# Giant negative magnetoresistance in uniaxially deformed, manganese-doped indium antimonide

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(Submitted 30 May 1984; resubmitted 11 June 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 2, 45–47 (25 July 1984)

The giant negative magnetoresistance and the Mott transition in a magnetic field which have been observed in uniaxially deformed, manganese-doped indium antimonide are discussed.

This letter reports observation of a giant negative magnetoresistance in uniaxially deformed, manganese-doped indium antimonide. The resistivity of a sample has been observed to decrease by a factor of more than $10^3$ in a magnetic field stronger than 8T (Fig. 1). The conductivity increase in a magnetic field is accompanied by a transition from a dielectric conductivity to a metallic conductivity (Fig. 2). A Mott transition in the dielectric-metal direction has thus been observed for the first time with an increasing magnetic field in a nonmagnetic crystal.

The negative magnetoresistance which we have observed is many orders of magnitude greater than that observed in crystalline semiconductors. The negative magnetoresistance in semiconductors is currently described by a theory of the scattering of current carriers by localized impurity moments[1] and by a theory of quantum corrections to the conductivity.[2] However, since each of these theories predicts small changes in the resistance in a magnetic field, they cannot be applied to the case at hand.

In this letter we offer a new model to describe the appearance of an anomalous temperature dependence of the conductivity and of a giant negative magnetoresistance. According to this model, these effects result from a change in the energy of an exchange interaction of holes at acceptors.

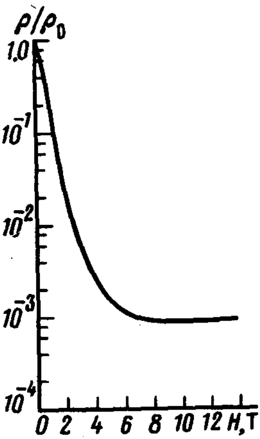

FIG. 1. The resistivity of $p$-InSb(Mn) versus the magnetic field. $\chi = 2.1\times10^3$ kgf/cm$^2$; $\vec{\chi}\,\|\mathbf{H}\|[110]$; $T = 1.26$ K.

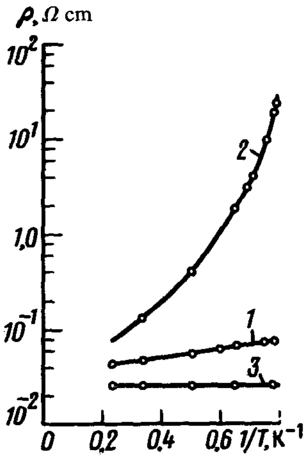

FIG. 2. The dielectric-metal transition induced by a magnetic field. 1— $\chi = 0$, $H = 0$; 2— $\chi = 2.1 \times 10^3$ kgf/cm$^2$, $H = 0$; 3— $\chi = 2.1 \times 10^3$ kgf/cm$^2$, $H = 8$ T.

The present experiments were carried out in a collaboration of the A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad, and the Institute of Technical Physics, Technical University of Braunschweig, in the laboratory of strong magnetic fields of that Institute.

A water-cooled Bitter magnet with an internal aperture 53 mm in diameter permitted measurements in magnetic fields up to 16 T. A double liquid-helium cryostat was used to produce low temperatures. Pressure was applied to an indium antimonide crystal $8 \times 1 \times 1$ mm in size along the long axis of the crystal. This pressure reached $\chi \approx 4 \times 10^3$ kgf/cm$^2$. The resistivity of the samples was measured at various magnetic fields under dc conditions at current values low enough to avoid heating of the samples. Magnetic fields ranging in strength from 0 to 16 T were applied for a time ranging from one to several minutes.

It has been shown elsewhere[3] that there is a definite interrelationship between the increase in resistivity caused by pressure in uniaxially deformed $p$-type indium antimonide and the onset of a negative magnetoresistance.

We attribute the observed transition to a dielectric state during uniaxial deformation to an intensification of the exchange interaction of holes at acceptors due to a splitting of the valence band. During uniaxial compression, the ground state of the carriers in the impurity band splits up in such a manner that only those holes which have an angular-momentum projection $m_j = \pm 1/2$ participate in the conductivity.[4] This increase in the number of possible states gives rise to an increase in the energy of the exchange interaction of an antiferromagnetic type. These events correspond to the Mott model, in which near a "critical" density for the metal insulator transition ($N_A = 2 \times 10^{17}$ cm$^{-3}$) we should observe an increase in the energy gap ($\Delta$) between the valence and impurity bands during the onset of an antiferromagnetic order.

An increase in the energy of the carrier exchange interaction in the impurity band during uniaxial deformation can be described analytically as follows. After we take an average over the directions of the axis connecting the impurities, we can write the Hamiltonian of the exchange interaction of two holes at adjacent acceptors as follows:

$$\hat{H} = A_0 + A_1(\bar{\mathbf{J}}_1\bar{\mathbf{J}}_2) + A_2(\bar{\mathbf{J}}_1\bar{\mathbf{J}}_2)^2 + A_3(\bar{\mathbf{J}}_1\bar{\mathbf{J}}_2)^3 \,. \tag{1}$$

The vector operators $\bar{\mathbf{J}}_1$ and $\bar{\mathbf{J}}_2$ are the total angular momenta of the holes at the acceptors ($J = 3/2$), and the $A_i$ are constants. Uniaxial deformation splits the ground energy level of the acceptor, and the lower of the resulting states is that in which the projection onto the deformation axis is $J_z = \pm 1/2$. Analysis of expression (1) shows that under the conditions

$$\frac{A_2}{A_3} < -\frac{2943}{20}\,; \quad \frac{A_1}{2A_3} - \frac{683}{80} < \frac{A_1}{A_3} < \frac{1}{3}\frac{A_2}{A_3} - \frac{529}{16}\,,$$

regardless of the value of $\chi$, the ground state of the pair of holes will be the level in which the vectors $\mathbf{J}_1$ and $\mathbf{J}_2$ are antiparallel. As $\chi$ increases, the energy gap between the impurity band and the valence band will increase. We wish to emphasize that expression (1) with $A_2 = A_3 = 0$ is ordinarily used to describe the exchange interaction of two holes, but if we choose only the single parameter $A_1$ in the present case we cannot obtain an increase in $\Delta$ with increasing $\chi$. The reason for the existence of $(\bar{\mathbf{J}}_1\bar{\mathbf{J}}_2)^2$ and $(\bar{\mathbf{J}}_1\bar{\mathbf{J}}_2)^3$ is that the charge carriers have $J = 3/2$; for $J = 1/2$, the operator $\hat{H}$ would contain only $A_0$ and $A_1$.

As expected, a magnetic field induces a transition to a metallic state with a conductivity close in magnitude to the minimum metallic conductivity, $\sigma_{\min} \approx 0.1$ S/cm. In a field $H \gtrsim 8$ T, which corresponds to the establishment of a metallic conductivity, the energy of the paramagnetic splitting of holes becomes roughly equal to the width of the impurity band. The giant negative magnetoresistance occurs because a longitudinal magnetic field reduces the energy of the exchange interaction as it flips the spins of the holes to the direction of the magnetic field, thereby decreasing the energy gap $\Delta$ and thus increasing the conductivity. In the "weak binding" model these events would correspond to an increase in the width of the impurity band due to an increase in the Fermi energy of the current carriers.

Evidence in favor of this interpretation comes from the fact that the paramagnetic energy of the holes is $g_{\text{eff}}\mu_0 H \approx 10$ meV, where[4] $g_{\text{eff}} \approx 12$, and this energy is sufficient to disrupt the antiferromagnetic order in the impurity band. The correlation between the magnitude of the negative magnetoresistance and the value of the hole $g$-factor can be seen by comparing the negative magnetoresistance in uniaxially deformed $p$-type indium antimonide with that in $p$-type germanium,[5] where the effect is considerably weaker and where the $g$-factor is $g \approx 6$.

For this reason we should expect both an intensification of the negative magnetoresistance in semiconducting crystals doped with magnetic impurities (since the effective g-factor may be substantially increased in this case) and a sharper transition to the dielectric state from the metallic state during uniaxial compression. In the latter case there may be an additional contribution to the antiferromagnetic-exchange energy of the conducting holes with the magnetic moments of the inner-shell electrons of the manganese.

We wish to thank M. G. Ryskin and M. I. D'yakonov.

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Translated by Dave Parsons
Edited by S. J. Amoretty