New Phenomena in the Change of Resistance of Bi Single Crystals in Magnetic Fields

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It is well known that of all metals Bi shows the greatest change of resistance of electrical conductivity in a magnetic field. These changes in conductivity are strongly dependent upon the orientation of the crystal and upon the direction of the crystal axes with respect to the directions of the field and of the current. In the present investigation it has been possible for the first time by means of a specially constructed crystal-goniometer to investigate the conductivity of a metal-crystal in every desired configuration of current, field and crystal axes, which has not previously been done.

The Bi single crystal rods of 5 cm length and 2–3 mm diameter were rotated about an axis, which was always perpendicular to the long-axis of the rod and to the magnetic field. The crystallographic orientation of the single crystal rods gave the following three cases: (1) The principal axis (111) perpendicular to the axis of the rod and parallel to the rotation axis (P_1-crystals); (2) The principal axis (111) perpendicular to the axis of the rod and perpendicular to the rotation axis (P_2-crystals); (3) The principal axis (111) parallel to the axis of the rod and perpendicular to the rotation axis (P_3-crystals).

Besides in each of these three cases one had to discriminate, whether the traces of the imperfect cleavage planes $(11\bar{1})$ in the (111)-plane were perpendicular or parallel to the directions of the current or of the field and whether such extreme positions could be obtained by the rotation of the crystal in the field. This led to a subdivision of the three groups in the following three subgroups: $P_1^{\perp}$ and $P_1^{\parallel}$, $P_2^{\perp}$ and $P_2^{\parallel}$, $P_3^{\perp}$ and $P_3^{\parallel}$.

Fig. 1 shows the behavior of the conductivity of a $P_1^{\perp}$ crystal at a rotation in the constant magnetic field of $H=3000\ AW/\text{cm}$; Fig. 2 shows the same for the $P_1^{\parallel}$-type. (φ= angle between current and magnetic field.)

It is evident that there is a fundamental difference between the resistance changes of a single crystal and of a polycrystal in a magnetic field. In polycrystalline materials it is well established except in the case of ferromagnetic metals that the change of resistance is greatest, when the direction of the current is at right angles to the magnetic field ($\varphi=90°$) and is least, when it is parallel or antiparallel to the field ($\varphi=0°$, 180°). These curves, however, show that this is not always the case for single crystals.

Measurements on *poly*crystals, therefore, are

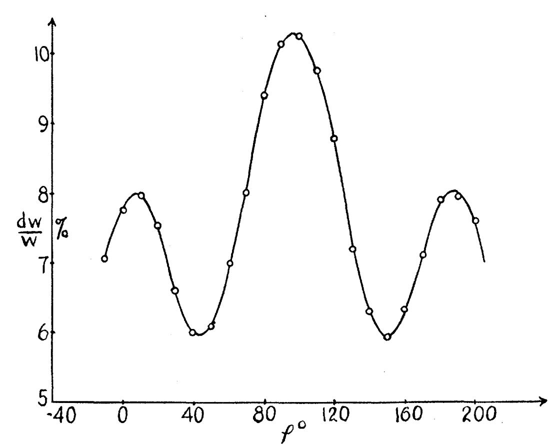

FIG. 1. $H=3000\ AW/\text{cm}$.

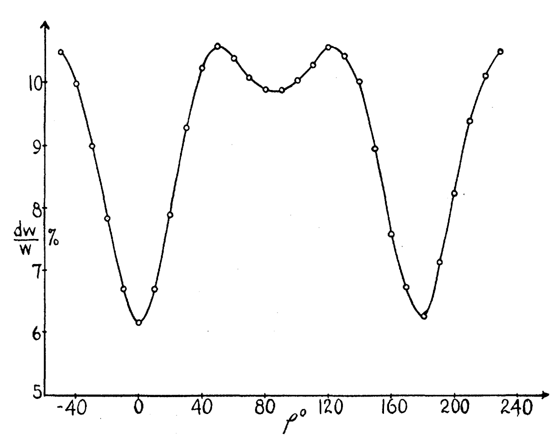

FIG. 2. $H=3000\ tW/\text{cm}$.

not in general capable of elucidating the real laws of magnetic resistance changes of metals.

The shapes of the curves Figs. 1 and 2 which repeat themselves with a period of 180°[1] suggested the calculation of the Fourier coefficients of these periodic functions. The analysis gave the following results:

$P_1^{\perp}$ (Fig. 1) $A_0=7.7$, $A_1=-1.35$, $A_2=1.5$, $A_3=0.12$.

$P_1^{\parallel}$ (Fig. 2) $A_0=9.2$, $A_1=-1.7$, $A_2=-1.16$, $A_3=-0.15$.

The coefficient A_0 is of little interest as it is independent of the rotation of the crystal in the field.

The frequency A_1 is determined by the variation of the angle between the current and the field and is in no way connected with the symmetry of the crystal. It characterizes only the *poly*crystalline behavior.

The crystallographic significance of the third Fourier coefficient, A_3, is very simple. It is due to the sixfold symmetry of the Bi lattice (six imperfect cleavage planes of the type $11\bar{1}$).[2]

Both frequencies A_1 and A_3 with reference to their respective symmetry elements obey a $\cos^2$ law. Further investigation showed that all the observed phenomena of the magnetic resistance variation of Bi can be expressed as a sum of a series of $\cos^2$ terms.

The last period, A_2, is very difficult to attribute to the primary structure of the Bi lattice, since it goes through not one or three but two cycles upon rotating the crystal through 180°. We shall see from the measurements upon crystals into which small amounts of impurities have been introduced that the Fourier analysis of the curves shows that the *secondary* structure of the Bi lattice is responsible for the frequency A_2.

The P_2 series shows a much simpler behavior of the conductivity in a magnetic field than the P_1 series. Fig. 3a shows the $P_2^{\parallel}$-type. None of the $(11\bar{1})$-planes are brought by rotation into an extreme position with respect to the field, and therefore make no contribution to the change of resistance. In the $P_2^{\perp}$-case (Fig. 3b), however, one of the $(11\bar{1})$-planes reaches a perpendicular position with respect to the field at $\varphi=18°\ 25'$ (or at $\varphi=-18°\ 25'$, depending on the starting position of the crystal in the field), and after a further rotation of 90° a parallel position. Therefore the maxima and minima of the curves 3b are shifted from their 0° and 90° positions.

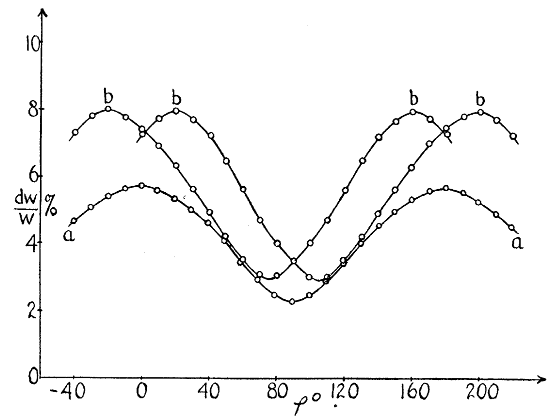

FIG. 3. $H=3000\ tW/\text{cm}$.

The P_3 crystal shows a very similar behavior.

The P_2 crystal is the first case observed for a nonferromagnetic material in which the magnetic change of resistance is greater when the current is parallel to the field than when it is perpendicular. Such a phenomenon previously has neither been observed nor suspected but follows simply from the fact that the influence of one of the crystal planes is far stronger than that of the direction of the current.

Finally, single crystals of the P_1-type with impurities have been investigated. These crystals show qualitatively the same picture as the pure Bi crystals, especially the appearance of the frequency A_2. Besides the *general* decrease of the resistance change with all kinds of impurities the frequency A_2 is affected in a *characteristic* way by the foreign metal atoms. This is another reason for the supposition that the frequency A_2 is due to a secondary structure. The frequency A_2 is diminished or increased with respect to the other frequencies A_n according to whether the impurities are to the left or to the right of the Bi column of the periodic system.

It is shown in all the above measurements that most of the important crystal planes influence the resistance change in some characteristic fashion.

[1] Complete polar-diagrams from 0° to 360° have been taken.

[2] Cf. Schubuikow and de Haas, Comm. Leid. 207.

This is true of all the planes which are necessary for the description of the elementary cell of Bi lattice. *Direct* electric or magnetic measurements do not discriminate these planes. The magnetic change of resistance may therefore be regarded as a means of crystal analysis. This type of crystal structure analysis is not as generally useful as the optical methods but is a very sensitive one for detecting structure elements which have not yet been found optically.