Scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the Academy of Sciences of the USSR (30–31 January 1985)

Usp. Fiz. Nauk **146**, 531–543 (July 1985)

A joint scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics, Academy of Sciences of the USSR, was held 30 and 31 January 1985 at the Lebedev Physics Institute in Moscow. The following papers were read at the sessions:

January 30

1. *S. M. Apenko, Yu. E. Lozovik, and V. M. Farztdinov.* 2D electron gas in a strong magnetic field and quantized Hall effect.
2. *Yu. A. Bychkov and É. I. Rashba.* Spectrum of a 2D electron gas in an inversion layer.
3. *V. M. Pudalov and S. G. Semenchinskiĭ.* Galvanomagnetic properties of a 2D electron layer in silicon under conditions of a quantized Hall resistance.
4. *V. M. Pudalov, S. G. Semenchinskiĭ, and V. S. Edel'man.* Charge and potential of an inversion layer in a metal-insulator-semiconductor structure in a quantizing magnetic field.

January 31

5. *A. I. Burshteĭn.* Collapse and narrowing of spectra during condensation of gases.
6. *A. V. Zalesskiĭ.* Domain walls in magnetic materials according to NMR spectroscopy.

Five of these papers are summarized briefly below.

Yu. A. Bychkov and É. I. Rashba. *Spectrum of a 2D electron gas in an inversion layer.* Theoretical predictions and experimental data show that the spin-orbit interaction causes substantial changes in the energy spectrum $E(\mathbf{k})$ of quasi-2D electrons at heterojunctions and in inversion layers in metal-insulator-semiconductor structures. Below we examine the spectrum $E(\mathbf{k})$, its changes in a magnetic field, and phenomena which exhibit the characteristic features of 2D bands.

1. Because of the invariant vector ν, which is the normal to the 2D layer, the Hamiltonian of the effective-mass method is

$$\hat{H} = \frac{\hbar^2\hat{\mathbf{k}}^2}{2m} + \alpha[\sigma\hat{\mathbf{k}}]\nu + \frac{1}{2} g\mu_B\sigma\mathbf{B}. \qquad (1)$$

It is assumed that there is a threefold or fourfold axis. Here the operator $\hat{\mathbf{k}}$ represents the 2D momentum in the magnetic field $\mathbf{B}\|\nu$, σ are the Pauli matrices, and g and μ_B are the g-factor and Bohr magneton. The dispersion relation $E^{\pm}(k) = (\hbar^2k^2/2m) \pm \alpha k$ has two branches at $B=0$. It corresponds to a spectrum with a ring of extrema[1] with a radius $k_0 = \alpha m/\hbar^2$, where E^- reaches a minimum $E^-(k_0) = -\Delta$, where $\Delta = m\alpha^2/2\hbar^2$. The parameter α is determined by the spin-orbit interaction. At $B \neq 0$, the spectrum consists of two sequences of nonequidistant levels $E_s^{\pm}$ (s is an integer), for which an explicit expression has already been derived.[2] The terms of higher order in $\hat{\mathbf{k}}$ and $\hat{\mathbf{H}}$ can usually be ignored if $n_{s_0}\langle z^2\rangle \ll 1$, where n_S is the surface electron density, and $\langle z^2\rangle \sim (40\ \text{Å})^2$ is determined by the average dimension of the ψ function along the direction of ν.

2. The coefficient α is not only a parameter of the material but also a parameter of the transition. It is formed by both the region of the transition itself (where the effective-mass method cannot be used) and the region of smooth field. The contribution of the latter region can be calculated by the effective-mass method. In addition, α may receive contributions from terms which are odd in $\hat{\mathbf{k}}$ from the Hamiltonian of the 3D crystal. In metal-insulator-semiconductor structures, α depends on the surface carrier density (n_S, p_S) through the change in the field near the surface. Figure 1 shows the behavior $\alpha(p_S)$ for a silicon-metal-insulator-semiconductor structure (a p-type inversion layer). We recalculated this function from $\Delta_S \equiv \alpha k_F$ (k_F is the Fermi momentum) from the measurements in Ref. 3 based on the spin relaxation time. The weak dependence $\alpha \approx 3\cdot 10^{-10}$ eV · cm on p_S confirms the use of Hamiltonian (1) and indicates a significant contribution to α from a narrow vicinity of the transition. Evidence of terms linear in k in silicon-metal-insulator-semiconductor structures was also found in Ref. 4.

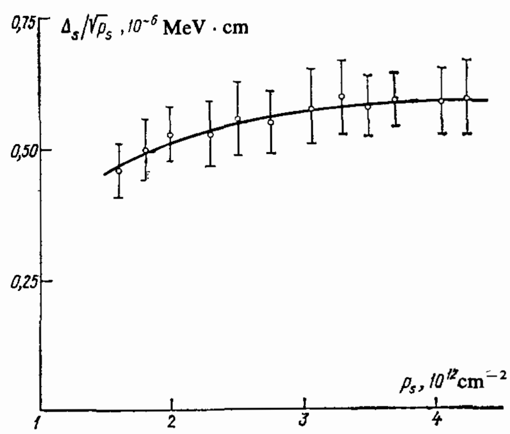

FIG. 1. $\Delta_S/\sqrt{p_S} \approx \sqrt{2\pi}\alpha$ for a silicon-metal-insulator-semiconductor structure. (Recalculated from the data of Ref. 3.)

 0038-5670/85/070632-08$01.80

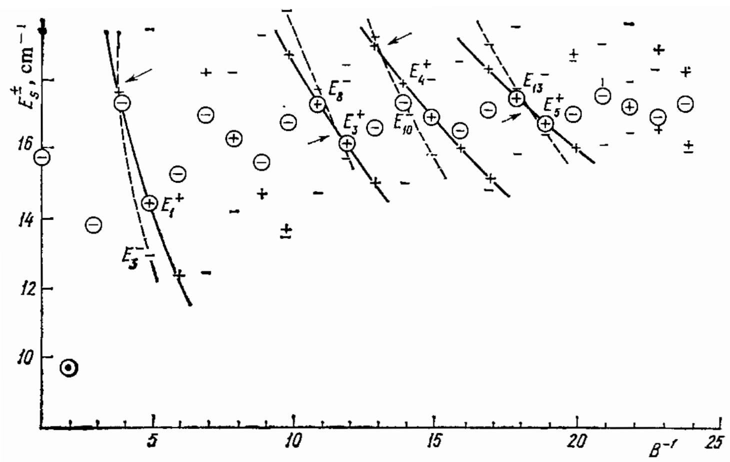

FIG. 2. Arrangement of quantum levels near the Fermi energy for a 2D electron gas with a spin-orbit interaction as a function of the reciprocal of the magnetic field B (Refs. 5b and 8).

3. At $k_F \gg k_0$, the semiclassical cyclotron resonance frequencies $\omega_c^\pm$ are[5]

$$\omega_c^\pm(B) = \omega_c^0(B)\left(1 \pm \sqrt{\frac{m\Delta}{\pi\hbar^2 n_s}}\right), \quad \omega_c^0(B) = \frac{eB}{mc}. \qquad (2)$$

The two signs in $\omega_c^\pm$ correspond to the two branches of the spectrum. Two bands of the hole cyclotron resonance have been observed at a GaAs-AlGaAs heterojunction.[6] The B dependence of the frequencies is approximately linear and corresponds to masses of $0.38m_0$ and $0.60m_0$, where m_0 is the mass of an electron in vacuum. The value which we found[5] for α from this experiment is $\alpha \approx 6 \cdot 10^{-10}$ eV · cm.

4. For the $N = 1$ Landau level the spin-resonance frequency is[5]

$$\omega_s = \frac{1}{\hbar}|g|\mu_B B - \frac{6\Delta}{\hbar\delta}\,\mathrm{sign}\,\{g\},$$

$$\delta = \frac{1}{2}\left(1 - \frac{gm^*}{2m_0}\right) \quad \text{for} \quad \hbar\omega_s \gg \Delta. \qquad (3)$$

An electron spin resonance has been observed[7] under such conditions at a GaAs-AlGaAs heterojunction. The value which we found[5] for α from the data of Ref. 7 is $\alpha \approx 2.5 \cdot 10^{-10}$ eV · cm. It was possible to detect the spin resonance because it is excited in an electric-dipole fashion (a combined resonance[2]). The ratio of the intensities of the electric and magnetic excitations of the cylotron resonance was $\sim 10^7$.

5. The distribution of levels near the Fermi energy is important for a determination of the picture of oscillation effects in a 2D gas. This distribution is shown in Fig. 2 (Refs. 5b and 8) for the particular parameters of Ref. 6. As the unit of the field B we are using the field at which the electrons fill one Landau level. The complicated arrangement of levels is a consequence of the spin-orbit interaction. The B dependence of the positions of the + and − levels is shown by the solid and dashed lines. The levels $E_s^\pm$ are shown by the + and −. We have shown here only the levels which lie near the Fermi energy. The upper filled level for each integer value of B^{-1} is shown by a circle. The distance from it to the next level plays the role of a gap in the spectrum. It can be seen from Fig. 2 that this gap oscillates. This is an important point, since the Shubnikov and de Haas oscillations are expressed strongly when there is a large gap but are blurred when there is a small gap. An interruption of the weak oscillations leads to an apparent change in their period. Oscillations of the gap have been observed experimentally,[6,9] although they have not been interpreted in these terms. The arrows in Fig. 2 show the positions of additional structural features associated with level crossings.

In summary, because of the high quality of the heterostructures and metal-insulator-semiconductor structures available, the relativistic terms in the dispersion relation of the 2D carriers are seen clearly in experiments of several types: at cyclotron and spin resonances, in Shubnikov oscillations, and in spin relaxation. The theory based on Hamiltonian (1) gives a complete description of these effects. Incorporating band corrugation,[4] nonparabolic effects, etc., should of course lead to refinements in the detailed interpretation of experiments and in the values of the parameters determined from them.

[1]É. I. Rashba and V. I. Sheka, Fiz. Tverd. Tela (Leningrad) **1**, (Appendix; collection II), 162 (1959) [Sov. Phys. Solid State 1, 143 (1959)].
[2]É. I. Rashba, Fiz. Tverd. Tela (Leningrad) **2**, 1224 (1960) [Sov. Phys. Solid State **2**, 1109 (1960)].
[3]G. M. Gusev, Z. D. Kvon, and V. N. Ovsyuk, J. Phys. C. **17**, 1683 (1984).
[4]A. D. Wieck, E. Batke, D. Heitmann, and J. P. Kotthaus, Phys. Rev. Lett. **53**, 493 (1984).
[5]Yu. A. Bychkov and É. I. Rashba, (a) Pis'ma Zh. Eksp. Teor. Fiz. **39**, 66 (1984) [JETP Lett. **39**, 78 (1984)]; (b) in: Proceedings of the Seventeenth International Conference on Physics of Semiconductors, San Francisco, 1984 (in press).
[6]H. L. Störmer, Z. Schlesinger, A. Chang, D. C. Tsui, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **51**, 126 (1983).
[7]D. Stein, K. von Klitzing, and G. Weimann, Phys. Rev. Lett. **51**, 130 (1983).
[8]Yu. A. Bychkov and É. I. Rashba, J. Phys. C **17**, 6039 (1984).
[9]J. P. Eisenstein, H. L. Störmer, V. Narayanamurti, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **53**, 2579 (1984).