Negative magnetoresistance and shift of mobility threshold in cadmium diarsenide

E. Zdanowicz[1)] and K. G. Lisunov

Institute of Applied Physics, Academy of Sciences of the Moldavian SSR; [1)]Division of Solid State Physics, Polish Academy of Sciences

(Submitted 18 January 1990)

Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 4, 207–209 (25 February 1990)

The negative magnetoresistance of cadmium diarsenide in the region of a hopping conductivity with a variable hopping length is analyzed. The analysis yields the first determination of the shift of the mobility threshold in a magnetic field.

Al'tshuler[1] showed that the negative magnetoresistance of a semiconductor in the region of a hopping conductivity with a variable hopping length (VLHC) near the metal-insulator transition might be due to a negative value of the shift of the mobility threshold in a magnetic field.[2] We have now carried out the first study of the negative magnetoresistance in cadmium diarsenide under conditions close to those for the applicability of the model of Ref. 1. As a result, it becomes possible to use this model to analyze experiments and to determine, for the first time, the negative shift of the mobility threshold which has been suggested.

Cadmium diarsenide ($CdAs_2$) is an n-type tetragonal semiconductor with an electron isoenergy surface which is an ellipsoid of revolution oriented along the C_4 axis, a band gap 1 eV wide, and an energy of about 20 meV for the donor level associated with $CdAs_2$ lattice defects.[3] The transition to a region of VLHC due to the Coulomb gap in the density of states[4] occurs at $T_V \approx 3$–5 K, according to the temperature dependence of the reduced local activation energy ε_a/kT and that of the resistivity ρ [Figs. 1(a) and 1(b)]. The gap width varies over the interval 2.5–1.5 meV. The proximity of a metal-insulator transition was established from the dependence of the activation energy on the donor concentration n, whose critical value n_c was $\approx 7\times 10^{17}$ cm^{-3}.

The test samples for the measurements of the negative magnetoresistance were four $CdAs_2$ samples with donor concentrations $0.1n_c < n < 0.5n_c$ and a degree of compensation of about 20% in the geometry $\mathbf{H}\perp\mathbf{j}, \mathbf{H}\perp C_4, \mathbf{j}\perp C_4$ (**H** is the magnetic field, and **j** the current density) in fields up to 15 kOe.

From Ref. 1 we have

$$X_\rho \equiv \ln\frac{\rho(T,H)}{\rho(T,0)} = -B\left(\frac{eH}{\hbar c}\frac{D'}{D}n^{-2/3}\right)^{1/2\nu}(T_0/T)^{1/p}, \qquad (1)$$

where

$$B = |A|\,\nu\frac{p-1}{p}. \qquad (2)$$

The constant A determines the size of the shift of the mobility threshold[1,2]; the value

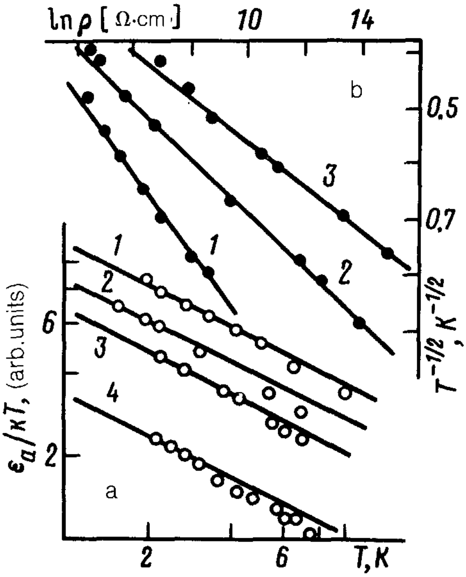

FIG. 1. Temperature dependence of (a) the reduced local activation energy and (b) the resistivity. n (10^{17} cm^{-3}): 1—3.0; 2—2.1; 3—1.2; 4—0.97.

of p is 2 for a VLHC due to a Coulomb gap; the parameter T_0 is related to the activation energy in the VLHC region[4] (in our samples, $T_0 = 760$–230 K); D and D' are determined by the components of the diffusion tensor[1] ($D'/D \approx 1.28$ for $CdAs_2$ in the indicated geometry); and ν is the critical index of the localization length ξ.

Al'tshuler[1] linked the appearance of a negative magnetoresistance with a quantum interference of electrons undergoing coherent hops along loop-shaped trajectories. The magnetic field affects this interference if the field flux through a typical loop is comparable to the flux quantum. We thus have the condition[1]

$$\frac{eH}{\hbar c}\left(\frac{T_0}{T}\right)^{1/p} \xi n^{-1/3} \gg 1, \qquad (3)$$

which imposes a lower limit on the region ΔH in which (1) applicable. An upper limit on ΔH results from the effect of a positive magnetoresistance[4] $\ln\rho \sim H^2$.

To determine ΔH (at $T < T_V$), we studied the behavior of the type shown in Fig. 2(a) [L_H is the magnetic length; $L' = (D'/D)^{1/2}(4\pi n/3)^{1/3}$.] In our samples we found $\Delta H \approx 3.5$–11 kOe. In the interval ΔH found in this manner, at $T < T_V$, the experimental curves of $x_\rho(H)$ were approximated by curves $y = ax^b$ [Fig. 3(a)]; the values $\nu = 0.94 \pm 0.05$ and $|A| = (9.6 \pm 1.3) \times 10^{-3}$ were found. It was also established that a negative magnetoresistance as in (1) agrees with the experimental results even at values of the left side of (3) in the interval 0.2–0.3; i.e., condition (3) overestimates the fields at which (1) begins to hold.

Figures 2(b) and 3(b) show the typical temperature dependence of the negative magnetoresistance. We see that p is close to 2 in the interval $1.6\ \mathrm{K} < T < T_V$, and we find $|A| = (10.5 \pm 2.5) \times 10^{-3}$.

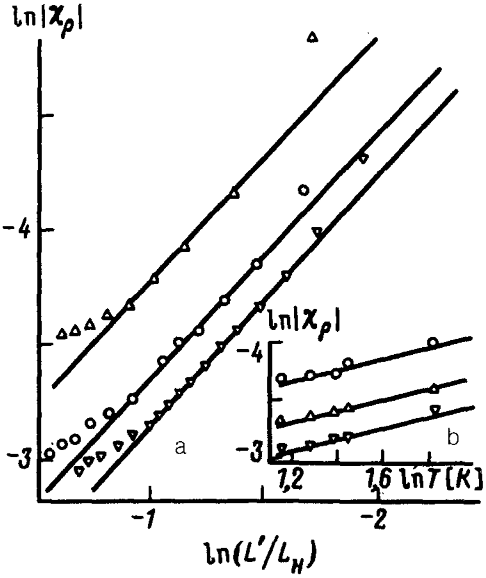

FIG. 2. Diagram used in determining (a) ΔH and (*b*) *p*. a: *n* ((10^{17} cm^{-3}); *T*(*K*): Δ—3.0, 4.2; ∇—2.1, 3.1; ○—1.2, 3.7. b: $n = 1.2 \times 10^{17}$ cm^{-3}. *H* (kOe): ○—2; Δ—4; ∇—8.

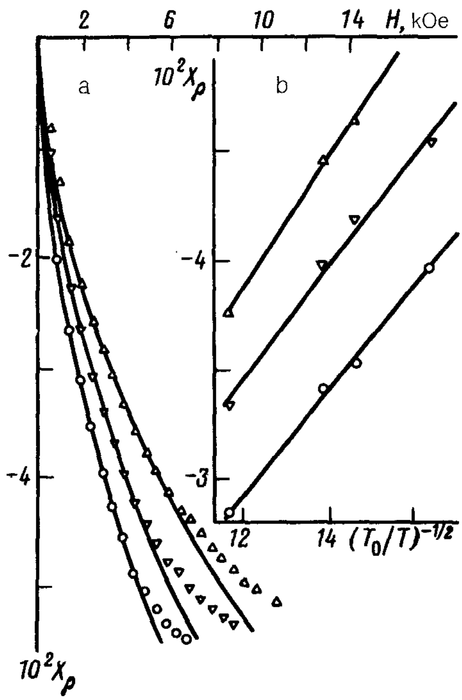

FIG. 3. Negative magnetoresistance versus (a) the magnetic field and (b) the temperature. a: $n = 2.1 \times 10^{17}$ cm^{-3}. *T*, K: ●—1.6; ∇—2.2; Δ—3.1. b: $n = 2.1 \times 10^{17}$ cm^{-3}. *H*(kOe): ○—3; ∇—4; Δ—5.

In summary, this study has established the existence of a region of magnetic fields and temperatures in which the behavior of the negative magnetoresistance corresponds completely to that predicted by Al'tshuler[1], even in the concentration range studied. The value found for ν is close to the values which have been found previously through a study of the metal-insulator transition in other semiconductors (e.g., Ge; Ref. 5). The values found for $|A|$ for the magnetic-field dependence and the temperature dependence agree well with each other. They are also considerably smaller than the estimate of $|A|$ offered in Refs. 1 and 2. As was pointed out in Ref. 6, the conductivity components stemming from the loop-shaped trajectories in the region of localized states should contain factors $\exp(-L_H/\xi)$, which are small in a weak magnetic field ($\xi \ll L_H$) (this condition is violated only at $H \sim 10^3$ kOe in our samples). The effect might be an effective decrease in the shift of the mobility threshold in such fields.

We wish to thank S. F. Marenkin for furnishing the samples, J. Portal for assistance in the experiments, and É. K. Arushanov and W. Zdanowicz for support of and interest in this study.

[1]B. L. Al'tshuler, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 157 (1982) [JETP Lett. **36**, 195 (1982)].
[2]D. E. Khmel'nitzkii and A. I. Larkin, Solid State Commun. **39**, 1069 (1981).
[3]D. I. Pishchikov *et al.*, in *Proceedings of the Seventh All-Union Conference on the Materials Science of II–V Semiconductor Compounds*, Vorontzh, 1987, p. 112.
[4]B. I. Shklovskiĭ and A. L. Éfros, *Electronic Properties of Doped Semiconductors*, Springer-Verlag, New York, 1984.
[5]A. G. Zabrodskiĭ and K. N. Zinov'eva, Pis'ma Zh. Eksp. Teor. Fiz. **37**, 369 (1983) [JETP Lett. **37**, 436 (1983)].
[6]B. I. Shklovskiĭ, Fiz. Tekh. Poluprovodn. **17**, 2055 (1983) [Sov. Phys. Semicond. **17**, 1311 (1983)].

Translated by Dave Parsons