Determination of the cross-sectional area of the isoenergetic electronic surfaces of different energies using magneto-optic measurements

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The areas of the nonextremal cross sections of the isoenergetic surfaces with the energy determined by the wavelength of the incident light were determined by measuring the optical transmission of size-quantized Bi films in a quantized magnetic field.

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It is well known that oscillations of the kinetic and thermodynamic characteristics of a degenerate electron gas in bulk crystals in a quantized magnetic field make it possible to determine the areas of the extremal cross sections of the Fermi surface. The nonextremal cross sections, which contribute to the monotonic part of the thermodynamic potential, cannot be determined.[1]

The nonextremal cross sections of the Fermi surface can be determined by similar measurements using size-quantized films.[2]

Investigation of thin films in a quantized magnetic field by the method of tunnel spectroscopy made it possible to determine the areas of the nonextremal cross section of the Fermi surface and of an arbitrary isoenergetic electronic surface.[3] The energy ϵ of the analyzed isoenergetic surface, which was determined by the bias voltage of the tunneling, was limited by the breakdown of the dielectric gap.

In this paper we propose a method of determining the nonextremal cross sections of the isoenergetic surfaces with energies $\epsilon > \epsilon_F$ (ϵ_F is the Fermi energy) from measurements of the absorption of light by a size-quantized film in a quantized magnetic field normal to the surface of the film. The value of ϵ is determined by the photon energy ϵ_p, which can be varied in a wide range.

In the case under consideration the condition for resonance in the absorption of light for the interband transition couples the discrete energy levels of the electron in the conduction band $\epsilon_{n,l,s}(H)$ and in the valence band $\epsilon'_{n',l',s'}(H)$ with the photon energy:

$$\epsilon_p = \epsilon_{n,l,s}(H) - \epsilon'_{n',l',s'}(H), \tag{1}$$

where H is the intensity of the magnetic field; n,n' are the dimensional quantum numbers; l,l' are the orbital quantum numbers; and s,s' are the spin quantum numbers coupled by the selection rules:

$$n = n + \Delta n, \qquad l' = l + \Delta l, \qquad s' = s + \Delta s .$$

The resolved transverse component of the quasi momentum of the electron p_z is coupled to n by the relation $|p_z| = \pi\hbar n/d$ (z is the direction normal to the film and $n = 1,2,3...$, d is the thickness of the film).

If the bands have mirror symmetry (for example, at point L in the Brillouin zone), then $\epsilon' = -\epsilon$ (the energy is measured from the middle of the forbidden band) and expression (1) has the following form (as in Ref. 2, we set $\Delta n = 0$):

$$\epsilon_p = \epsilon_{n,l,s}(H) + \epsilon_{n,l+\Delta l,s+\Delta s}(H) = 2\epsilon_{n,l,s}(H) + \Delta\epsilon . \tag{2}$$

The value of $\Delta\epsilon$ in Eq. (2) is of the same order of magnitude as the distance between the neighboring Landau levels. Disregarding $\Delta\epsilon$ in contrast to $\epsilon_{n,l,s}$ at $l > 1$, we obtain:

$$\frac{\epsilon_p}{2} \approx \epsilon_{n,l,s}(H). \tag{3}$$

The last condition indicates that the characteristic features of the absorption of light due to the variation of H are observed whenever the cyclotron orbit, which is characterized by the quantum numbers n,l, and s coincides with the isonergetic surface $\epsilon(\mathbf{p}) = \epsilon_p/2$ (Fig. 1). Using the Quasi-classical expression for the area bounded by the cyclotron orbit in the $\mathbf{p}$ space,[4] we can show that the peculiarities of the absorption of light are periodic in $1/H$. The periods $\Delta_n(1/H)$ are determined by the cross-sectional area S_n of the surface $\epsilon(\mathbf{p}) = \epsilon_p/2$ by the planes $p_z = \pi\hbar n/d$[1]:

$$\Delta_n\left(\frac{1}{H}\right) = \frac{2\pi e\hbar}{c S_n} . \tag{4}$$

The aforementioned arguments were used in analyzing the transmission of light by single-crystal Bi films in a transverse magnetic field $H \| z \| C_3$. The thickness was in the range of 500 to 1500 Å. The mobility of the current carriers in the indicated range of thickness was $\sim 3\times10^4$ cm²/V-sec.

We measured the dependence $dI/dH\,(H)_0$ (I is the intensity of transmitted light in the field H up to 60 kG at $T = 4.2$ K in the range of wavelengths $\lambda \approx 11$–17 μm).

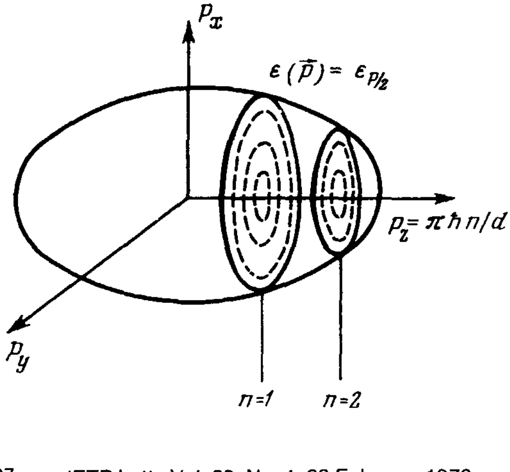

FIG. 1.

FIG. 2.

The experimental dependences $dI/dH(H)$ had a pronounced oscillating nature; the oscillations were periodic in the reverse magnetic field. The cross-sectional areas

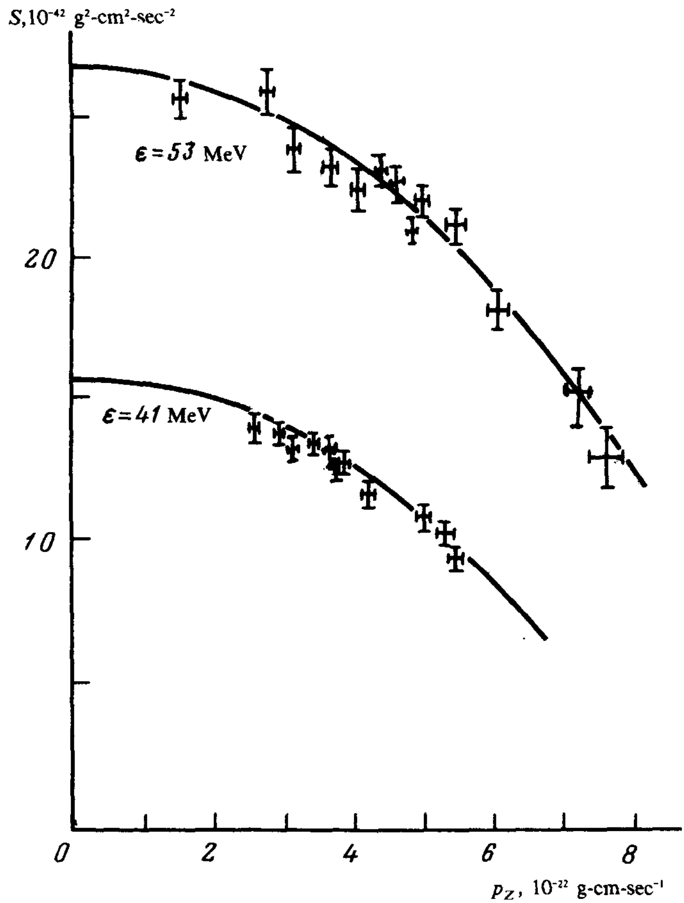

FIG. 3.

S_n were determined from the period of the strongest harmonic $n = 1$ of the dependence $dI/dH(H)$ (Fig. 2).

Figure 3 shows the dependence $S(p_z)$ for two isoenergetic surfaces. The dependence $S(p_z)$ obtained experimentally was compared with the theoretical curve derived from the two-band model of the spectrum. The solid lines in Fig. 3 represent the result of the calculation with the parameters $(m_z/m_0)\beta = 2\times10^{-3}$ MeV/kG and $\epsilon_g\beta = 11$ MeV^2/kG, which give the best agreement with the experimental data [$\beta = (e\hbar/m_c c)$, m_c is the effective cyclotron mass, m_z is the effective mass in the z direction at the bottom of the conduction band, m_0 is the free electron mass, and ϵ_g is the width of the forbidden band].

The parameters of the electron energy spectrum were determined by comparing the location H_i of the observed peculiarities of the optical transmission with the corresponding theoretical expression obtained from the two-band model of the electronic spectrum,[5] taking into account the size-quantization and selection rules in Ref. 5. Using the method for evaluation of experimental data similar to that used for analysis of the spectra of magnetic reflection of massive Bi (Ref. 6), we obtained the following parameters of the model: $\epsilon_g \approx 20$ MeV and $\epsilon_g\,\beta \approx 11$ MeV^2/kG. Moreover, the magneto-optic measurements under the conditions of the quantum-size effect make it possible to determine [from the $H_i(d)$ dependence] the parameter m_z ($m_z \approx 0.004\, m_0$).

It can also be show that by extrapolating the dependences $\epsilon_p(H_i)$ to $H = 0$ we can determine the dependence $\epsilon(p_z) - \epsilon'(p_z)$ without using *a priori* models of the spectrum.

Thus, the magneto-optic measurements under conditions of the quantum-size effect make it possible to determine the areas of the nonextremal cross sections of the isoenergetic electronic surfaces with $\epsilon > \epsilon_F$ and also the parameters characterizing the law of electron dispersion.

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[1)]We note that, in the absence of size quantization in a bulk crystal, for example, the areas of the extremal cross sections of the isoenergetic surfaces with the energy $\epsilon > \epsilon_F$ can be determined by the proposed method.

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