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SHUBNIKOV—DE HAAS OSCILLATIONS IN BiSeJ CRYSTALS

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The present paper presents results of the investigation of the magnetoresistance of BiSeJ single crystals at a temperature of 4.2 °K in pulsed magnetic fields with an amplitude of up to 150 kOe. The oscillations of the electric resistance were observed for various orientations of the magnetic field with respect to the crystal axes of the sample.

I. INTRODUCTION

The physical properties of crystals of the type $A^{V}B^{VI}C^{VII}$, to which also BiSeJ belongs, have been the subject of considerable interest in the last years. The physical properties of these crystals and thus their energy spectrum have so far not been fully known. This paper is devoted to the study of some peculiarities of the energy spectrum of BiSeJ single crystals using the Shubnikov—de Haas (*SdH*) effect.

The crystals of BiSeJ have a chain structure. Within the chains — similarly as in SbSJ — strong covalent forces are acting, while the mutual coupling between chains is effected by means of weak Van der Waals forces. An apparent anisotropy of the lattice causes an anisotropy of the majority of the physical properties of these substances. Especially in the chain structures there is an apparent anisotropy of the ellipsoidal surface of a constant energy. The smallest semi-axis, and of course also an effective mass of carriers, will in this case be

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oriented in the direction along the chains in the straight lattice. A small overlap of the wave functions between adjacent chains causes that in the direction perpendicular to the chain the effective mass of the charge carriers will be large.

For these reasons we studied the *SdH* effect on BiSeJ crystals with the aim to determine at least qualitatively the peculiarities of their band structure.

II. MEASURING METHOD

For the measurements of the oscillations of resistance an apparatus was used whose circuit diagram is shown in Fig. 1. After charging the condenser

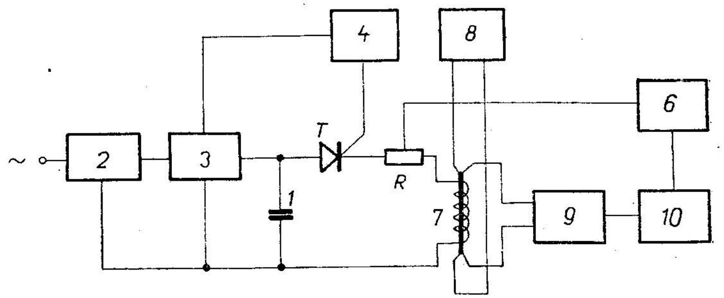

Fig. 1. Diagram of the measuring apparatus.

bank 1 (the maximum energy of the bank is 5 kJ) to the required voltage from source 2 through the regulating circuit 3, five parallelly connected thyristors *T* 250/1200 were started by a pilot pulse from the control circuit 4. The condenser bank was discharged into the pulse solenoid 5. In series with the pulse solenoid an inductance free resistor was connected, the output signal from which was conducted to the horizontal amplifier of the oscilloscope 6. A direct current of constant amplitude was passed through the sample 7. The voltage drop on the sample was after the amplification in a high impedance amplifier 9 conducted to the differential amplifier 10 and then to the vertical amplifier of the oscilloscope 6. The resulting signal on the screen was photo graphed.

This apparatus was able to generate pulse magnetic fields up to about 150 kOe. The field was homogeneous in the volume of about 75 mm³. The pulse width on the level of 10 % was approximately 100 ms. The pulse solenoid together with the sample was immersed in a Dewar flask containing liquid helium.

III. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

BiSeJ samples were prepared by the method of chemical transport reactions [1]. Crystals prepared in this way had the form of plates with dimensions of $10 \times 4 \times 2$ mm³.

The structural X-ray analysis of BiSeJ crystals was made by E. Dönges [2] who found that BiSeJ crystallizes in a lattice with the symmetry D_{2h}^{16} — — P_{nam}. The measurements of the magnetoresistance were carried out for the following orientations of the magnetic field:

a. The magnetic field was in the direction of the *c* axis, that is in the direction of the chains (a longitudinal effect).

b. The magnetic field was in the direction of the *a* axis (a transverse effect).

c. The magnetic field was in the direction of the *b* axis (the direction of the current in all cases was parallel to the *c* axis).

Measurements of the coefficient of the differential thermal *e.m.f.* of measured samples show that BiSeJ crystals have the electron type of electric conductivity. According to the analysis of the temperature dependence of the thermal *e.m.f.*, the electron gas in these crystals is degenerate, which was confirmed also by the study of the photoemission [3, 4]. The estimation of the Fermi level E_F based on the analysis of photoemissive voltampere characteristics gives the value of 0.9 ± 0.1 eV.

The results of measurements of the longitudinal magnetoresistance oscillation $(\Delta\varrho/\varrho_0)_{\parallel}$, for the case **a.** are shown in Fig. 2. Fig. 3 shows the dependence of the transverse magnetoresistance $(\Delta\varrho/\varrho_0)_{\perp}$, upon the magnetic field (cases **b** and **c**). It is evident from these figures that the magnetoresistance exhibits an oscillation character in all cases. The transverse magnetoresistance in-

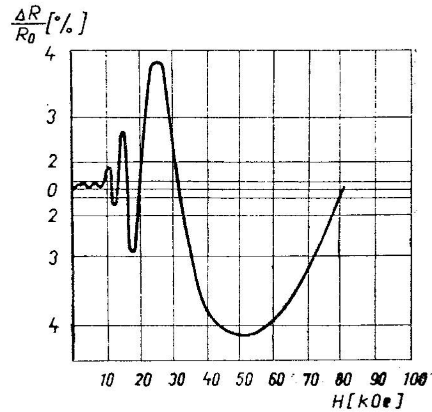

Fig. 2. Dependence of the longitudinal magnetoresistance upon the magnetic field *H*.

creases with the increase of the magnetic field, which is in agreement with the general theory of the transverse effect ($\varrho_\perp(H) \sim (H/e\,n\,c)^2\,\sigma_{zz}$).

The explanation of the mechanism of the SdH effect in BiSeJ crystals is very difficult, because there is a lack of many experimental data for these crystals, for example the concentration and the mobility of carriers, the temperature dependence of mobility etc. In addition the dispersion law for these crystals deviates considerably from the quadratic dependence $\varepsilon(k)$ in the extreme points of the Brillouin zone. For these reasons only qualitative conclusions can be drawn from the obtained dependences.

It is known [5] that the period of magnetoresistance oscillations in the magnetic field is given by the value of the extreme cross-sectional area of the isoenergy surface ($\Delta(1/H) = 2\pi e/\hbar c A_H$) in the direction perpendicular to the magnetic field. From the obtained experimental data the value $\Delta_{\parallel}(1/H) =$

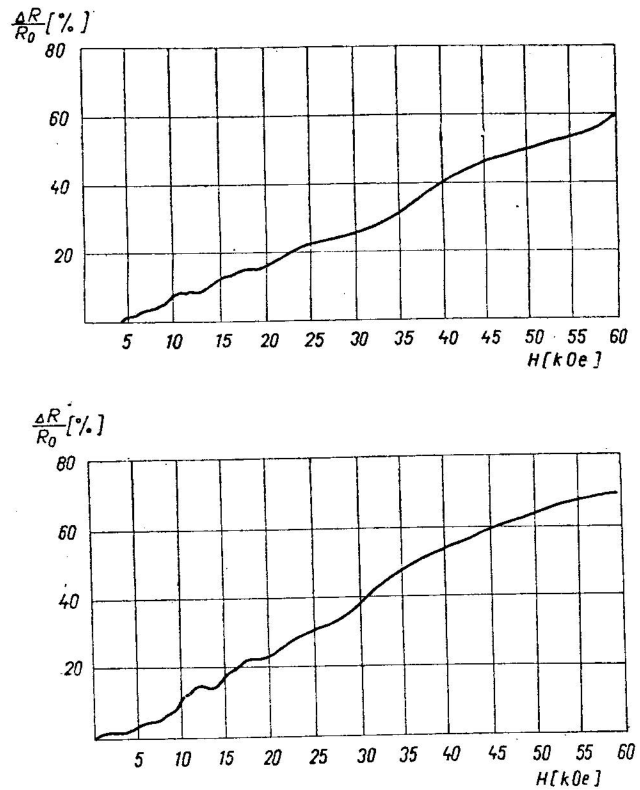

Fig. 3. Dependence of the transverse magnetoresistance upon the magnetic field H.

$= 2.7 \times 10^{-5}\,\mathrm{Oe}^{-1}$ was found for the period of the longitudinal magnetoresistance oscillations.

It was shown in [6] that the surface of constant energy in BiSeJ crystals in the vicinity of the extreme points located inside the Brillouin zone have for low energies the form of threeaxis ellipsoids. It was shown, however, that a and b differ only slightly, so that for the components of the tensor of the effective mass the approximation $m_{xx} \approx m_{yy}$ is valid. It means that the surfaces of constant energy in this case are represented by rotational ellipsoids with the axis of rotation $z(z \parallel c)$ and with a shorter semi-axis in the direction of the c axis. The period of the transverse magnetoresistance oscillations was determined from the position of oscillation maxima in the dependence $\Delta\varrho/\varrho_0\,(H)_\perp$ [7]. We obtained the values $\Delta_\perp(1/H) = 4.3\times10^{-5}\,\mathrm{Oe}^{-1}$ for the magnetic field in the direction of the b axis and $\Delta_\perp(1/H) = 4.8\times10^{-5}\,\mathrm{Oe}^{-1}$ for the magnetic fields in the direction of the a axis. From these values of the oscillation periods $\Delta(1/H)$ a coefficient of the anisotropy of effective masses of electrons was found

$$K = \left(\frac{A_H^{\parallel}}{A_H^{\perp}}\right)^2 = 3.2, \quad \text{where } K = \frac{m_\perp^*}{m_\parallel^*}.$$

This result indicates a considerable anisotropy of the conduction band. However, the numerical value of the coefficient K is not in egreement with the value of the anisotropy of electrical conductivity. which was between 25—30 for the majority of the investigated crystals. This discrepancy is probably caused by the inaccurate orientation of the sample to the crystallographic axes.

The splitting of the oscillation maxima was observed in the case of transverse magnetoresistance (Fig. 3a,b). This splitting is associated with the splitting of the Landau levels, whose magnitude and anisotropy is given by the g-factor. In our case we obtained from the course of the splitted maxima the value of $g \approx 20$.

In the case of rhombic crystals, to which also BiSeJ belongs, only a spin degeneration may exist in the points inside the Brillouin zone [6]. It can be therefore shown when the symmetry of the problem is considered and when the spin-orbital coupling is included that the terms containing magnetic fields are relativistic corrections of the (k^2c^{-2}) order [8]. Then the anisotropy of the g-factor will be small, that is $g \approx 2$.

The deviation of the value the of g-factor from 2 indicates the complicated character of the isoenergy surfaces of the BiSeJ crystals. If we consider the interaction between two near situated subbands of the conduction zone due to the presence of two chains in an elementary cell [9], then the surfaces of constant energy have the form of cut-off ellipsoids. In a secular problem the interference terms (k_y, k_z) leading to the increase of paramagnetism in the direction $H \parallel c$ will appear when a similar interaction is considered. On the other hand the above mentioned experimental results show that spin splitting of the oscillation maxima appears in the case of the transverse and not the longitudinal magnetoresistance. This may be explained assuming that the conduction band is localized in the points $T(0, \pi/a_2, \pi/a_3)$ and $U(\pi/a_1, 0, \pi/a_3)$ or on the axes of symmetry of the surface of the Brillouin zone.

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