SHIFT OF END-POINT ENERGY OF BISMUTH ELECTRONS IN A MAGNETIC FIELD

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The oscillations and displacement of the Fermi level were measured in single crystals of bismuth at liquid-helium temperature in pulsed magnetic fields up to 50 kOe. The results agree well with those of [1,2] where the shift of the Fermi level in the magnetic field was determined indirectly on the basis of an analysis of the deviation of the hole oscillations from periodicity. Data on the observed spin splitting of the Landau levels are presented.

1. INTRODUCTION

ONE of the methods of determining the parameters of the equal-energy surface of carriers in metals is to study different oscillation effects. It was shown theoretically [3,4] that quantization of the state density in a magnetic field near the end-point energy makes possible oscillations of the Fermi level. These oscillations have the same periodicity as other oscillation effects, i.e.,

$$\Delta\left(\frac{1}{H}\right)=\frac{eh}{cS_{extr}}, \tag{1}$$

where S_{extr} is the extremal intersection of the Fermi surface and the plane perpendicular to the magnetic-field direction. Thus, by investigating the periodic shifts of the Fermi level in a magnetic field it is possible to obtain the same information on the electron spectrum as is derived from other oscillation effects.

Fermi-level oscillations were observed recently in a number of metals. [5-8] Interest attaches in this connection to the results obtained with lead [6] and zinc [7], in which oscillations connected with small carrier groups were obtained, at an amplitude of the order of the interval between the Landau levels. It might seem that a large carrier group would "dampen" the contribution made by small groups to the oscillating increment, so that the theoretical estimates turn out to be smaller by several orders of magnitude than the experimental data. Experiments with lead and zinc have shown that the number of metals on which it is possible to investigate relatively simply the oscillations of the Fermi level increases considerably. Simple experiments and high resolution [7] lead to results that are analogous to those of other oscillation effects.

However, the investigation of the behavior of the Fermi level in a magnetic field makes it possible to solve in principle new problems connected with the study of the electron spectrum in metals. We have in mind measurement of the shift of the Fermi level.

The question of the behavior of the Fermi level in a magnetic field was considered theoretically by Azbel' and Brandt. [9] In addition, on the basis of galvanomagnetic investigations of bismuth in strong magnetic fields (Smith et al. [1] and Brandt et al. [2] used fields up to 88 and 450 kOe, respectively) it became possible to estimate indirectly the shift of the Fermi level. By specifying a definite relation, which does not contradict the experimental data, between the spin and orbital splitting, we have analyzed the deviations in the period of the hole oscillations. For example, the frequencies of the hole oscillations along the binary and bisector axes become higher with increasing magnetic field, thus indicating an increase in the area of the extremal section of the hole ellipsoid. The change in the periodicity of the hole oscillations can be explained by assuming that the Fermi energy decreases smoothly with increasing magnetic field, relative to its value at H = 0.

The previously developed procedure [5] of investigating quantum oscillations of the Fermi level by determining the change of the contact potential difference has made it possible to measure directly also the smooth shift of the Fermi level in the magnetic field. The experiment was carried out at liquid-helium temperature and in pulsed magnetic fields up to 50 kOe.

2. EXPERIMENTAL PROCEDURE

The object of the investigation was single-crystal bismuth whose electric resistivity varied by a

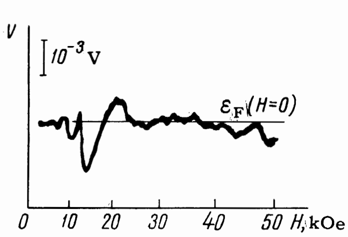

FIG. 1. Shift of Fermi level in a magnetic field. The magnetic field is parallel to the bisector axis of the bismuth single crystal. The scale along the V axis is for the oscillating component of the Fermi level.

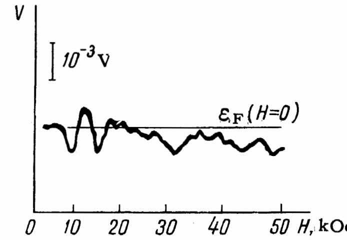

FIG. 2. Shift of Fermi level in a magnetic field. The magnetic field is parallel to the binary axis of the single-crystal bismuth. Scale along the V axis is for the oscillating component of the Fermi level.

factor 150—200 and 500 times when the temperature changed from room to helium.[1)] The investigated sample was a plane-parallel capacitor, one electrode of which was the single-crystal bismuth and the other polycrystalline niobium or tantalum. The dielectric was niobium (tantalum) pentoxide. The high dielectric constant ($\epsilon_{Ta_2O_5} \sim 25$) [10] greatly simplified the construction of miniature high-capacitance samples, making it possible to perform the measurements in solenoids with small working volumes.

To observe the Fermi-level shift it is necessary to satisfy the same conditions as were proposed by Kulik and Gogadze [4] and by Caplin and Shoenberg [6] to observe the oscillating component. The only difference is that the shift of the Fermi level is a process of lower frequency, and to satisfy the conditions imposed in [4,6] it was necessary to have samples with larger capacitance than those employed by us earlier [5] to observe the Fermi-level oscillations. We were unable to obtain samples of the (theoretically) required capacitance $\sim 5 \times 10^{-8}$ F, and all the measurements were made with samples of capacitance $1 \times 10^{-8} - 2 \times 10^{-8}$ F, so that the observed shifts of the Fermi level are somewhat underestimated (the "leakage" of the charge from the capacitor sample was faster than the change in the Fermi level). Using an equivalent circuit in which the sample capacitor was replaced by a fixed capacitor of the same rating, we were able to estimate accurately the true change in the Fermi level. Thus, besides qualitative agreement with the results of [1,2], a quantitative comparison is also possible.

To exclude completely the electric induction in the sample, due to the pulsed magnetic field (although its value can be easily taken into account), we chose the sensitivity of the measuring circuits such that there was no induction at 77°K and the magnetic-field interval in which the measurements were made at 4.2°K. No quantum oscillations of the Fermi level are observed at 77°K, so that no shift of the end-point energy could be observed.

3. EXPERIMENTAL RESULTS

Figures 1 and 2 show oscillograms of the shift of the Fermi level, for a magnetic field directed along the principal crystallographic axes C_1 and C_2 (the bisector and binary axes, respectively). Figures 3 and 4 show the shift of the Fermi level (including the oscillating component) as a function of the reciprocal magnetic field, with allowance for the correction for the decrease in the observed shift due to the methodological factors indicated above. No shift of the Fermi level was observed when the magnetic field was oriented along the trigonal axis (C_3) in fields up to 50 kOe. The error in the determination of the shift did not exceed $\pm 10^{-3}$ eV in our experiment. The accuracy of the orientation of the crystallographic axes in the single-crystal bismuth, relative to the direction of the magnetic field in the solenoid, was estimated to be not worse than ± 4°.

4. DISCUSSION OF RESULTS

The fact that a change in the carrier density is observed in bismuth even at relatively weak magnetic fields[1,2,11-14] allows us to postulate a possi-

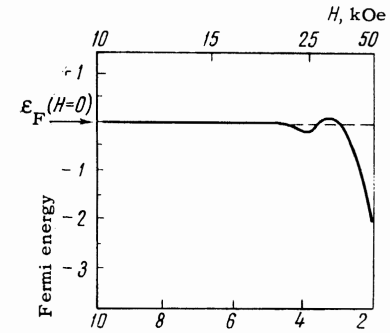

FIG. 3. Monotonic component of the Fermi level (MeV) in a magnetic field. Magnetic field parallel to the bisector axis.

[1)]We take the opportunity to thank B. N. Aleksandrov for supplying the bismuth with a ratio $\rho(300°)/\rho(4.2°) = 500$.

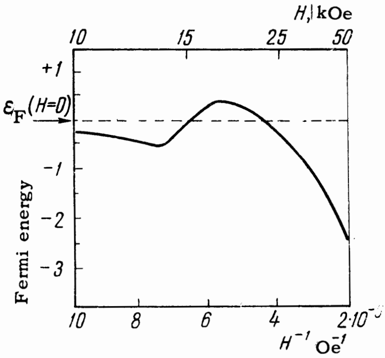

FIG. 4. Monotonic component of the Fermi level in a magnetic field. Magnetic field parallel to the binary axis.

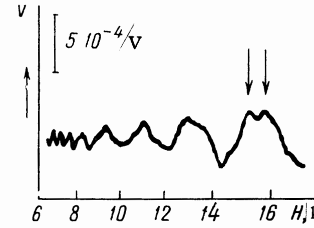

FIG. 6. Oscillations of Fermi level in a magnetic field. Magnetic field parallel to the trigonal axis. The arrows indicate the spin splitting.

ble change in the Fermi level. Grenier et al.[11] considered a case in which the last Landau level moves past the Fermi level in one of the electron ellipsoids; this can occur if the spin splitting is smaller than the orbital splitting. In this case the ellipsoid becomes depleted, leading to a change in the carrier density in the other ellipsoids. This results in a change in the Fermi level and, if we neglect the fact that the carrier density could change even before the ultraquantum limit $\mu^*H \sim \epsilon_F$ could be reached in the indicated electronic ellipsoid (μ^*—effective Bohr magneton, ϵ_F—Fermi energy), the proposed change in the Fermi level should have a positive sign and should occur jumpwise. However, in the case when the spin splitting exceeds the orbital splitting, one (last) Landau level will always be lower than the Fermi level. With increasing magnetic field, the level will drop to a lower energy, leading to a decrease in the end-point energy, a fact considered by Smith et al.[1] and studied in greater detail in magnetic fields up to 450 kOe by Brandt et al.[2]

The Fermi-level shift observed by us directly agrees qualitatively (within the limits of experimental accuracy) and quantitatively with the results of[1,2].

When the magnetic field direction is along the binary axis (C_2), a slight lowering of the Fermi level is observed in fields up to ~15 kOe (see

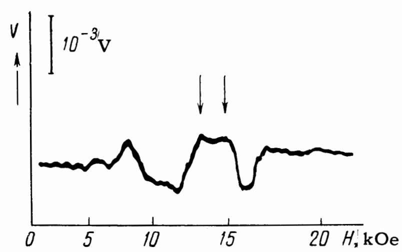

FIG. 5. Oscillations of Fermi level in a magnetic field. Magnetic field parallel to the binary axis. The arrows indicate the spin splitting.

Fig. 5); in order to correctly separate the monotonic variation against the background of the oscillating increment, it is necessary to take account of the fact that the oscillations connected with the Landau levels having a small principal quantum number n have a sharply asymmetrical form (in the form of peaks[12]). The asymmetry of the form of the oscillations of the Fermi level can be verified by measurements on samples of small capacitance, in which the Fermi level shift could not be observed. In magnetic fields stronger than 30 kOe, the observed shift agrees well with the data of[1,2]. When the magnetic field is oriented along the bisector axis (C_1), the Fermi level begins to drop smoothly after going through oscillations connected with the passage of two Landau levels with $n = 0^+$ and $n = 1^-$ past the Fermi level (the plus and minus signs correspond to addition of an energy $\pm(1/2)g^*\mu H$, where g^* is the effective g-factor and μ is the Bohr magneton[1]). In a 50-kOe field, the Fermi level decreases by $\sim 2\times10^{-3}$ eV relative to the value ϵ_F (H = 0), in agreement with the data of[1,2].

5. SPIN SPLITTING OF THE LANDAU LEVELS

The question of the spin splitting of the Landau levels in bismuth was considered both theoretically[15-17] and experimentally[1,2,18-23]. Figures 5 and 6 show Fermi-level oscillations in bismuth for magnetic-field directions along the binary (C_2) and trigonal (C_3) axes. For H ∥ C_2 in a magnetic field of ~15 kOe, spin splitting is observed with a period $\Delta(1/H) = 0.7\times10^{-5}$ Oe^{-1}. It is impossible to conclude any relation between the spin and orbital splittings directly on the basis of the obtained value of the spin splitting of the Landau level. Assuming that the spin splitting is much smaller than the orbital one, we can estimate[2)] the magnetic field necessary to observe the last Fermi oscillation,

[2)]The values of the cyclotron masses were taken from the paper of Édel'man and Khaikin [24], and the end-point energy from the papers of Smith et al. [1] and Brandt et al. [25].

connected with the passage of the Landau level n = 0 through the end-point energy, for the given field orientation ($H \parallel C_2$). According to the estimates, this should take place in a magnetic field ~40 kOe. If we make no assumptions whatever, for example, that the electronic ellipsoid has become depleted before reaching the ultraquantum limit, then we can understand why no oscillation of n = 0 is observed in such a field (~40 kOe).

Thus, it remains to assume that we have observed a large spin splitting, which is either somewhat smaller[19] or somewhat larger[1,2] than the orbital splitting. In the former case the observed splitting can be connected with the passage of the two Landau levels $n = 1^-$ and $n = 0^+$ past the Fermi level. In the latter case the observed splitting is identified with the levels $n = 0^+$ and $n = 1^-$; the level $n = 0^-$ never crosses the Fermi level and drops with increasing magnetic field, in good agreement with the observed decrease of the end-point energy. Spin splitting when the magnetic field is oriented near the C_1 axis was considered by us earlier[26]. Figure 6 shows an oscillogram of the Fermi-level oscillations when the magnetic field is directed along the C_3 axis. The observed splitting has a period $\Delta(1/H) = 0.5 \times 10^{-5}\ \mathrm{Oe}^{-1}$.

6. CONCLUSION

According to Azbel' and Brandt[9] measurement of the end-point energy can be used to investigate the dispersion law in an energy interval on the order of μH. We have carried out the measurements in magnetic fields up to 50 kOe, when the distance between Landau levels is commensurate with the end-point energy for certain directions. The reaching of the ultraquantum limit for one of the electronic ellipsoids leads to singularities in the behavior of the Fermi level in the magnetic field (see Figs. 3 and 4). For free electrons this question was considered in detail by Rumer[27]. For bismuth, however, a separate analysis is necessary, since we have in mind the singularities in its band structure. The presence of carriers as a result of an overlap of a perfectly empty and completely filled bands causes the electronic characteristics of bismuth to have a number of singularities when the overlap changes in the magnetic field[9]. Thus, measurement of the shift of the Fermi level makes it possible to estimate directly the changes that occur in the metal carrier bands in a magnetic field. It should be noted that the observed lowering of the Fermi level can be regarded as a peculiar oscillation connected with the fact that the energy of the Landau level $n = 0^-$ is decreased, with increasing magnetic field, in the electronic ellipsoid where the ultraquantum limit is reached.

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