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*LETTER TO THE EDITOR*

# ANOMALOUS MAGNETORESISTANCE OF SINGLE CRYSTALS OF DOPED BISMUTH

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Measurements of magnetoresistance of single crystals of bismuth doped with tin and lead in the temperature range 100 K to 300 K are reported. Both tin and lead have a marked effect in changing the band structure of bismuth. Temperature variations show that with the increased concentration of impurity, $\Delta\rho/\rho_0$ is less dependent on temperature, and the magnetic field variation of $\Delta\rho/\rho_0$ does not obey the quadratic dependence on magnetic field strength.

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Bismuth exhibits a number of very interesting transport properties due to the presence of its overlapping bands [1–5]. Doped-bismuth materials show interesting variations of galvanomagnetic properties [6,7]. For example, variation of the Hall coefficient of doped bismuth with magnetic field at steady temperature shows that the Hall coefficient undergoes a change of sign from negative to positive [7]. Therefore, we decided to investigate whether the magnetoresistance also shows an unusual variation with magnetic field. We found no such previous report.

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Tanaka [2] investigated the magnetoresistance of doped samples of bismuth, but his observations were confined to the variation with temperature only. We have, therefore, undertaken the study of magnetic field variation of magnetoresistance of doped bismuth and also its temperature variation. The doping was also variable within the limits of solid solubilities of Pb and Sn in Bi (up to 1%).

Single crystals of doped bismuth were prepared in our laboratory by the vertical Bridgman technique [8]. Samples were cut from ingots in rectangular shape of dimension 1 cm×0.3 cm×0.1 cm. The percentages of doping of the studied samples, as determined by the atomic absorption spectra, are given in Table 1. The measurements of resistance were made using a Keithley microvoltmeter.

*Table 1. Conductivities ($\sigma$) of four samples of doped bismuth ($S_i$) in zero field and at room temperature.*

| Sample | Impurity (at.%) | $\sigma$ ($\Omega^{-1}$cm$^{-1}$) |
|---|---|---|
| $S_1$ | 0.17% Pb | 1850 |
| $S_2$ | 0.56% Pb | 1500 |
| $S_3$ | 0.3% Sn | 700 |
| $S_4$ | 0.71% Sn | 1420 |

In the present investigation, the current was applied in the direction perpendicular to the trigonal axis, and magnetic field was applied parallel to the trigonal axis, i.e. the C-axis.

Since bismuth is a semimetal, it contains two types of carriers, holes and electrons, even in the pure state. The numbers of these carriers can be drastically altered by the addition of impurities. The expression for the magnetoresistance of the two types of carriers is given by [9]

$$\frac{\Delta\rho}{\rho_0} = \frac{\sigma_1\sigma_2(\beta_1-\beta_2)^2B^2}{(\sigma_1+\sigma_2)^2+B^2(\beta_1\sigma_1+\beta_2\sigma_2)^2}\,, \tag{1}$$

where $\beta_1 = e\tau_1/m_1c$ and $\beta_2 = e\tau_2/m_2c$. Equation (1) illustrates the main features of the phenomenon of magnetoresistance. Typically, $\Delta\rho/\rho_0$ is proportional to $B^2$ for small fields, but it tends to saturate at higher fields.

In this note, the temperature variation of magnetoresistance in a constant magnetic field, and also the magnetic field variation of magnetoresistance at various constant temperatures are reported for four specimens of single crystals of doped bismuth.

The magnetoresistance shows large values. Figure 1 shows the temperature variation of $\Delta\rho/\rho_0$ in a magnetic field of 0.675 T for the four samples. It is seen that the temperature variation of $\Delta\rho/\rho_0$ shows a peak which is most prominent in

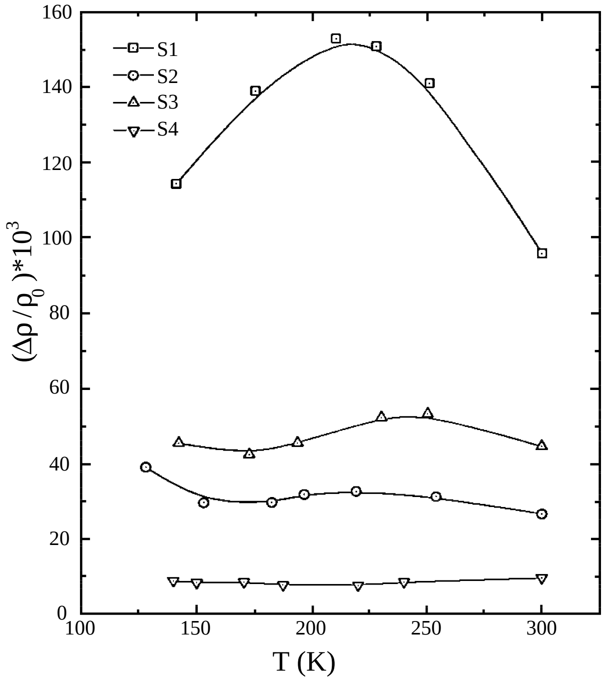


*Fig. 1. Temperature variation of magnetoresistance of samples* $S_1$, $S_2$, $S_3$ *and* $S_4$, *of bismuth.*

the sample $S_1$ with the lowest percentage of Pb impurity. The position of the peak is at about 200 K. The prominence gradually decreases with increasing percentage of acceptor impurity. In the case of the sample $S_4$, a slight increase of $\Delta\rho/\rho_0$ with temperature can be seen. The position of the peak also shifts to higher temperature as the percentage of impurity increases. Presence of such a peak was also observed in the temperature variation of the Hall coefficient of the same specimens [8].

The conductivities of the four samples in zero field and at room temperature are given in Table 1. The field dependence of magnetoresistance is shown by the Kohler plots in Figs. 2a and b, and the results are also given in Table 2.

It is seen that $\Delta\rho/\rho_0$ varies as $B^x$ where $x \lesssim 2$ for all samples at different temperatures and magnetic field $B < 0.3$ T. But for $B > 0.3$ T, the values of $x$ are in the range $0.7 \lesssim x < 1.5$.

For all four samples in low fields and at $T = 300$ K, it is seen that the value of $x$ is about 2.

It appears that the magnetic field dependence of the magnetoresistance is complicated, making the explanation of the observed values difficult. However, a reason for these properties may be sought in another galvanometric effect. It has been observed that the Hall coefficient of Bi doped with Sn and Pb changes its sign from negative to positive when magnetic field increases, keeping the temperature

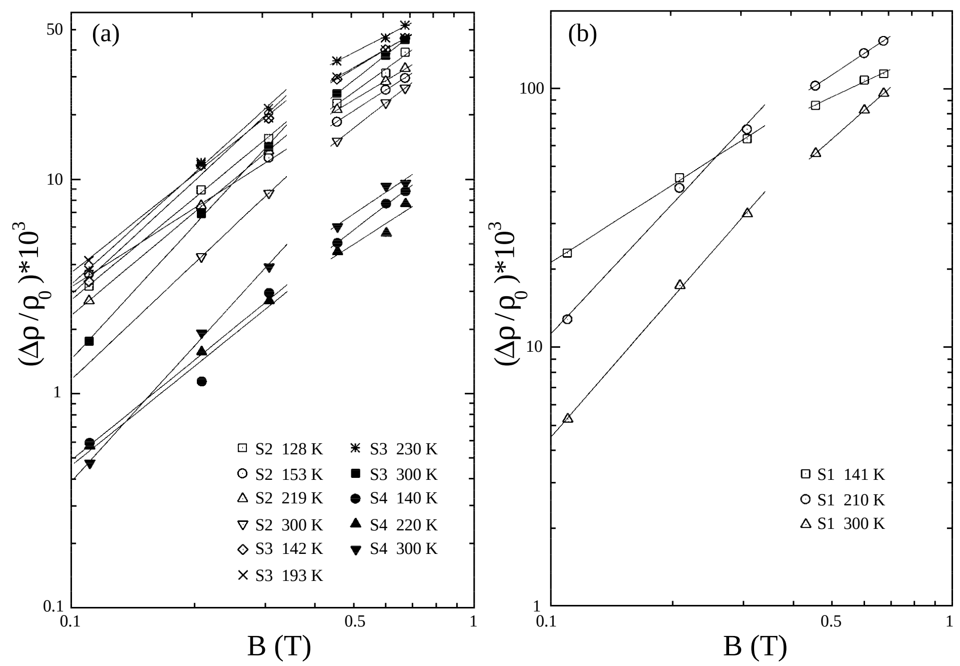


*Fig. 2. Magnetic field variation of magnetoresistance of samples* $S_1$, $S_2$, $S_3$ *and* $S_4$ *at different constant temperatures (Kohler plot).*

*Table 2. Magnetic-field and temperature dependence of magnetoresistance of four samples of doped bismuth* ($S_i$)*.*

| Sample $S_1$ | | | Sample $S_2$ | | |
|---|---|---|---|---|---|
| Temp. (K) | Slope ($x$) | | Temp. (K) | Slope ($x$) | |
| | $B < 0.3$ T | $B > 0.3$ T | | $B < 0.3$ T | $B > 0.3$ T |
| 141 | 0.987 | 0.737 | 128 | 1.54 | 1.356 |
| 210 | 1.65 | 1.027 | 153 | 1.193 | 1.21 |
| 300 | 1.767 | 1.37 | 219 | 1.557 | 1.13 |
| | | | 300 | 1.756 | 1.45 |
| Sample $S_3$ | | | Sample $S_4$ | | |
| Temp. (K) | Slope ($x$) | | Temp. (K) | Slope ($x$) | |
| | $B < 0.3$ T | $B > 0.3$ T | | $B < 0.3$ T | $B > 0.3$ T |
| 142 | 1.718 | 1.129 | 140 | 1.499 | 1.438 |
| 193 | 1.49 | 1.078 | 220 | 1.51 | 1.198 |
| 230 | 1.687 | 0.967 | 300 | 2.045 | 1.27 |
| 300 | 2.02 | 1.47 | | | |

constant [7]. This indicates that there is a change in the carrier concentration of electrons and holes as the magnetic field changes. This may be responsible for such a dependence on magnetic field.

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## ANOMALAN MAGNETOOTPOR MONOKRISTALA DOPIRANOG BIZMUTA

Izvješćujemo o mjerenjima magnetootpora monokristala bizmuta dopiranog kositrom i olovom pri temperaturama 100 do 300 K. I kositar i olovo jako utječu na strukturu vrpci u bizmutu. Mjerenja pokazuju da za povećane koncentracije onečišćenja, $\Delta\rho/\rho_0$ slabije ovisi o temperaturi, a promjene $\Delta\rho/\rho_0$ s magnetskim poljem nemaju kvadratnu ovisnost o jakosti magnetskog polja.