

Fig. 1. Binding energy of nucleus  $\epsilon$  vs. mean-square radius of the nucleus  $R_0^2$ ; I - experiment, II - V - calculation.

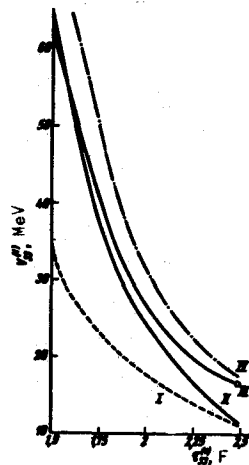


Fig. 2. Boundaries of saturation of nuclear forces.

of the nuclei. The best results are obtained for points in the region of curve II. Curve IV is the limit of collapse, obtained from the Calogero and Simonov [4] strongest condition for saturation of nuclear matter, in which no account is taken of the Coulomb interaction. Allowance for the

Coulomb interaction shifts the collapse boundary IV appreciably towards curve III.

It is important to note that the potential  $V_{3,3}$  from the region of saturation of nuclear matter (it is limited from below by curve III of Fig. 2) leads to a "disintegration" of the nuclei, as is seen, for example, on curve IV of Fig. 1. This curve was obtained from the parameters  $V_{3,3}$  lying on the collapse boundary III (Fig. 2).

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#### ELECTRONIC MECHANICS OF CHANGING THE PHOTON THERMAL CONDUCTIVITY OF PIEZOSEMICONDUCTORS

Yu.P. Mukhortov and V.I. Pustovoit  
 All Union Research Institute of Physico-technical and Radiotechnical  
 Measurements  
 Submitted 25 June 1970  
 ZhETF Pis. Red. **12**, No. 3, 153 - 156 (5 August 1970)

It is known that at an electron concentration less than  $10^{19} \text{ cm}^{-3}$  the main contribution to thermal conductivity is made by phonons [1]. In crystals with relatively large electron-phonon interaction, however, the electrons, in spite of their small concentration, can play an important role as before, since they

determine the phonon mean free path. Moreover, by varying the electron concentration in the semiconductor by means of some mechanism (and consequently by varying the mean free path of the phonons) it is possible to control significantly the value of the thermal conductivity of crystals at low temperatures. Conversely, at a fixed electron concentration, owing to the temperature dependence of the electronic absorption of the phonons in the piezosemiconductor, there occurs also a sharp decrease of the thermal conductivity in a definite temperature interval.

We shall assume that the free path of the phonons is determined in the considered temperature interval principally by their interaction with the electrons; the latter, in turn, are scattered predominantly by impurities, dislocations, etc. Then umklapp processes can be disregarded in this model [1] and the expression for the conductivity tensor will be:

$$\kappa_{ij} = k \sum_{\alpha} \int d\omega d^3q \frac{v_i^{\alpha} v_j^{\alpha}}{2\gamma^{\alpha}(\omega, \vec{q})} \frac{\partial \epsilon^{\alpha}(\omega, \vec{q})}{\partial T} \quad (1)$$

Here  $k$  is Boltzmann's constant,  $\vec{v}^{\alpha}$  is the group velocity of the acoustic waves with polarization  $\alpha$ ,  $\gamma^{\alpha}(\omega, \vec{q})$  is the time decrement of the damping (see [2],  $\epsilon^{\alpha}$  is the thermodynamic equilibrium energy density of the radiation of the acoustic phonons corresponding to a Planck distribution, and  $T$  is the absolute temperature in energy units. The damping decrement  $\gamma^{\alpha}(\omega, \vec{q})$ , of the acoustic waves, as is well known [2], depends essentially on the interaction of the electrons with the phonons, and for the case of a piezosemiconducting crystal, where this interaction is the strongest, it can be represented in the form

$$\gamma^{\alpha}(\omega, \vec{q}) = \frac{1}{2} \eta_{\alpha}^2 \omega \operatorname{Im} \frac{\epsilon_0}{\zeta_{\parallel}(\omega, \vec{q})} + \frac{\mu_{\alpha} \omega^n}{2\rho (v^{\alpha})^n} \quad (2)$$

Here  $\eta_{\alpha}^2$  is the square of the constant of the electromechanical coupling, which is connected with the piezoelectric tensor  $\beta_{i,jl}$  by the relation

$$\eta_{\alpha}^2 = \frac{4\pi (\beta_{i,kl} q_l q_k b_i^{\alpha})^2}{\rho v_{\alpha}^2 \epsilon_0 q^2}$$

( $\rho$  is the density of the crystal,  $\epsilon_0$  the dielectric constant of the lattice,  $\vec{b}^{\alpha}$  a unit vector of polarization,  $\mu_{\alpha}$  the phenomenological phonon viscosity, and  $n = n(\alpha)$  a numerical factor determining the frequency dependence of the non-electronic absorption of the phonons). It is seen from (1) and (2) that the electronic part of the absorption decrement has a strong influence on the thermal conductivity tensor of the crystal. To calculate the explicit form of the coefficients of thermal conductivity, let us consider the simplest case of low frequencies, when it is possible to use the hydrodynamic model for the calculation of the longitudinal dielectric constant  $\epsilon_{\parallel}(\omega, \vec{q})$  of the plasma medium. Then, as is well known [2],

$$\zeta_{\parallel}(\omega, \vec{q}) = \epsilon_0 + \frac{4\pi\sigma_0}{i\omega} \frac{1}{1 + iq^2 v_T^2 / \omega\nu} \quad (3)$$

where  $\sigma_0 = e^2 N / m\nu$  is the conductivity,  $N$  the electron concentration,  $e$  the charge,  $m$  the effective mass of the electron,  $\nu$  the effective frequency of the collision of the electrons with the scattering centers, and  $v_T$  the thermal velocity of the electrons. Substituting (3) in (2) and (1) we obtain for the

thermal conductivity tensor the final expression:

$$\kappa_{ij} = \sum_{\alpha} \frac{\kappa_{\alpha}^0}{A} \int_0^{A/T} dx \int d\Omega \frac{x^{4-n}}{\text{sh}^2 x} \frac{v_j^{\alpha} v_j^{\alpha} / v_{\alpha}^2}{1 + \frac{\sigma \Delta^{\alpha} x^{2-n}}{(\sigma + b^{\alpha} x^2)^2}}, \quad (4)$$

where

$$\sigma = \frac{4\pi e^2 N \hbar}{2T m \nu \epsilon_0}, \quad b^{\alpha} = \frac{2T^2}{\hbar m \nu v_{\alpha}^2}, \quad \Delta^{\alpha} = \eta_{\alpha}^2 T r_{ph} / \hbar, \quad r_{ph}^{-1} = \frac{\mu_2}{2} (2T / \hbar v_{\alpha})^n$$

$\hbar$  is Planck's constant,  $\theta$  is the Debye temperature,  $\kappa_{\alpha}^0$  is the partial thermal conductivity of the piezodielectric, due to the phonons with polarization  $\alpha$ , and

$$A^{-1} = \frac{4\pi}{3} \int_0^{\theta/T} \frac{x^{4-n}}{\text{sh}^2 x} dx$$

is the numerical coefficient.

The relative change of the thermal conductivity tensor due to the change in the number of electronic (e.g., the case of a photoconductor) will be

$$\frac{\kappa_{ij}(N) - \kappa_{ij}(0)}{\kappa_{ij}(0)} = - \sum_{\alpha} \kappa_{\alpha}^0 \int_0^{A/T} dx \int d\Omega \frac{x^{4-n}}{\text{sh}^2 x} \frac{v_j^{\alpha} v_j^{\alpha}}{v_{\alpha}^2} \phi_{\alpha}(x) [\sum_{\alpha} \kappa_{\alpha}^0]^{-1}, \quad (5)$$

where

$$\phi_{\alpha}(x) = \frac{\sigma \Delta^{\alpha} x^{2-n}}{(\sigma + b^{\alpha} x^2)^2 + \sigma \Delta^{\alpha} x^{2-n}}.$$

It is seen from (5) that the integrand function in the integral with respect to  $x$  consists of a product of two functions:  $\phi_{\alpha}(x)$  and  $g(x) = x^{4-n} / \text{sh}^2 x$ . It is clear that the value of the integral itself will depend strongly on the relative placements of the maxima of these functions: if the maxima coincide, then the integral has a maximum value. The latter precisely corresponds to the largest change of the thermal conductivity as a function of the electron concentration. It is easy to see that the maximum of  $\phi_{\alpha}(x)$  occurs at

$$x = \frac{1}{2} \sqrt{\frac{2-n}{2+n}} \frac{\hbar v_{\alpha}}{r_D T}$$

( $r_D$  - Debye radius of the electrons), and the maximum of  $g(x)$  is reached near  $x \approx 1$  ( $n < 2$ ). We see therefore that the greatest change of the thermal conductivity tensor occurs at

$$\frac{1}{2} \sqrt{\frac{2-n}{2+n}} \frac{\hbar v_{\alpha}}{r_D T} = 1 \quad (6)$$

This condition has a simple physical meaning. It is known that in a piezosemiconducting crystal the largest electron absorption is possessed by those acoustic phonons whose wavelength coincides with the Debye radius of the electrons.

On the other hand, the maximum contribution to the phonon thermal conductivity is made by phonons with wavelength  $\lambda_T \approx T/\hbar v_\alpha$ . Therefore the condition (6) actually denotes  $\lambda_T = r_D$ , apart from a numerical factor that depends, naturally, on the frequency index  $n$  of the non-electronic absorption mechanism. Relation (6) determines in essence the values of the concentration of the electrons  $N$  and of the temperature  $T$ , at which the effect considered above is possible. It is important that condition (6) does not contain the constant of the electromechanical coupling - it determines only the magnitude of the effect. In order for the effect to be large, it is necessary to satisfy near the maximum, i.e., near  $x \approx 1$ , the condition

$$(a + b\alpha)^2 < a\Delta^\alpha \quad (7)$$

for all the acoustic modes simultaneously. Recognizing that near the maximum  $a \approx b\alpha$ , we obtain the sufficient condition  $\Delta^\alpha/a > 1$ . If a stronger condition is satisfied in place of (7), then the change of the thermal conductivity will be gigantic. By way of an example, let us estimate the change of the partial phonon thermal conductivity  $\kappa_\alpha$  for a fixed  $\alpha$ , say, due only to longitudinal phonons. For a crystal of the CdS type, the optimal values of the concentration and of the temperature will be  $N = 10^{16} \text{ cm}^{-3}$  and  $T = 4^\circ\text{K}$ . If at the same time  $\tau_{ph} \approx 10^{-9} \text{ sec}$ , then the partial value of the thermal conductivity is decreased by a factor of 3 compared with the value of  $N = 0$  (or  $N = \infty$ ).

The indicated effect will be large if the symmetry of the crystal and the chosen direction of heat-flow propagation (the  $x$  direction) are such that the components of the piezo tensor  $\beta_{x,xx}$ ,  $\beta_{x,xy}$ , and  $\beta_{x,xz}$  are simultaneously different from zero. It is precisely under these conditions that the free paths of both the longitudinal and transverse phonons will change simultaneously with changing concentration (temperature).

In conclusion we note that in a crystal with a sufficiently strong electron-phonon interaction, all the mechanisms (magnetic, electric fields, traps, etc.) influencing the electron decrement can lead to a sharp change in the phonon thermal conductivity of the crystal. This principle can be used to develop devices for automatic control and stabilization of the temperature.

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#### CHOICE OF OPTIMAL CONDITIONS FOR EXPERIMENTAL OBSERVATION OF COHERENT SCATTERING OF $\gamma$ QUANTA BY NUCLEI

V.G. Kudryavtsev and M.I. Ryazanov  
 Moscow Engineering Physics Institute  
 Submitted 1 July 1970  
*ZhETF Pis. Red.* 12, No. 3, 157 - 158 (5 August 1970)

1. An experimental study of coherent scattering of  $\gamma$  quanta in a Coulomb field is of considerable interest, since this process is the simplest process connected with the nonlinear properties of vacuum in quantum electrodynamics [1, 2]. However, observation of coherent scattering by nuclei at not too large quantum frequencies  $\omega \lesssim m$  is inhibited by the need for separating the "nuclear" scattering from the background of the much more probable process of Compton scattering. The intensity of scattering by nuclei greatly exceeds the intensity of Compton scattering only at very high frequencies,  $\omega \gg m$ , and small