was established in Ref. 3. Several attempts have been made to evaluate Δ_v through an analysis of the Shubnikov-de Haas effect (see the review by Ando *et al.*[1] and also Ref. 4). So many assumptions were introduced, however, that the results do not inspire much confidence.[5]

In strong fields the inequality $\hbar\omega_c > g\mu_B H > \Delta_v$ holds, and the energy levels are ordered, as shown in Fig. 1. As the field is varied, the Fermi level (determined entirely by electrons) hops from one energy level to another at a fixed value of n_s; these hops occur at values of the field H corresponding to the condition $n_s ch/eH = \nu$, where the numbers ν are integers. Correspondingly, there is an abrupt change in the potential of the isolated gate of the metal-oxide-semiconductor structure, reckoned from the contact potential at the two-dimensional layer.[6,7]

It can be seen from Fig. 1 that for transitions with odd values of ν the observed

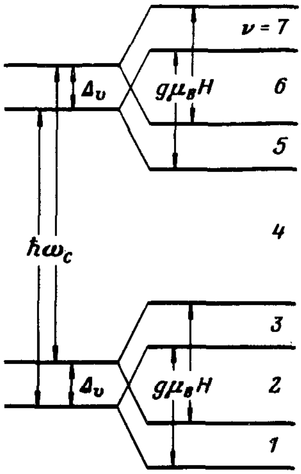

FIG. 1. Electron levels of the inversion layer in a (001) Si metal-oxide-semiconductor structure in a magnetic field.

potential change ΔU_g is determined by Δ_v. In the present letter we report the first successful observations of variations in the gate potential associated with these transitions. It thus becomes possible to determine the valley splitting.

The measurements are carried out in magnetic fields in the range 30–80 kOe at temperatures 0.4–0.8 K. Two test samples with dimensions 0.8×5 mm with a capacitance $\sim$700 pF are used. The electron mobility reaches a maximum $\sim 4\times 10^4$ cm^2·V/s at low temperatures. The carrier density in the layer, $n_s = (3.5–10)\times 10^{11}$ cm^{-2}, is set by applying a voltage to the gate with respect to one of the contacts to the $2d$ layer; the gate is then disconnected from the voltage source and connected to an electrometer for measuring the dependence $U_g(H)$. Figure 2 shows a representative experimental record as the magnetic field is changed, for the case $\nu = 3$.

To determine Δ_v, we compare the experimental curves (with a $\sim 10\%$ correction for the parasitic capacitance of the electrometer and the leads) with the dependence of the Fermi level on the magnetic field found through a numerical solution of the equa-

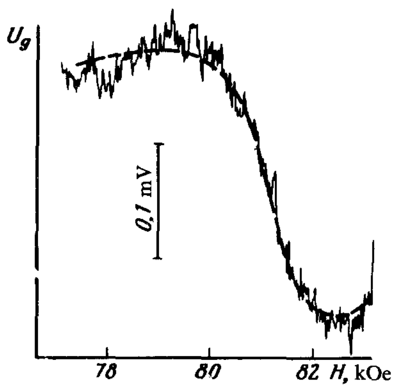

FIG. 2. The potential difference between the gate and the inversion layer versus the magnetic field H ($n_s = 5.8\times 10^{11}$ cm^{-2}, $\nu = 3$, $T = 0.8$ K). The dashed line is theoretical, calculated with the parameter values $\Gamma = 0$ and $\Delta_v = 8.0$ K.

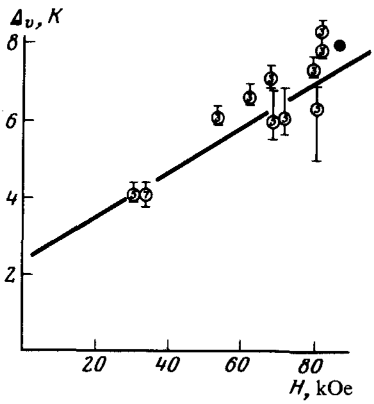

FIG. 3. The valley-splitting energy Δ_v versus H. The numbers in the circles are the values of ν at which the corresponding values were obtained. The filled circle shows a value of Δ_v from Ref. 4.

tion

$$\sum_i \frac{eH}{\cosh} \int_0^{\infty} D(\epsilon - E_i, \Gamma) f(\epsilon, E_F, T)\, d\epsilon = n_s , \tag{2}$$

where $D = (\Gamma/\sqrt{\pi})\exp((\epsilon - E_i)^2/\Gamma^2)$ incorporates the level broadening in the actual sample, the parameter Γ is assumed identical for all levels for a given field, and $f(\epsilon, E_F, T)$ is the Fermi distribution function. It can be seen from Fig. 2 that a good agreement of Eq. (2) with the experimental data can be reached at reasonable values of the parameters.

The possible values of Γ which are consistent with the experimental data lie in the range $0 < \Gamma \lesssim 1$ K at $n_s \lesssim 5\times 10^{11}$ cm^{-2} or $0 < \Gamma \lesssim 2$ K for 5×10^{11}–10^{12} cm^{-2}. The best agreement is reached with $\Gamma \approx 0$ in the former case and $1\ \mathrm{K} \lesssim \Gamma \lesssim 2$ K in the latter. Figure 3 shows the values found for Δ_v. The indicated error corresponds to the uncertainty in the parameters of the calculation, primarily, Γ.

We wish to emphasize several circumstances: 1) The value of Δ_v agrees well with the results of Ref. 4 and with the estimates in Ref. 5. Calculations show that since Δ_v is small, the structural features in U_g associated with the transitions $\nu = 3, 5, \ldots$ can be observed only at $T \lesssim 1$ K. 2) Comparison of our results as identical fields and different values of ν, i.e., at different values of n_s, shows that if Δ_v does depend on n_s, then the dependence is extremely weak. The value of Δ_v found in Ref. 4 for $n_s = 2.8\times 10^{12}$ cm^{-2}, i.e., at a density ~ 4.8 times higher than in the present experiments, is a firmer basis for asserting that Δ_v is independent of n_s. 3) Δ_v depends on H. A linear extrapolation to $H = 0$ shows that a valley splitting $\Delta_v = 2.4$ K remains even in a zero field. The data found by Kawaji *et al.* (cited in Ref. 1) in fields above ~ 100 kOe also agree with a linear extrapolation of our results if we assume that in this field region Δ_v depends not on n_s but on H.

According to the present theoretical understanding,[1] Δ_v should be proportional to n_s. This understanding is not in agreement with experiment, although the theoretical numerical estimate of this quantity is correct in order of magnitude. The dependence of Δ_v on the field H and, simultaneously, the weakening of the n_s dependence arise in the theory when the electron-electron interaction is taken into account, but here the values of Δ_v turn out to be an order of magnitude above the measured values. Our results thus imply that further theoretical work is necessary.

We wish to thank A. S. Borovik-Romanov for the opportunity to work at the Institute of Physical Problems and M. A. Khaĭkin and Ch. V. Kopetskiĭ for interest in this study.

[1]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[2]U. Kunze and G. Lautz, Surf. Sci. **142**, 314 (1984).
[3]A. B. Fowler, F. F. Fang, W. E. Howard, and P. J. Stiles, Phys. Rev. Lett. **16**, 901 (1966).
[4]H. Köhler, Surf. Sci. **98**, 378 (1980).
[5]K. Von Klitzing, Surf. Sci. **98**, 98 (1980).
[6]V. M. Pudalov, S. G. Semenchinsky, and V. S. Edel'man, Solid State Commun. **51**, 713 (1984).
[7]V. M. Pudalov, S. G. Semenchinskiĭ, and V. S. Edel'man, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 474 (1984) [JETP Lett. **39**, 576 (1984)].

Translated by Dave Parsons