of Δ and G at p = 11.9 and p = 12.3 kbar, calculated from the experimental data. The shift of the gap functions of the ED with increasing H corresponds to motion of the band boundaries in the magnetic field. At p = 12.3 kbar and H = 65 kOe, the gap G of the unreconstructed spectrum is close to zero, and consequently the energy gap $\Delta E \approx 7°K$, determined from the dependence of $\ln[\sigma_{11}(T) - \sigma_{11}(0°K)]$ on 1/T, coincides practically entirely with the maximum value of Δ of the ED phase at H = 65 kOe.

No ED phase is produced at $p \leq 11.4$ kbar and $p \geq 12.9$ kbar in fields $H \leq 65$ kOe, because $|G| > \Delta$ at these pressures.

In conclusion, we take the opportunity to thank A.A. Abrikosov and L.V. Keldysh for a discussion of the results and V.G. Karavaev for help with the measurements.

[1] E.W. Fenton, Phys. Rev. 170, 816 (1968).
[2] Y. Yafet, R.W. Keys, and E.N. Adams, J. Phys. Chem. Sol. 1, 137 (1956).
[3] N.F. Mott, Phil. Magazine 6, 287 (1961).
[4] L.V. Keldysh and Yu.V. Kopaev, Fiz. Tverd. Tela 6, 2791 (1964) [Sov. Phys.-Solid State 6, 2219 (1965)].
[5] A.N. Kozlov and L.A. Maksimov, Zh. Eksp. Teor. Fiz. 48, 1184 (1965) [Sov. Phys.-JETP 21, 790 (1965)].
[6] D. Jerome, T.M. Rice, and W. Kohn, Phys. Rev. 158, 462 (1967).
[7] N.B. Brandt and Ya.G. Ponomarev, Zh. Eksp. Teor. Fiz. 55, 1215 (1968) [Sov. Phys.-JETP 28, 635 (1969)].
[8] A.A. Abrikosov, Low Temp. 2, 37, 175 (1970).
[9] N.B. Brandt and B.A. Svistova, Usp. Fiz. Nauk 101, 249 (1970) [Sov. Phys.-Usp. 13, 370 (1970)].
[10] N.B. Brandt and S.M. Chudinov, Zh. Eksp. Teor. Fiz. 59, 1494 (1970) [Sov. Phys.-JETP 32, No. 5 (1971)].

ELECTROMAGNETIC WAVES NEAR HOLE CYCLOTRON RESONANCE IN BISMUTH

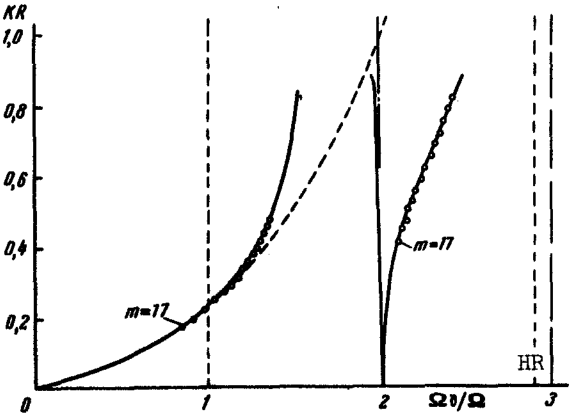
V.P. Naberezhnykh, D.E. Zherebchevskii and V.L. Mel'chik
Donets Physico-technical Institute, Ukrainian Academy of Sciences

Submitted 4 January 1971
ZhETF Pis. Red. 13, No. 3, 150 - 153 (5 February 1971)

The spectrum of the cyclotron waves predicted by Kaner and Skobov [1] consist of three branches. In the case of a strong spatial dispersion (KR >> 1, where K is the wave number and R is the cyclotron radius), two branches of the spectrum have a normal dispersion and lie near the cyclotron-resonance line on the side of the strong magnetic fields ($\omega < n\Omega$, where ω is the frequency of the electromagnetic wave, n the number of the harmonic of the cyclotron resonance, and Ω the cyclotron frequency), while the third branch has a normal dispersion and approaches closely the resonance on the side of the weak magnetic field. In the case of weak spatial dispersion (KR << 1) in metals with a quadratic carrier dispersion law, all the branches of the spectrum have anomalous dispersion and are located near the resonance on the side of the strong magnetic field [2, 3]. In metals with nonquadratic dispersion, there can exist at small KR cyclotron-wave branches that are far from the cyclotron-resonance line. In compensated metals having several types of carriers (electrons and holes) with equal concentration, there can exist in some cases cyclotron-wave spectrum branches at small KR, approaching closely to the cyclotron-resonance line not only from the strong-field side, as in the case of longitudinal polarization [4, 5], but also from the weak-field side1).

---

1) Similar questions were considered in a paper by E.A. Kaner and V.G. Skobov, delivered at the Soviet-Japanese Conference in Novosibirsk, 1969.



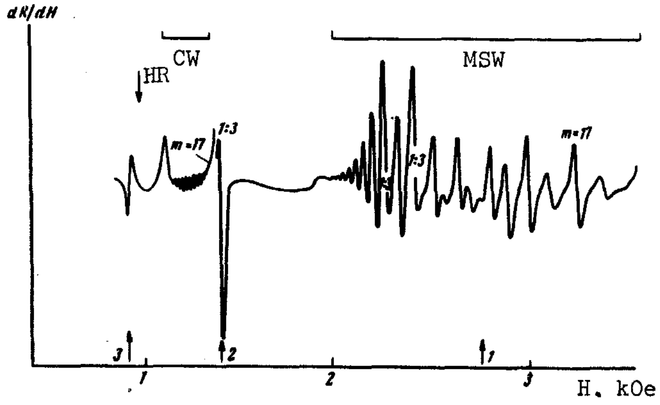


Fig. 1. Spectrum of long-wave electromagnetic waves in bismuth at $\vec{H} \parallel \vec{C}_1$, $\vec{H} \perp \vec{n} \parallel \vec{C}_3$, and $\vec{E} \perp \vec{H}$. The solid lines represent the calculated spectrum, and the points the experimental results. A dashed line shows schematically the spectrum of the "fast" magnetosonic wave in the absence of spatial dispersion (HR - hybrid resonance).

Fig. 2. Standing electromagnetic waves in a bismuth plate, observed in the experiment (CW - cyclotron wave, MSW - "fast" magnetosonic wave. The arrows below indicate the positions of the hole cyclotron resonances and their numbers).

Let us consider the asymptotic ($KR << 1$) behavior of the conductivity tensor in a compensated metal placed in a constant magnetic field in the case when the cyclotron mass of the holes greatly exceeds the cyclotron mass of the electrons. At a constant magnetic field intensity corresponding to the first hole resonances for electrons, the strong-magnetic-field condition is satisfied ($\Omega_{el} >> \omega$) and the nonlocal effects in the electronic part of the conductivity are small. In the hole part of the transverse conductivity, the nonlocal effects play an important role near the cyclotron resonances, starting with the second. Near the first hole resonance, the local hole conductivity increases strongly and greatly exceeds the electronic conductivity, but it decreases rapidly with decreasing magnetic field, and the contribution of the electrons in the hole terms to the local conductivity exceeds the contribution of the holes already between the first and second resonances. As a result, a situation different from that obtained in ordinary metals is produced near the hole electron resonances, starting with the second. The dielectric constant of a compensated metal in this case is positive on both sides of the cyclotron resonance with $n \geq 2$. Consequently, the electronic wave near the hole-cyclotron resonances can propagate both from the side of the strong magnetic fields and from the side of the weak ones.

Besides the cyclotron waves a "fast" magnetosonic wave can propagate in compensated metals in the vicinity of the cyclotron resonances [1]. If the nonlocal effects in the conductivity are small [$(KR)^2 >> \nu$, where ν is the effective hole collision frequency], then the spectrum of this wave should end at the frequency of the hybrid resonance. Allowance for the nonlocal effects in the case when $(KR)^2 >> \nu$ causes the spectrum of the "fast" magnetosonic wave not to reach even the frequency of the second hole resonance.

The spectrum of the "fast" magnetosonic resonance and of the cyclotron waves with transverse polarization in the vicinity of the second hold resonance in bismuth is shown in Fig. 1. In obtaining this spectrum, it was assumed that the direction of the static magnetic field is parallel to the surface of the metal and coincides with the direction of the bisector axis of the crystal, where the normal to the surface is parallel to the trigonal axis (in such a situation $M_1/M_2 \sim 11$, where M_1 and M_2 are the cyclotron masses of the holes and of the electrons, respectively).

An experimental investigation of the spectrum of the electromagnetic waves in bismuth was also carried out in the geometry described above. The sample was a plane-parallel single crystal with normal to the surface parallel to the trigonal axis, and was placed in a rectangular resonator operating at the H_{102} mode. The frequency of the external electromagnetic field was 3.6×10^{10} Hz.

An experimental plot of the derivative of the surface impedance dR/dH against the magnetic field H at a sample thickness $d = 90\ \mu$ and a temperature 1.5°K is shown in Fig. 2. The points on Fig. 1 show the experimental values of KR obtained under the condition that the first observed peak corresponds to $m \equiv Kd/\pi = 17$. As seen from the figure, there is not only good qualitative agreement but also quantitative agreement between the theoretical and experimental data.

In conclusion, the authors thank E.A. Kaner for a useful discussion of the results.

[1] E.A. Kaner and V.G. Skobov, Fiz. Tverd. Tela 6, 1104 (1964) [Sov. Phys.-Solid State 6, 851 (1964)].
[2] W.M. Walsh and P.M. Platzman, Phys. Rev. Lett. 15, 784 (1965).
[3] D.G. Lominadze, M.A. Savchenko, and K.N. Stepanov, Zh. Eksp. Teor. Fiz. 53, 1296 (1967) [Sov. Phys.-JETP 26, 757 (1968)].
[4] V.S. Edel'man, ZhETF Pis. Red. 9, 302 (1969) [JETP Lett. 9, 177 (1969)].
[5] N.B. Brovtsina and V.G. Skobov, Zh. Eksp. Teor. Fiz. 56, 694 (1969) [Sov. Phys.-JETP 29, 379 (1969)].

ACTIVATION CONDUCTIVITY OF ALMOST FULLY COMPENSATED n-GERMANIUM

I.S. Shlimak and V.V. Emtsev
A.F. Ioffe Physico-technical Institute, USSR Academy of Sciences

Submitted 4 January 1971
ZhETF Pis. Red. 13, No. 3, 153 - 157 (5 February 1971)

Shklovskii and Efros [1] have shown that at low temperatures the Fermi level in a compensated semiconductor does not tend to a constant limit when the degree of compensation $K = N_A/N_D$ approaches unity, as would follow from the theory of Miller and Abrahams [2], but drops deep into the forbidden band. This is connected with the fact that the electrons that remain on the uncompensated donors are located in the deepest regions of the potential relief produced by the large-scale fluctuations of the charged-impurity concentration.

We investigate in this paper the temperature region in which the electric conductivity is connected with the electrons activated in the conduction band. As shown in [1], the mobility of the electrons in the conduction band differs from zero, starting with a certain energy called the "flow-through energy," while the conductivity activation energy ε_1 equal to the difference between the "flow-through" energy and the Fermi energy, is given by the expression

$$\epsilon_1 = \epsilon_B + a\frac{e^2 N_D^{1/3}}{\kappa(1-K)^{1/3}}. \qquad (1)$$

Here ε_B is the ionization energy of the isolated donor, κ is the dielectric constant, and α is a numerical coefficient on the order of unity. The