ANOMALOUS DEPENDENCE OF THE THERMAL CONDUCTIVITY OF CADMIUM SELENIDE ON THE RESISTIVITY

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It was observed experimentally that the thermal conductivity of the piezo-semiconductor CdSe depends anomalously on the resistivity at low temperatures. The observed phenomenon is interpreted in terms of the theory of electron-phonon interaction in piezo-semiconductors.

We investigated the behavior of the thermal conductivity as a function of the resistivity and of the temperature of photosensitive CdSe crystals at "helium" temperatures. The thermal conductivity was measured by the thermal-potentiometer method (the temperature pickup was an AuFe0.035 - Cu thermocouple), and measurements were made simultaneously of the conductivity of the crystal. Part of the chamber for the measurement of the thermal conductivity was made transparent, so that the illuminator could be located outside the cryostat (the crystal was illuminated through a gap in the dewar and through the glass of the chamber.

The experimental results are shown in Fig. 1. We studied altogether four crystals. It turned out that when a resistivity $\rho \approx 10^4 - 10^5$ Ω-cm is reached the thermal conductivity of all the investigated crystals decreases strongly with increasing resistivity. As seen from Fig. 1, the thermal conductivity of crystal No. 1 decreased by a factor of four as a result of the illumination. In addition, we investigatted the dependence of the thermal conductivity coefficient on the temperature for crystals No. 1 and 4 (Fig. 2). This coefficient was found to be almost constant in a wide range of temperatures. The resistivity ranged in these measurements from 10^2 to 10^4 Ω-cm.

The phonon-electron interaction in piezo-semiconductors is quite large [1] and it can be assumed that it causes the observed effect[1)]. In the analysis of the interaction between an acoustic wave and electrons it is customary to consider two limiting cases [1]: $\ell_{el} \ll \lambda$ and

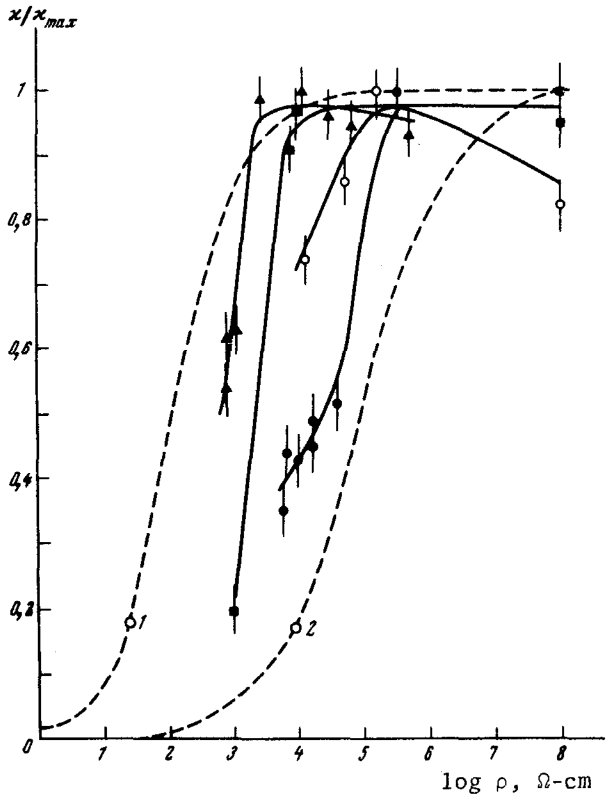

Fig. 1. Relative change of thermal conductivity as a function of the resistivity of the crystals: ■ - crystal No. 1, o - No. 2, ▲ - No. 3, ● - No. 4. 1, 2 - results of computer calculation: 1) $\ell_{el} \gg \lambda$, 2) $\ell_{el} \ll \lambda$. In the recalculation of the resistivity from the electron density, the electron mobility was assumed equal to 100 cm^2/V-sec.

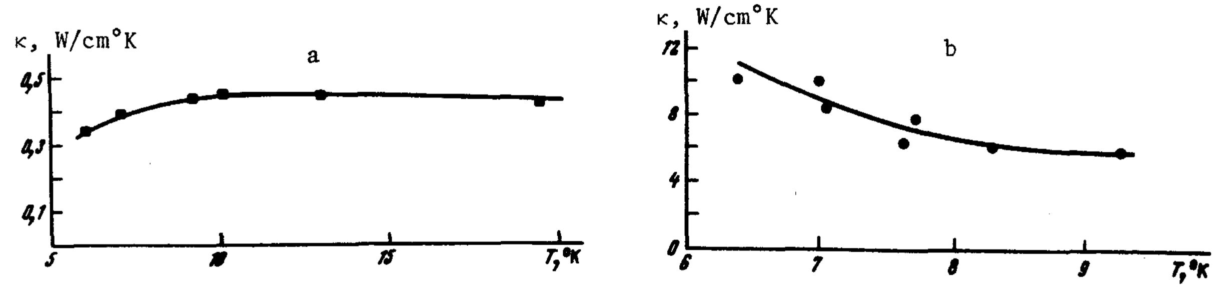

Fig. 2. Temperature dependence of the thermal conductivity: a - crystal No. 1, b - crystal No. 2. When the temperature was increased, ρ of crystal No. 1 decreased from 10^3 to 10^2 Ω-cm and that of crystal No. 2 decreased from 10^4 to 10^3 Ω-cm.

$\ell_{el} >> \lambda$, where λ is the acoustic wavelength and ℓ_{el} is the electron mean free path. An expression for the thermal-conductivity coefficient κ with allowance for the electron-phonon interaction was obtained in [4] for the first limiting case $\ell_{el} << \lambda$:

$$\kappa_{ij} = \left(\sum_\alpha \kappa_0^\alpha / A\right) \times \int_0^{\Theta/2T} dx \int d\Omega \left(x^{4-n}/Sh^2 x\right)\left(v_i^\alpha v_j^\alpha / v_\alpha^2\right) \Big/ \left(1 + C_\alpha \Phi^\alpha(x)\right) \quad (1)$$

where

$$\Phi^\alpha(x) = \left(\Delta_1^\alpha a^\alpha p_n^\alpha x^{2-n}\right) / \left(1 + a^\alpha x^2\right)^2;$$

$$A = 4\pi/3 \int_0^{\Theta/2T} dx \left(x^{4-n} / Sh^2 x\right)$$

Θ is the Debye temperature, T is the temperature in energy units, κ_0^α is the thermal conductivity due to the phonons of polarization α at zero carrier density, v^α is the speed of sound, n and p_n^α are parameters that determine the non-electronic phonon scattering, and Δ_1^α, a^α, and C_α determine the electronic part of the scattering and are given by the following relations:

$$T^2/\hbar^2 = \left[(\epsilon_0 m)/(\pi e^2 N)\right] (v_T/v^\alpha)^2,$$

$$C_\alpha = \nu (v^\alpha / v_T)(\hbar/2T)$$

ε_0 is the dielectric constant of the lattice; m is the effective mass, e is the charge, and N is the concentration of the electrons, v_T is the thermal velocity and ν is the effective collision frequency of the electrons, and η_α is the electromechanical coupling constant.

The thermal conductivity as a function of the carrier density reaches a minimum under the condition

$$\lambda_T \sim r_D. \quad (2)$$

Here $\lambda_T \simeq 2T/\hbar$ is the wavelength of the thermal phonons, $r_D \simeq \sqrt{\varepsilon_0 T/4\pi e^2 N}$ is the Debye radius for electrons.

We obtained an expression for the thermal conductivity in the second limiting case $\ell_{el} >> \lambda$. It turned out to be similar to (1), but

$$C_\alpha = x(v_\alpha/v_T). \quad (3)$$

This expression was obtained under the assumptions made in [4] and [1]. In this case, too, the thermal conductivity as a function of the density has a minimum when (2) is satisfied.

A computer calculation was also made of the dependence of the thermal conductivity on the electron concentration. It shows that in both limiting cases $\ell_{el} << \lambda$ and $\ell_{el} >> \lambda$ the thermal conductivity can change by hundreds of times with changing free-carrier density, the minimum being attained at $N \approx 5\times10^{16}$. In the former case, however, the minimum is somewhat wider and deeper than in the second. All the remaining crystal parameters also influence only the width and the depth of the minimum. The two limiting curves abtained as a result of the calculation are shown dashed in Fig. 1. All the experimental results, as seen from the figure, lie in the band bounded by the limiting curves.

The fact that the thermal conductivity does not depend on the temperature (Fig. 2) can apparently be attributed to the fact that the increase of the carrier density due to heating hinders the thermal-conductivity growth usually observed in dielectrics at "helium" temperatures [5].

The observed phenomenon gives grounds for assuming that the thermal conductivity at helium temperatures is determined by the scattering by the carriers even at electron densities 10^{13} - 10^{14}.

It should be noted that the observed influence of the photoconductivity on the thermal conductivity makes it possible in principle to control thermal processes inside a semiconductor, and the characteristic time of the thermal conductivity is determined by the time needed for the photoconductivity to become established.

1) The decrease in the thermal conductivity can be qualitatively explained also with the aid of other mechanisms (see, e.g., [2, 3]). Quantitatively, however, only the effect of the free carriers can be accounted for at present.

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EXPERIMENTAL VERIFICATION OF THE DYNAMIC SCALE THEORY OF THE CRITICAL POINT

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The frequency and temperature dependences of the absorption and velocity of sound were investigated in the region of the critical point. The existence of a characteristic critical frequency uniquely determined by the equilibrium correlation radius is demonstrated.

Concepts based on the assumed existence of a characteristic frequency ω_c uniquely determined by the equilibrium correlation radius r_c have recently gained currency as applied to kinetic phenomena near the critical point [1 - 4].

Thus, the ratio of the "order parameter" relaxation frequency to ω_c, with allowance for the spatial dispersion, is a universal function of $y = kr_c$ (k is the wave number)

$$\omega(k, r_c)/\omega_c = F(y), \tag{1}$$

where

$$\omega_c = 2Dr_c^{-2} \equiv k_B T / 3\pi\eta(y) r_c^3, \tag{2}$$

(y) is the "high-frequency" shear viscosity [5].

The anomalous part of the complex bulk viscosity θ_c is determined by a universal function of $\omega^* = \omega/\omega_c$ (ω is the external frequency) [4]