YU ISSN 0015-3206
FZKAAA 19 (1) 51 (1987)

THE LINEAR TERMS OF MAGNETORESISTANCE FOR *n*-TYPE LEAD SULPHIDE AT 300 K

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Received 18 February 1985

Revised manuscript received 24 December 1986

UDC 538.93

Original scientific paper

The longitudinal magnetoresistance (MR) of *n*-type lead sulphide PbS with carrier concentration of 10^{15} cm^{-3} was measured at 300 K. These measurements were done under a weak electric and magnetic fields. The anomalous linear terms $\Delta\varrho/\varrho_0\,(B)$ and the positive normal components $\Delta\varrho/\varrho_0\,(B^2)$ of MR were calculated from B-MR dependence at different rotational angles Θ between the magnetic field B and current direction I. This shows that the MR is not only even power of B dependent, but also an odd power of B dependent phenomenon. The anomalous behaviour of longitudinal MR was observed at the two reversal directions of B. These results may be attributed to the irregular change in the direction of induced Hall field at different Θ as a result of deviation of the current flow direction from the axis of symmetry.

1. Introduction

It is well known that lead salts, PbS, PbSe and PbTe are partially polar semiconductors with an average valence of five and crystallize in the rock salt structure. The early measurements of Hall coefficient, conductivity and thermoelectric power, showed that these compounds could exist either as *n*-type or *p*-type and having fairly small energy gaps, low resistivities, large carrier mobilities and unusally high dielectric constants which do not usually appear in polar crystals. Their characteristics have made the various electrical, optical and galvanomagnetic measurements possible[1–5].

From the solution of Boltzmann's transport equation for arbitrary band shape at low magnetic field strength, it was observed that the magnetoresistance MR should depend only on even powers of applied magnetic field[6] which was called *normal positive effect*. In the metallic conduction range of n-Ge at low temperature ($T =$ $= 4.2$ K), it was found that the MR was separated into two components[7]. One being positive and proportional with B^2, and the other being negative which was called *anomalous effect*.

The negative MR of n-type PbS (nature galena) was observed under a weak B and at very low temperatures[8-10]. This behaviour is explained on the basis of Toyozawa's theory[11].

The aim of this work is to calculate the linear terms of longitudinal MR for n-PbS crystal at $T = 300$ K by measuring the B-$\Delta\varrho/\varrho_0$ relation at different rotational angles Θ, when the current passing through the sample does not flow along any of the symmetry axes related to the set of ellipsoides.

2. *Experimental procedure*

Measurements have been performed at $T = 300$ K on n-type lead sulphide with charge carriers of 10^{15} cm^{-3} and n is determined from the Hall effect measurement at the investigated temperature. The PbS sample was cut out from monocrystalline material in a direction at which the current flow direction was deviated from the axis of symmetry. Typical samplê geometries were $10 \times 1.5 \times 0.6$ mm^3. Electrical ohmic contacts of the sample which has a bridge shape were carefully realized. Their ohmic nature was verified by measuring the resistivity of the sample as a function of current when $B = 0$, because the contact resistance must be small compared with the bulk resistance of the sample, especially for PbS.

The sample could be rotated with respect to the magnetic field direction by using a cryostat. The strength of D. C. electro-magnet was measured by a calibrated gaussmeter. The measurements were made in a weak electric field (the measurable voltage drop was of the order of 10 mV beacuse of the high conductivity of n-PbS) and under a low magnetic field up to 0.3 T.

3. *Results and discussion*

In Fig. 1 the longitudinal MR is plotted against B at different rotational angles Θ between the directions of both B and I. These measurements were performed at $T = 300$ K. The parabolic curves of MR are positive at some angles like $\Theta = 100°$, $\Theta = 220°$ and $\Theta = 310°$, but at the other angles the MR curves are partially negative at low fields and become positive for relatively high B. The negative saturation case of some MR curves were showed at $\Theta = 40°$ and $\Theta = 270°$ i. e. the negative MR area is well visible. The anomalous behaviour of MR at the two opposite directions of B is to be ncticed, i. e. the MR curves at $\Theta = (40°, 220°)$, $\Theta = (90°, 270°)$ and $\Theta = (130°, 310°)$ are not symmetric. Also the magnitude of this effect depends on the negative depth of each MR curve. Fig. 1 shows that the MR is not only magnetic field and temperature[8,10,12,13] dependent, but also angle dependent phenomenon. The different distributions of the longitudinal MR measurements at different Θ, show that at least neither the conduction band nor donor level of n-PbS can be regarded as spherical.

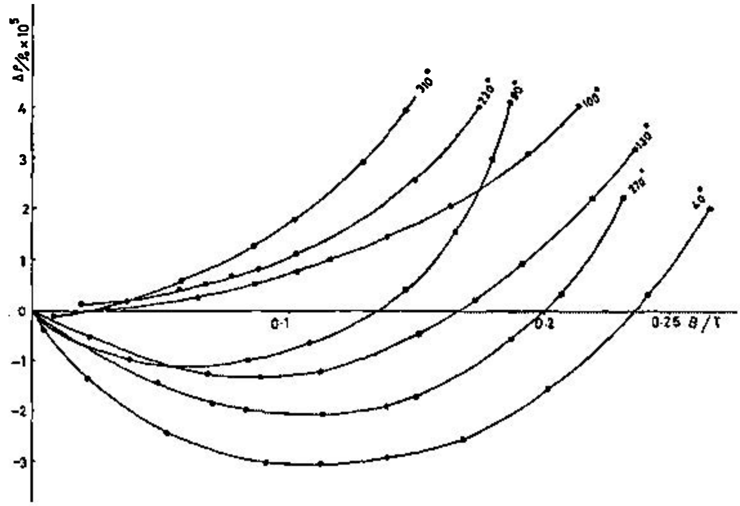

Fig. 1. The field dependence of magnetoresistivity $\Delta\varrho/\varrho_0$ at temperature 300 K for different rotational angles Θ.

For calculating the two contributions of the longitudinal MR at different Θ, the measured magnetoresistivity could be written in the power series of B as given from the following empirical expression

$$\Delta\varrho/\varrho_0 (B) = a_0 + a_1 B + a_2 B^2 + \dots$$

where the first order term represents the linear anomalous dependence $\Delta\varrho/\varrho_0 B$ (odd power of B) and the second order component describes the normal positive dependence $\Delta\varrho/\varrho_0 B^2$ (even power of B). The constants a_0, a_1 and a_2 depend on the temperature and the geometry of the sample (orientation). This formula was fitted to the experimental data at every rotational angle in order to calculate the two contributions of MR at $T = 300$ K as shown in Figs. 2 and 4.

From the fundamental basis of theoretical calculations[14-16] for the relation between the MR and the power series of B, it was found that MR depends only on the even power of B. This means that the Onsager symmetry[17] is automatically contained in solutions of Boltzmann equation. In addition, it has been shown that $B_{ijk} = -B_{ijk}$ and $\varrho_{ijk} = -\varrho_{ijk}$ so the Boltzmann equation does not explain the anomalous linear term $F\varrho/\varrho_0 (B)$ of MR. Moreover, Toyozawa[11] gave a theoretical interpretation of the negative MR occuring in some semiconductors on the basis of second order arising from perturbation analysis.

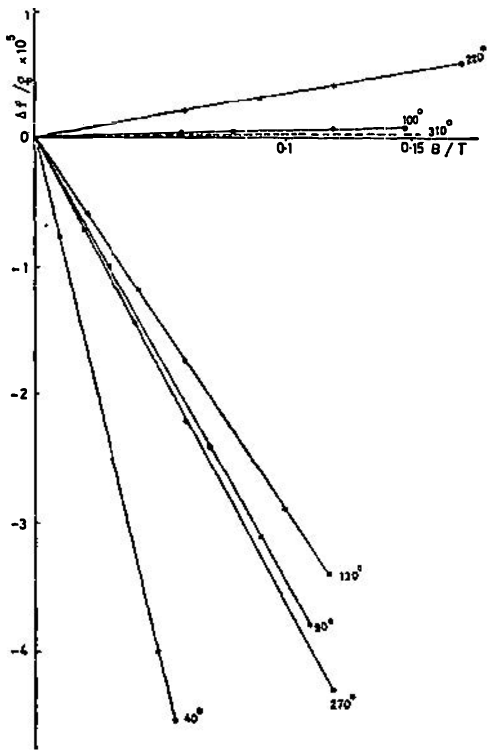

Fig. 2. The calculated linear terms $\Delta\varrho/\varrho_0(B)$ of MR versus B at several rotational angles Θ at $T = 300$ K.

In Fig. 2 it was observed that the calculated anomalous linear terms of MR have positive and negative values over a wide range of different Θ, but at certain angles like $\Theta = 100°$ and $\Theta = 310°$, the non-parabolic components are not detectable. However, the anomalous behaviour of linear components at the two opposite directions of B has an irregular distribution, i. e. the anomalous linear term at $\Theta = 220°$ is positive and the other is negative at $\Theta = 40°$, but there is no considerable change between the two anomalous terms of MR $\Theta = 90°$ and $\Theta = 270°$. This shows that the linear terms of MR are highly dependent on the variation of rotating angle Θ. In this arrangement, it could be seen that under a low magnetic field up to 0.3 T, the calculations shows a good agreement for the dependence of magnetoresistivity on the odd power of B. If the current flows along the axis of symmetry, the anomalous effect, vanishes, because in this case the general behaviour of MR is obeying Onsager relation's[15] as shown in Fig. 3. The relative change in the magnetoresistivity at $T = 300$ K has a quadratic dependence on the magnetic field strength. The appearance of this normal behaviour of MR is due to the current along the axis of symmetry.

In Fig. 4 it is shown that there is no considerable change between the two calculated normal positive terms at the two opposite directions of B for $\Theta = 130°$ and $\Theta = 310°$, in contrast to the linear components (Fig. 2) at the same angles. This

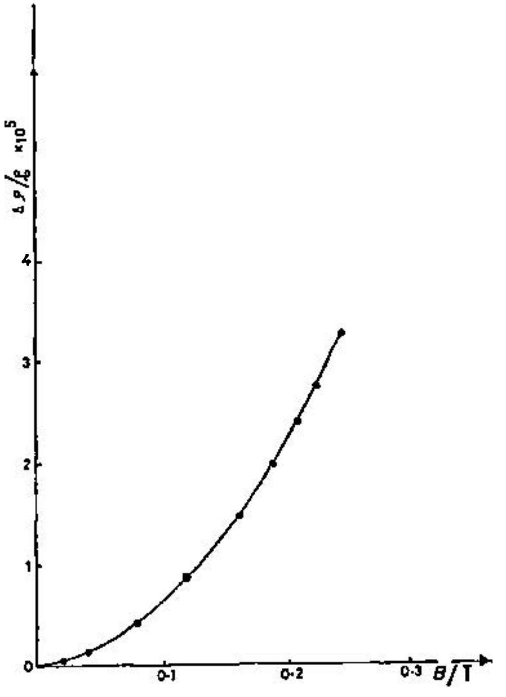

Fig. 3. Dependence of $\Delta\varrho/\varrho_0$ on B, in the case of current flowing along the axis of symmetry at $T = 300$ K.

means that the MR is not only dependent on the even power of B, but is also an odd power of B dependent phenomenon. On the other hand the values of non-parabolic terms (Fig. 2) are several times greater than the parabolic terms of MR (Fig. 4). In general the values and anomalous effect of the two contributions of longitudinal MR are not symmetric at the same angles, so the following relationship may be valid:

$$\Delta\varrho/\varrho_0\,[B\,(\Theta)] \neq \Delta\varrho/\varrho_0\,[B^2\,(\Theta)].$$

From the above mentioned, it was noticed that the distribution of measured MR curves at relatively high temperature are negative at certain angles (Fig. 1). Moreover the linear components of MR at definite angles are equal zero (Fig. 2). Also the anomalous effect of normal positive terms of MR (Fig. 4) is very small at some opposite angles ($\Theta = 130°$, $\Theta = 310°$) and becomes very large when the direction of B was reversed at $\Theta = 40°$ and $\Theta = 220°$. These results may be readily understood if the angle effect is taken into account.

From the evaluation of experimental data for longitudinal MR, it was found that the measured curve of MR represents the sum of two contributions, one of them being a anomalous linear term, and the other the positive normal one. This assumption was examined as shown in Figs. 5 and 6. In Fig. 5 at $\Theta = 90°$ the ano-

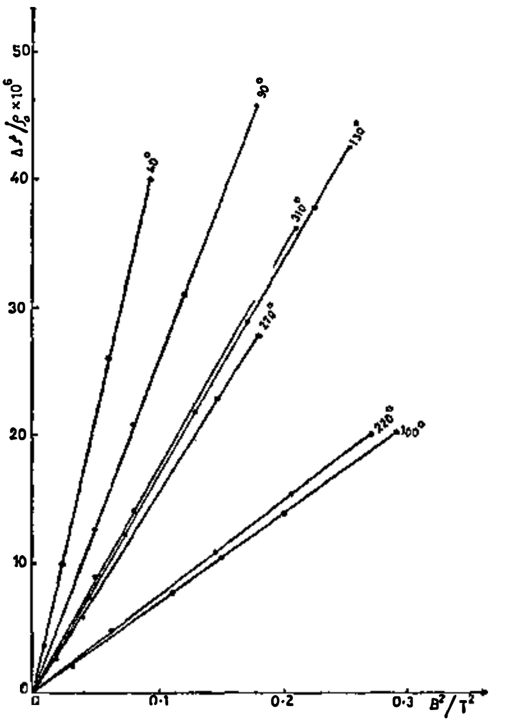

Fig. 4. The calculated normal terms $\Delta\varrho/\varrho_0\,(B^2)$ versus B^2 at several rotational angles Θ at $T = 300$ K.

malous linear term is positive, but in Fig. 6 at $\Theta = 220°$ the anomalous non-parabolic component is negative and the reason of changing the linear term position may be due to the variation of rotational angle.

The angular dependence of transverse MR at $B = 0.2$ T and $T = 300$ K is shown in Fig. 7. The transverse MR exhibits a strong type of anomalous effect where the MR is negative at $\Theta = 0°$ and becomes positive at $\Theta = 180°$. This means that the anomalous behaviour of transverse MR is very sensitive for any small variation in angle Θ, i. e. the general shape of the transverse MR curve is cos 2Θ independent.

4. Conclusions

The calculation of linear terms of longitudinal MR and the appearance of negative MR in n-PbS ($n = 10^{15}$ cm^{-3}) under a low electric and magnetic fields at relatively high temperature ($T = 300$ K) may be attributed to the irregular change in the direction of induced Hall field at different rotational angles Θ between the directions of both current and magnetic field. The deviation of current vector $I_{B(\Theta)}$ from the axis of symmetry by angle φ, gives asymmetry relation between the $I_{B(\Theta)}$

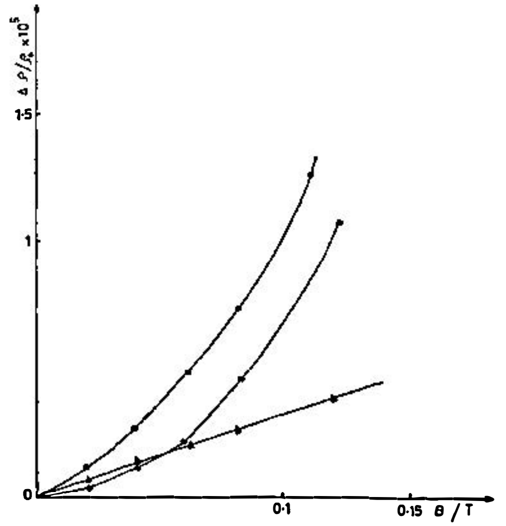

Fig. 5. Dependence of the measured $\Delta\varrho/\varrho_0$ (-•-) on the field B at $\Theta = 90°$ and $T = 200$ K. The calculated anomalous $\Delta\varrho/\varrho_0\,(B)$ and the normal components $\Delta\varrho/\varrho_0\,(B^2)$ of MR are represented by symbols (▲) and (■), respectively.

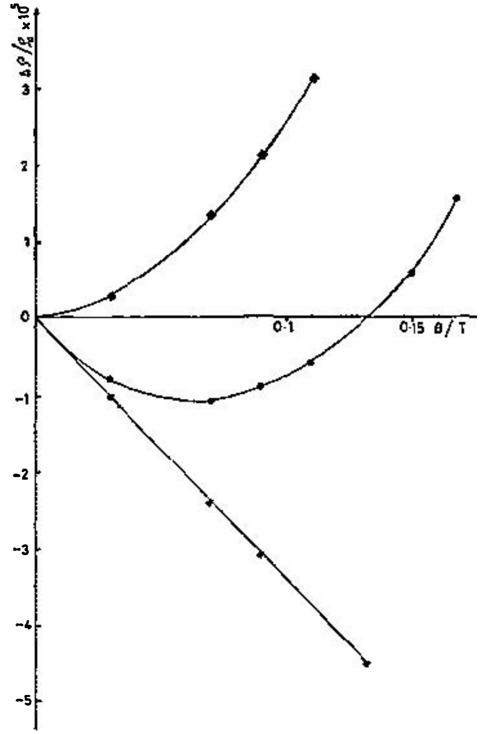

Fig. 6. Dependence of the measured $\Delta\varrho/\varrho_0$ (-•-) on the field B at $\Theta = 220°$ and $T = 300$ K. The calculated anomalous $\Delta\varrho/\varrho_0$ (B) and normal components $\Delta\varrho/\varrho_0$ (B^2) of MR are represented by symbols (▲) and (■), respectively.

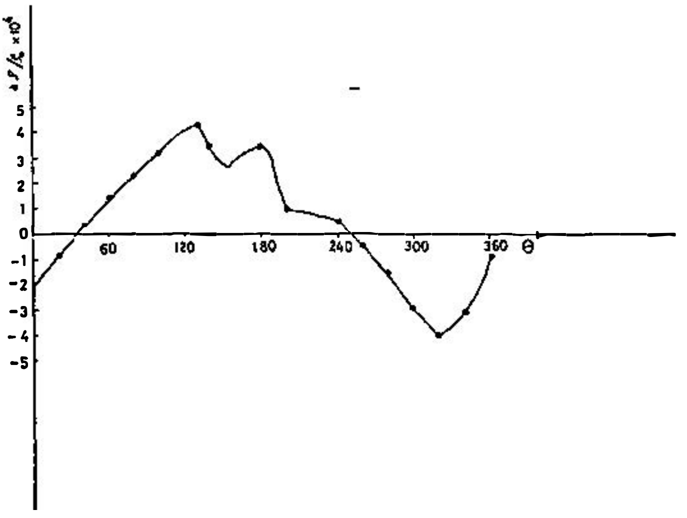

Fig. 7. Dependence of the transverse MR on the magnetic field direction $\Theta_{(B,I)}$ for $B = 0.2$ T at $T = 300$ K.

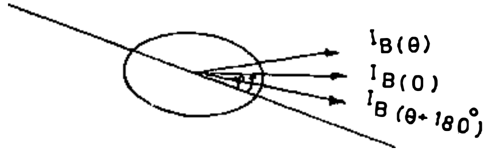

Fig. 8. Directions of the current vectors at the two opposite directions of B.

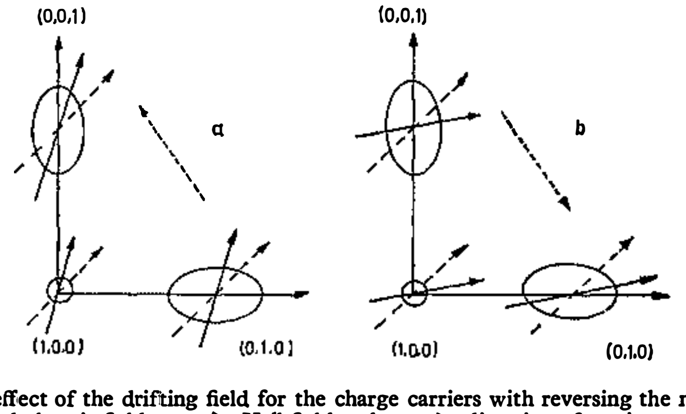

Fig. 9. The effect of the drifting field for the charge carriers with reversing the magnetic field. – – –▶ applied electric field, - - - - ▶ Hall field and ——▶ direction of carrier motion along the ellipsoids.

and $I_{B(\Theta+180°)}$ as shown in Fig. 8. This means that the magnetic field modifies the direction motion of the charge carriers in $\vec{k}$-space by an angle Θ, this in turn could contribute to the variation of both mobility and effective mass m^* of charge carriers during applied electric and magnetic fields[12,13,18]. The relation among these parameters are seen from the following definitions:

$$\Delta\varrho/\varrho_0 = \frac{\varrho_{(B)} - \varrho_{(0)}}{\varrho_{(0)}} = \frac{\mu_{(0)} - \mu_{(B)}}{\mu_{(B)}};$$

$$\sigma^{-1} = \varrho \sim m^*.$$

For the magnetic field vector B pointing in a direction which is not a symmetry direction with the axis of PbS crystal, one may expect a deviation of the induced Hall field from the direction perpendicular to B. This indicates that at the two reversal directions of induced Hall field, the motion of charge carriers along a set of ellipsoids have anomalous direction as given in Fig. 9.

From the above mentioned it can be seen that the relative change in the resistivity depends mainly on the two opposite directions of $B\,(+B, -B)$. This in turn explains the responsibility of induced Hall field for the appearance of anomalous effect.

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LINEARNI MAGNETOOTPOR *n*-TIPA OLOVNOG SULFIDA (PbS) NA 300 K

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UDK 538.93

Originalni znanstveni rad

Izloženi su rezultati mjerenja longitudinalnog magnetootpora uzoraka *n*-tipa PbS (koncentracije primjesa 10^{15} cm^{-3}) na 300 K u slabim magnetskim poljima. Iz eksperimentalne ovisnosti $\varrho(B) - \varrho(B=0)$ o kutu Θ između struje i polja određeni su anomalni linearni i normalni pozitivni doprinosi magnetootporu. Nesimetrično ponašanje longitudinalnog magnetootpora javlja se za neke vrijednosti kuta Θ. Rezultati se mogu objasniti nepravilnom ovisnošću smjera induciranog Hallovog polja o kutu Θ zbog činjenice da se smjer struje ne poklapa s osima simetrije kristala.