Intervalley splitting in the energy spectrum of two-dimensional electrons at the (100) surface of silicon

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(Submitted 23 December 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 5, 222–225 (10 March 1987)

The intervalley splitting in the energy spectrum of two-dimensional electrons in Si-MIS structures is determined by the optical-spectroscopy method. In a perpendicular magnetic field this splitting increases by almost an order of magnitude due to the electron-electron interaction.

1. The lowest dimensionally quantized subband of two-dimensional electrons at the (100) surface of silicon is comprised of states belonging to two valleys of the conductivity band that lie on the [100] axis.[1] It has been shown experimentally that in a magnetic field (H) perpendicular to the 2D layer this valley degeneracy is lifted, as is evident, for example, in the Shubnikov–de Haas oscillations.[2] There are several theories[3–8] which attempt to explain this experimental fact. It was shown in Refs. 3–6 that the valley splitting, which is calculated without regard for the electron-electron ($e-e$) interaction (ΔE_V^0), is determined by the gate field, i.e., it is proportional to the density of 2D electrons, n_S:

$$\Delta E_V^0 = \alpha (\partial V/\partial Z) \sim n_s , \tag{1}$$

where $\alpha = \text{const}$, and $(\partial V/\partial Z)$ is the potential gradient. It was noted in Refs. 7 and 8 that in a perpendicular magnetic field the valley splitting should increase appreciably due to the contribution ΔE_V^* which occurs as a result of interaction of 2D electrons. For the total intervalley splitting (ΔE_V) we thus can write

$$\Delta E_V = \Delta E_V^0 + \Delta E_V^* . \tag{2}$$

It is important to note that since ΔE_V^0 and ΔE_V^* depend differently on H, n_s, and the filling factor $\nu = hn_S/eH$, they must be analyzed separately in an experiment.

2. The quantity ΔE_V was determined experimentally on the basis of an analysis of the distinctive features of the magnetoconductivity oscillations[9–11] and the contact potential difference.[12] In Refs. 9–12 the splitting was determined indirectly with use of the adjustable parameters and assumptions requiring special substantiation. A radiative recombination of 2D electrons on the (100) surface of silicon with photoexcited holes was recently observed in Refs. 13–15. It was shown in Ref. 14 that the spectral distribution of this radiation corresponds directly to the energy spectrum of 2D electrons. In a magnetic field perpendicular to the 2D layer, for example, the Landau level pattern changes upon rotation of the field in accordance with the variation of the normal component of H (Ref. 14). The use of optical spectroscopy methods has made it possible to measure ΔE_V directly as the energy interval between the corresponding lines in the radiative recombination spectra. This method also makes it possible to distinguish between ΔE_V^0 and ΔE_V^* in the intervalley splitting and to separately analyze the dependence of these contributions on n_S, H, and ν.

3. In our experiments we studied two MIS transistors with a maximum mobility of 2D electrons at $T = 1.6$ K, $\mu = 3.1\times10^4$ cm^2/(V·s) and 1.8×10^4 cm^2/(V·s). The nonequilibrium electron-hole pairs were generated through a semitransparent gate by means of an argon laser. The characteristic power density was $\sim10^{-3}$ W/cm^2. The output intensity of the laser was recorded with a cooled photomultiplier FEU-62 under photon counting conditions with a subsequent storage of the signal. The magnetotransport measurements were carried out at the same time as the optical measurements. The other details of the experiment were reported in Ref. 15.

4. Figure 1 shows plots of the $\sigma_{xx}(\nu)$ curves (the inset) and of the spectra for the radiative recombination of 2D electrons measured at $H = 7$ T and $T = 1.6$ K. The arrows above the $\sigma_{xx}(\nu)$ curve indicate the σ_{xx} minima for odd integers $\nu = \nu^*$, which correspond to the intervalley splitting. At $\nu = 3.0$ the recombination spectrum exhibits a single line which is associated with the recombination of 2D electrons from the lower electronic valley. These electrons have a spin projection $S_Z = 1/2$ and belong to the Landau ground level ($N = 0$) [at low temperatures ($T \cong 1.6$ K) the recombination involves only holes from the ground state with $J_Z = -3/2$, the optical transitions with the electrons with $S_Z = -1/2$ are forbidden, and the corresponding emission lines are not observed[14]]. At $\nu > 3$ the next electronic valley begins to be filled and the recombination spectrum exhibits a new line whose relative intensity corresponds to the deviation of ν from 3. The energy interval between the lines corresponds to the intervalley splitting ΔE_V (Fig. 1). Note that even in those cases where ΔE_V is smaller than the line width and the lines cannot be resolved completely, the quantity ΔE_V is determined with a good accuracy, since the line shape (measured at $2 < \nu < 3$) is known,

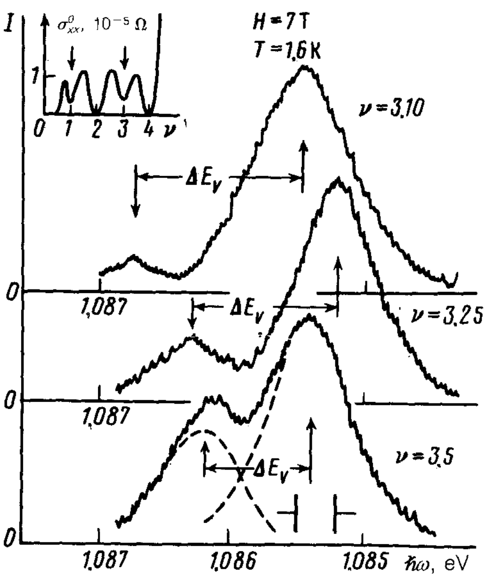

FIG. 1. Radiative recombination spectra for 2D electrons with photoexcited holes, measured at $H = 7$ T, $T = 1.6$ K, $W = 10^{-3}$ W/cm^2, and different values of the filling factor ν: 3.1, 3.25, and 3.5. ΔE_V corresponds to the intervalley splitting. The inset shows the $\sigma_{xx}(\nu)$ curve, measured simultaneously for the same parameter values of H, T, and W. The minima of σ_{xx}, indicated by the arrows, correspond to the intervalley splitting.

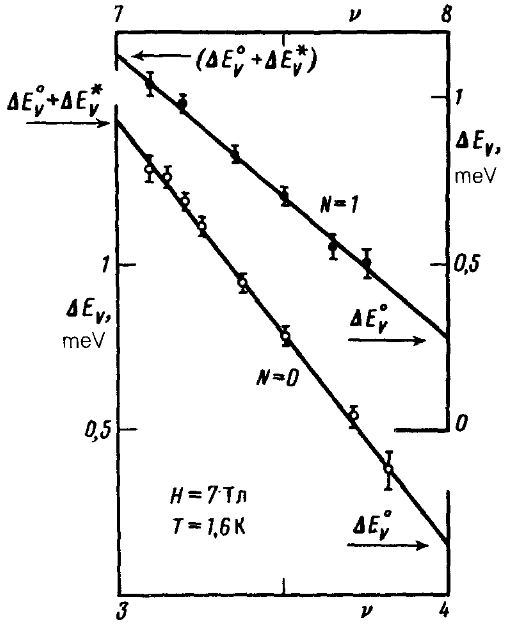

FIG. 2. Variation of ΔE_V determined by the optical-spectroscopy method versus the filling factor ν at $H = 7$ T and $T = 1.6$ K for the Landau levels with $N = 0$ (open circles) and $N = 1$ (filled circles).

and since the ratio of their intensities for the specified ν is also known. The use of the optical spectroscopy methods thus makes it possible to not only determine ΔE_V directly but also to measure the $\Delta E_V(\nu)$ curve.

Figure 2 shows the curves for $\Delta E_V(\nu)$ measured at $H = 7$ T and $T = 1.6$ K for two Landau levels with $N = 0$ and $N = 1$. We see that ΔE_V peaks at $\nu = \nu^* = 3,5,...$, and that the absolute value of ΔE_V measured by the optical spectroscopy method is much higher than the values obtained by other methods in Refs. 9–12. It can be seen, moreover, that ΔE_V decreases when ν deviates from ν^* as a given valley is filled. Such a behavior of $\Delta E_V(\nu)$, which corresponds to the valley-splitting mechanism based on the $e - e$ interaction, is at variance with the renormalized ΔE_V^0. According to Ref. 7, the intensification of ΔE_V occurs because the electrons from different valleys with different quantum numbers are not forbidden by the Pauli principle to be situated near each other. This situation gives rise to additional repulsion which leads to an increase in ΔE_V^0 by ΔE_V^*. The effect produced by the increase in ΔE_V is similar to the intensification of the g-factor of 2D electrons due to the $e - e$ interaction.[16,17] In the screened Hartree-Fock approximation, ΔE_V^* is given by the expression[7]

$$\Delta E_V^* = (\nu_1 - \nu_2) \sum_q [L_N^0 \, (l^2 q^2/2) \exp(-l^2 q^2/2)]^2 \, V(q)/\epsilon(q), \qquad (3)$$

where ν_1 and ν_2 are the filling factors of the lower and upper valleys, $V(q)$ is the Fourier transform of the $e - e$ interaction, $\epsilon(q)$ is the static dielectric constant, l is the magnetic length, and L_N^0 are the associated Laguerre polynomials. It is evident from Eq. (3) that ΔE_V^* is maximum when one valley is filled completely and the other

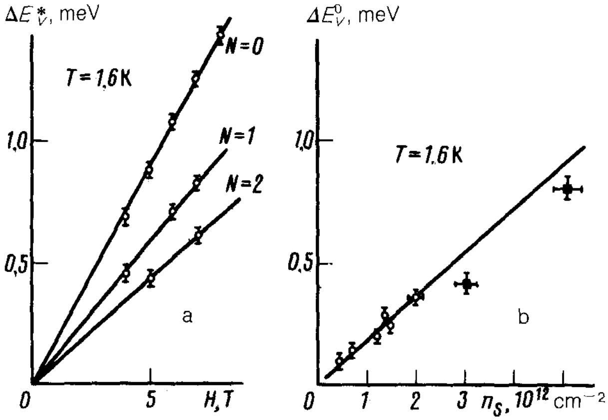

FIG. 3. (a) Plots of $\Delta E_V^*(\nu^*)$ versus the magnetic field, measured for various Landau levels at $T = 1.6$ K, (b) plot of ΔE_V^0 versus the density (n_S) of 2D electrons, measured at $T = 1.6$ K (open circles). The filled squares correspond to the results of Ref. 11 and the straight line, which corresponds to the theory of Ref. 4, was plotted for $n_d = 0$, since there is no depletion layer under photoexcitation conditions.

valley is empty (i.e., when $\nu = \nu^* = 1,3,5,...$) and vanishes when both valleys are filled equally (when $\nu = \nu^0 = 2,4,6,...$). Such a behavior of $\Delta E_V^*(\nu)$ fully account for the experimental data shown in Fig. 2 and allows us to determine ΔE_V^* and ΔE_V^0 separately, since $\Delta E_V^* \to 0$ and $\Delta E_V \to \Delta E_V^0$ as $\nu \to \nu^0$ (Fig. 2). Our studies have shown that ΔE_V^0 is independent of H and N and is determined exclusively by n_S. At the same time, ΔE_V^* depends strongly on H and N, as well as on the temperature and width of the Landau level. The ΔE_V^* vs H plots for different N are shown in Fig. 3a and the ΔE_V^0 vs n_S plot is shown in Fig. 3b. Also shown in Fig. 3b are the points from Ref. 11, in which the values of ΔE_V^0 were determined, since the measurements were carried out for large values of n_S and N.

5. By using the optical spectroscopy method we were thus able to 1) determine directly the value of ΔE_V without the use of adjustable parameters and certain assumptions, 2) show that at $N = 0$ and $N = 1$ the valley splitting increases dramatically (by almost an order of magnitude) due to the $e - e$ interaction, 3) measure the function $\Delta E_V(\nu)$, 4) distinguish ΔE_V^0 from ΔE_V^* in the total quantity ΔE_V, 5) measure the H dependence of ΔE_V^* for different N, 6) show that ΔE_V^0 is independent of H and N and that it is determined exclusively by n_S.

I wish to thank V. B. Timofeev for useful discussions.

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Translated by S. J. Amoretty