Cyclotron waves in semiconducting Bi–Sb alloys

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It is shown that cyclotron waves can be observed in Bi–Sb alloys. An investigation of their spectrum makes it possible to determine such characteristics of matter as the effective carrier masses, the dielectric constant of the crystal lattice, etc., and to investigate the electron spectrum in the ultraquantum limit.

Observation of standing magnetoplasma waves of frequency $f=\omega/2\pi\approx 10^{11}$ Hz in semiconducting Bi-Sb alloys was reported for $\mathbf{H}\parallel\mathbf{k}$ in[1] and for $\mathbf{H}\perp\mathbf{k}$ in[2] ($\mathbf{k}$ is the wave vector, and since $v=\omega/k\ll c$ it follows that $\mathbf{k}$ is normal to the plane of the sample surface). Waves with $\mathbf{k}\parallel\mathbf{H}$ are helicons and their investigation makes it possible to measure the carrier density N. The nature of waves with $\mathbf{k}\perp\mathbf{H}$ is not explained in[2]. It will be shown here that these are cyclotron waves and have a spectrum similar to that of cyclotron waves in pure bismuth.[3]

The experiment was performed with n-type $Bi_{0.865}Sb_{0.135}$ samples with $N=(5-6)\times 10^{14}$ cm^{-3}. The electron density was determined from the velocity of the helicons observed in the same samples. Samples in the form of plane-parallel plates ~0.7–0.3 mm thick were spark-cut from single-crystal stock. The samples were placed against an opening of 1.2 mm diameter in the wall of a resonator for the 2-mm band. The change in the sample impedance following excitation of standing magnetoplasma waves was revealed by the change in the microwave power passing through the resonator.[1] An experimental plot is shown in Fig. 1.

Let us calculate the spectrum of the wave at $\mathbf{H}\parallel C_1$ (C_1, C_2, and C_3 are respectively the bisector, binary, and trigonal axis of the crystal). According to the experiment, the waves are best excited when the microwave current $\mathbf{I}$ in the resonator is parallel to $\mathbf{H}$. At $\mathbf{H}\parallel C_1$, owing to the symmetry, the conductivity tensor components $\sigma_{zx}=\sigma_{xz}=\sigma_{zy}=\sigma_{yz}=0$. The spectrum of the wave is therefore determined only by σ_{zz}, which can be calculated, if the Fermi surface is known, from the formulas given in[4].

The Fermi surface of the investigated alloy consists of three equivalent ellipsoids that are transformed into one another by a 120° rotation about the C_3 axis.[5] The ratio of the principal axis of the ellipsoids is $p_{C_2}:p_{C_3}:p_{C_1}=1:\alpha:\beta=1:1.4:15$. (We neglect the ~6° inclination of the ellipsoids in the basal plane.)

Performing the corresponding calculations, we obtain from Maxwell's equations, with allowance for the displacement currents,

$$k^2=\frac{\omega^2}{c^2}\epsilon+\frac{4\pi}{3c^2}\frac{Ne^2}{m}\alpha\left(\frac{6\omega^2/\Omega^2}{1-4\omega^2/\Omega^2}-\frac{9}{\beta^2}\right), \qquad (1)$$

where ϵ is the dielectric constant of the crystal lattice, m is the minimal effective mass of the electrons at $\mathbf{H}\parallel C_1$, and $\Omega=eH/mc$. Expression (1) is valid in the classical limit. In our case, standing waves were observed at $H\gtrsim 300$ Oe. According to the estimates, a single Landau level remains at $H>350$–400 Oe for each section of the Fermi surface below the Fermi level (we assume that the spin splitting, as in pure bismith, is close to the cyclotron splitting). Quantization at $\mathbf{k}\cdot\mathbf{v}/$

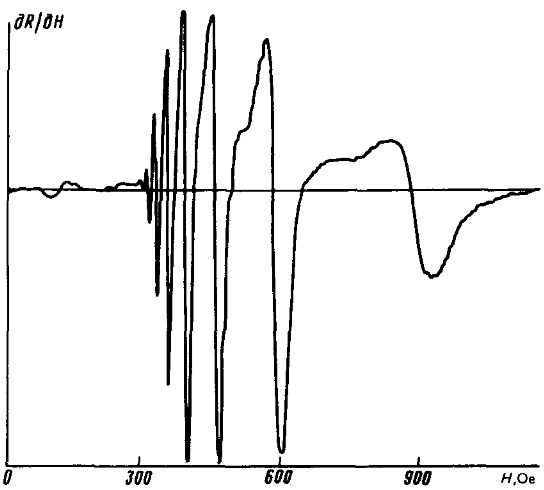

FIG. 1. n-BiSb surface-impedance oscillations due to excitation of standing cyclotron waves: $f=131$ GHz; $\mathbf{H}\parallel C_1$; $\mathbf{k}\parallel C_3$; $\mathbf{I}\parallel\mathbf{H}$; sample thickness 0.32 mm; $T=1.5$°K; $N=5\times 10^{14}$ cm^{-3}.

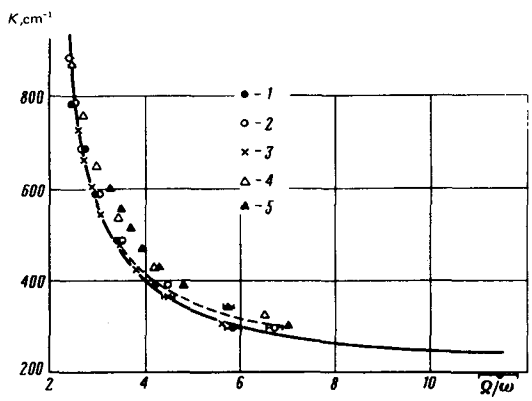

FIG. 2. Plot of $k(\Omega/\omega)$ for cyclotron waves at $\mathbf{H}\parallel C_1$: 1, 2) $\mathbf{k}\parallel C_3$, $d=0.32$ mm, $N=5\times 10^{14}$ cm^{-3}; $f=120.5$ GHz (1), $f=130.1$ GHz (2); 3) $\mathbf{k}\parallel C_3$, $N=5\times 10^{14}$ cm^{-3}, $d=0.52$ mm, $f=135.7$ GHz; 4) $\mathbf{k}\parallel C_2$, $N=6\times 10^{14}$ cm^{-3}, $d=0.29$ mm, $f=132.1$ GHz; 5) $\mathbf{k}\parallel C_2$, $N=6\times 10^{14}$ cm^{-3}, $d=0.73$ mm, $f=140.2$ GHz. Solid curve—calculated from (2) at $f=120.5$ GHz, dashed—$f=135.7$ GHz.

$\omega \gg 1$ (**v** is the electron velocity) does not change σ_{zz} for a quadratic isotropic spectrum.[6] The anisotropy of the Fermi surface leads to a redistribution of the electrons among its different sections. Since the electron density is $dn = [eH/(2\pi\hbar)^2 c]\, dp_z$, it follows that in both "inclined ellipsoids" the total number of electrons becomes equal to the number of electrons in the "right ellipsoid." Taking this circumstance into account, we obtain

$$k^2 = \frac{\omega^2}{c^2}\epsilon + \frac{\pi}{c^2}\frac{Ne^2}{m}a\left(\frac{6\omega^2/\Omega^2}{1-4\omega^2/\Omega^2} - \frac{10}{\beta^2}\right). \qquad (2)$$

Figure 2 shows the experimental values of $k(H)$ and a plot of (2) calculated at $N = 5 \times 10^{14}$ cm^{-3}, $m = 2.8 \times 10^{-3}$ m_e, $\epsilon = 90$. It is interesting to note that at these values of the parameters the sample is transparent for all fields H such that $\Omega/\omega > 2$. The calculation agrees well with experiment. Some difference is observed at $\Omega/\omega = 11$. This may be due to a shift of the electron band,[7] which leads to a further redistribution of the electrons among the different sections of the Fermi surface.

Thus, cyclotron waves in semiconducting alloys were observed for the first time in[2]. Their investigation makes it possible to determine many parameters of the electron spectrum and to study their behavior in a quantizing field.

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