Metal-insulator-metal transition induced by a uniaxial strain in a gapless semiconductor $Hg_{1-x}Cd_xTe$

S. G. Gasan-zade, V. A. Romaka, and G. A. Shepel'skiĭ
Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR

(Submitted 20 October 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 11, 518–520 (10 December 1986)

A metal-insulator-metal transition is shown to occur in a uniaxially strained gapless semiconductor $H_{1-x}Cd_xTe$. In the absence of a strain, the metallic conductivity is determined by the free electrons and when P is maximum, it is determined by the valence-band holes. A conductivity inversion is caused by a structural change in the hole spectrum.

We have previously reported the results of a study of the conductivity inversion of a gapless semiconductor $Hg_{1-x}Cd_xTe$ resulting from a uniaxial strain.[1] The inversion was attributed to the formation of an energy gap in the gapless semiconductor[2] and to cold-trapping of free electrons from the conduction band to the impurity acceptor states. It was also assumed that because of the change in the structure of the valence band, the conductivity of a gapless semiconductor at maximum strain ($P \geqslant 3$ kbar) is determined by the free holes with anomalously high mobilities.

We report here the results of a study of the strain-induced dependence, temperature dependence, and field dependence of the conductivity and the Hall coefficient R_X, which are experimental proof of the structural change in the band spectrum of the gapless semiconductor, of the inversion of the electrical-conductivity sign, and of the dominant role of the light holes in the conductivity of a uniaxially strained gapless HgCdTe.

The measurement procedure and the parameters of the samples were described in an earlier study.[1] For all the samples which we studied, the following conditions were satisfied: $N_A \gg N_D$ and $N_A - N_D \sim 10^{16}$–10^{17} cm^{-3}, where N_A and N_D are the acceptor and donor concentrations, respectively.

In the absence of strain because of the small effective mass of the free electrons of the gapless semiconductor $Hg_{1-X}Cd_XTe$, the condition for strong doping of a semiconductor, $na_B^3 > 0.02$, holds with a wide margin.[3] The conductivity of the gapless semiconductor in this case is determined by the free electrons, which can be inferred from the sign of R_X (Fig. 1) and is metallic in nature (Fig. 2).

The uniaxial strain initially leads to an increase in ρ and R_X as P is increased (Fig. 1). The functional dependence $\rho(P)$ is nearly exponential. This circumstance, along with the increase in R_X, shows that the effect is of a concentration nature. It also shows that an energy gap is formed and that the free electrons are cold-trapped to the acceptor impurity states. The temperature dependence $\ln\rho(1/T)$ in this case reveals the presence of activation regions which stem from the activation of free electrons and at the lowest temperatures stem from the hopping conductivity in the acceptor band. As a result, a metal-insulator transition occurs.[3] In this deformation region, R_X has a clearly defined maximum, which is attributable to the contribution to the conductivity of the gapless semiconductor, at least for two types of current carriers, and it then changes sign as P is raised.

Interestingly, the nature of the hopping conductivity changes with increasing

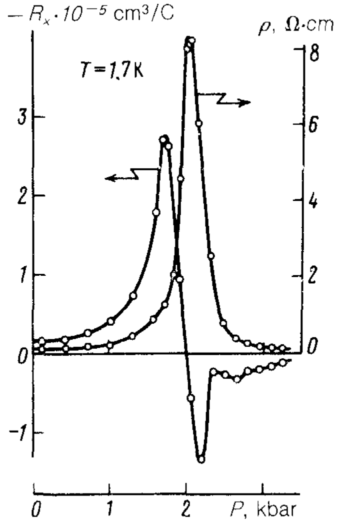

FIG. 1. Plots of $\rho(P)$ and $R_X(P)$ for a gapless semiconductor $H_1\ {}_x Cd_x Te$. $x = 0.157$.

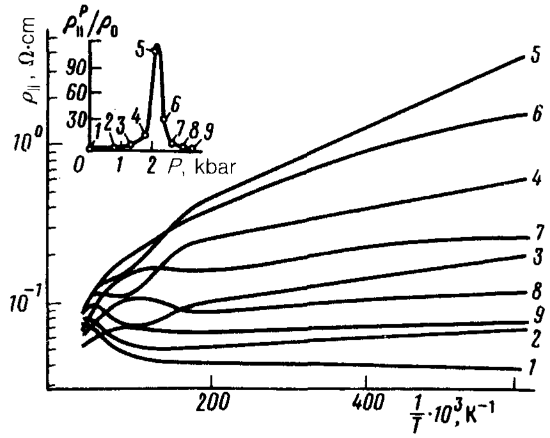

FIG. 2. Temperature dependence of $\ln\rho$ $(1/T)$ for various magnitudes of the uniaxial strain of a gapless semiconductor (the magnitude of the strain is indicated in the inset).

strain from a hopping conductivity with a constant activation energy, E_3, to a hopping conductivity with a variable hopping length.

A further increase in the strain leads to a decrease of the activation energy and then to its disappearance. At maximum P the conductivity of the gapless semiconductor again becomes metallic in nature (curve 9 in Fig. 2). The curve $R_X(P)$ (the sign is positive) in this case reaches a plateau. The mobility of the holes, which can be estimated from the product $|\sigma_x R_X| = \mu_h > 10^5$ cm^2/(V·s) is evidence that these holes belong to the valence-band spectrum. According to the calculations of Refs. 1 and 4, the values of μ_h are large because of the formation of lateral extrema with a small effective mass in the valence band Γ_8.

Another important argument showing that there is a conductivity inversion and that the light holes play a dominant role is the field dependence of R_X of a uniaxially strained crystal (Fig. 3). At $P = 0$ the Hall coefficient does not depend on the magnet-

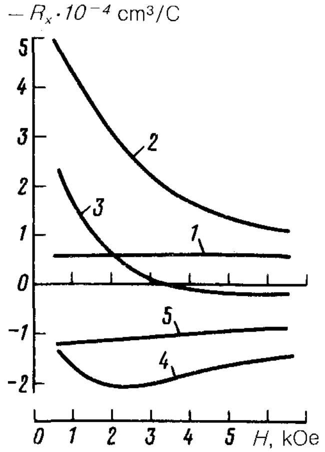

FIG. 3. Field dependence of R_X for the following values of P, kbar: 1—0; 2—2.04; 3—2.17; 4—2.42; 5—2.80. $T = 4.2$ K.

ic field strength ($H \leqslant 7$ kOe), consistent with the fact that the dominant contribution to the conductivity comes from the free electrons. As the strain is increased, the H dependence of R_X plays an increasingly smaller role, indicating that the conductivity of a gapless semiconductor involves several types of current carriers. Finally, when P is maximum, R_X is positive and again is virtually independent of H, since the free holes play a dominant role in the conductivity: an insulator-metal transition occurs.

The strain, temperature, and field dependences of ρ and R_X thus show that the structure of the band spectrum of a gapless semiconductor changes appreciably and that the conductivity is inverted. Both these effects occur as a result of the dominant role of the light holes in the conductivity of a uniaxially strained gapless semiconductor $Hg_{1-X}Cd_XTe$.

[1] F. T. Vas'ko, S. G. Gasan-zade, V. A. Romaka, and G. A. Shepel'skiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 100 (1985) [JETP Lett. **41**, 120 (1985)].

[2] G. L. Bir and G. E. Pikus, Simmetriya i deformatsionnye effecty v poluprovodnikakh (Symmetry and Strain-Induced Effects in Semiconductors), Nauka, Moscow, 1972, p. 584 [Israel Program for Scientific Translations, Jerusalem; Wiley, New York (1975)].

[3] B. I. Shklovskiĭ and A. L. Éfros, Elektronnye svoĭstva Legirovannykh poluprovodnikov (Electronic Properties of Doped Semiconductors), Nauka, Moscow, 1979, p. 416.

[4] M. Cardona, Solid State Commun. **5**, 233 (1967).

Translated by S. J. Amoretty