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ACOUSTO-ELECTRIC ABSORPTION IN NONDEGENERATE SEMICONDUCTORS AT HIGH TEMPERATURES

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Using the modified collision term of electrons we derive the expression for conductivity using the Boltzmann equation and hence calculate the absorption coefficient for non degenerate semiconductors. The optical phonon scattering associated with the acoustical phonon scattering has been considered the electron scattering mechanism.

KEYWORDS : Non degenerate Semiconductors, optical phonon, acoustical phonon, absorption coefficient, Conductivity tensor, Boltzmann distribution function.

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INTRODUCTION

A great deal of attention has been paid to the theoretical study of attenuation and amplification of the acoustic waves in solids [1-7]. Most of the earlier theoretical investigators ignored the energy dependence of the relaxation time. However, Jacoboni and Prohofsky [2] and Sharma [3] have realized the importance of taking into account the relevant energy dependence of the relaxation time. In both of these investigations these authors have used the CHH model of the collision term. In a paper Sharma and Kaw [4] have pointed out that the Cohen, Harrison and Harrison (CHH) model cannot be used for energy-dependent relaxation time since this model does not conserve the particle density. Using an appropriate collision term they calculated the absorption coefficient for a simple model semiconductor. Their analysis is, however, valid only in the temperature range (100-300°K) when acoustic phonon scattering is dominant scattering mechanism. Their analysis is not applicable for temperatures above room temperature since at these temperatures (300-500°K) the optical phonon scattering becomes significant. In this paper we extend the analysis of Sharma and Kaw to apply to the high temperature region by taking into account both acoustic phonon scattering as well as optical phonon scattering. Using a simple model of band structure and a collision term used by Sharma and Kaw, we drive expressions for the conductivity tensor and absorption coefficient of an acoustic wave [8-11]. We have computed the absorption coefficient of an acoustic wave for various temperatures and the results have been shown in the form of a graph.

BOLTZMANN DISTRIBUTION FUNCTION AND CONDUCTIVITY TENSOR

Sharma and Kaw have pointed out that one cannot use the CHH model for the collision term in the presence of an acoustic wave for energy-dependent relaxation time, for the simple reason the CHH model fails to conserve the particle density. For such relaxation times they have suggested to use a modified collision term; such a collision term was used by Bogdanor and Willet [5] in their investigation of damping of plane waves in weakly ionized gases. Thus the rate of change of the distribution function in the presence of an acoustic wave is given by

$$\left(\frac{\partial f}{\partial t}\right)_{coll} = -\frac{f - \langle f \rangle}{\tau(\in)} \qquad \ldots (1)$$

where < > refers to the average over $d\Omega$, (*i.e.*, the solid angle).

For small perturbations the distribution function can be expanded as

$$f = f^0 + {}^1, \qquad \ldots (2)$$

where $f_0 = K_n \exp(-[m v/k_B T])$ is the isotropic part of the distribution function; ($Kn = (N_0/\pi^{3/2}\nu_0^3)$.... is the normalizing constant, N_0 is electron density, ν_0 is the average thermal velocity) and f^1 is the anisotropic part.

The Boltzmann equation for electron in the presence of an acoustic wave may be written as

$$\frac{\partial f^1}{\partial t} + \bar{\nu}.\frac{\partial f^1}{\partial r} - \frac{e\bar{E}_S}{m}.\frac{\partial f^0}{\partial \bar{\nu}} = -\frac{f^1 - \langle f^1 \rangle}{\tau} \qquad \ldots (3)$$

where $$E_S = E - icq^2 u/ew_C, \qquad (5.4)$$

and all other notations are usual. Equation (3) can readily be solved for f ' to present the following form.

$$f^{\,1} = \frac{eE_S\tau}{m\gamma}\frac{\partial f^0}{\partial \nu}\left[\xi + \frac{\langle \xi/\gamma \rangle}{(1 - \langle 1/\gamma \rangle)}\right], \qquad \ldots (5)$$

where $\xi = \cos\theta$, $\gamma = a + b\xi$, $a = 1 - i\omega_C\tau$, $b = iq\nu_0\tau\, x^{1/2}$.

For the mixed scattering of optical and acoustic phonons the collision frequency of electrons can be expressed as

$$\nu_1 = Ax^{1/2} + B\left(x + \frac{\hbar\omega_C}{k_B T}\right)^{1/2}, \left(x < \frac{\hbar\omega_C}{k_B T}\right), \qquad \ldots (6)$$

$$\nu_2 = Ax^{1/2} + B\left[C\left(x - \frac{\hbar\omega_C}{k_B T}\right)^{1/2} + \left(x + \frac{\hbar\omega_C}{k_B T}\right)^{1/2}\right], \left(x > \frac{\hbar\omega_C}{k_B T}\right), \qquad \ldots (7)$$

where, $$x = \frac{E}{k_B T}, \qquad C = \exp\left(\frac{\hbar\omega_C}{k_B T}\right),$$

$$A = \frac{\sqrt{2}E_{ac}^2 m^{3/2}(k_B T)^{3/2}}{\pi\rho\, u^2\hbar^4}, \qquad n_0 = (C-1)^{-1},$$

$$B = \frac{E_{OP}^2 m^{3/2} \omega_C n_0 (k_B T)^{1/2}}{\sqrt{2}\pi\hbar^3 \rho\ u^2},$$

E_{OP} is the deformation potential for optical scattering,

E_{aC} is the change in band edge energy per unit dilation.,

ρ is the crystal density, u is the sound velocity,

$\hbar$ is the Plank's constant divided by 2π, k_B is the Boltzmann constant,

ω_C is the Phonon frequency.

The current density J_Z associated with an acoustic wave is given by

$$J_Z = -e\int \nu_Z f^1 d^3\nu \qquad \ldots (8)$$

Substituting f^1 from eqn. (5) in eqn. (8) we get

$$\sigma_Z = \frac{J_Z}{E_S} = -\frac{e^2}{m}\int_0^{\alpha}\int_{-1}^{+1} \frac{\nu^3}{\nu}\frac{\partial f^0}{\partial \nu}\left[\xi + \frac{\langle \xi/\gamma\rangle}{(1-\langle 1/\gamma\rangle)}\right]\frac{\xi}{\gamma} d\nu d\xi \qquad \ldots (9)$$

This equation may easily be transformed to the following one

$$\sigma_Z = -\frac{e^2}{m}\int_0^{\alpha}\int_{-1}^{+1} \frac{\nu_0{}^3}{\nu} x^{3/2} f^0\left[\xi + \frac{\langle \xi/\gamma\rangle}{(1-\langle 1/\gamma\rangle)}\right]\frac{\xi}{\gamma} dx d\xi \qquad \ldots (10)$$

Using eqns (6) and (7), eqn (10), *i.e.* the expression for the conductivity tensor, can be written as

$$\sigma_Z = -\frac{e^2}{m}\left[\int_0^{\hbar\omega_C}\int_{-1}^{+1} \frac{\nu_0{}^3}{\nu} x^{3/2} f^0\left[\xi + \frac{\langle \xi/\gamma\rangle}{(1-\langle 1/\gamma\rangle)}\right]\frac{\xi}{\gamma} dx d\xi + \int_{\hbar\omega_C}^{\alpha}\int_{-1}^{+1} \frac{\nu_0{}^3}{\nu_2} x^{3/2} f^0\left[\xi + \frac{\langle \xi/\gamma\rangle}{(1-\langle 1/\gamma\rangle)}\right]\frac{\xi}{\gamma} dx d\xi\right] \qquad \ldots (11)$$

Expressing the conductivity in dimensionless form we have

$$\sigma^1 = \frac{\sigma_Z}{\sigma_0} = -\frac{e^2}{m\sigma_0}\left[\int_0^{\hbar\omega_C}\int_{-1}^{+1} \frac{\nu_0{}^3}{\nu_1} x^{3/2} f^0\left[\xi + \frac{\langle \xi/\gamma\rangle}{(1-\langle 1/\gamma\rangle)}\right]\frac{\xi}{\gamma} dx d\xi + \int_{\hbar\omega_C}^{\alpha}\int_{-1}^{+1} \frac{\nu_0{}^3}{\nu_2} x^{3/2} f^0\left[\xi + \frac{\langle \xi/\gamma\rangle}{(1-\langle 1/\gamma\rangle)}\right]\frac{\xi}{\gamma} dx d\xi\right] \qquad \ldots (12)$$

where $$\sigma_0 = \frac{4N_0 e^2}{3m\sqrt{\pi}}\left[\int_0^{\hbar\omega_C} \exp(-x)\frac{\partial}{\partial x}\left(\frac{x^{3/2}}{\nu_1}\right)dx + \int_{\hbar\omega_C}^{\infty} \exp(-x)\frac{\partial}{\partial x}\left(\frac{x^{3/2}}{\nu_2}\right)dx\right] \qquad \ldots (13)$$

is the d.c. conductivity [6] of the semiconductor. Now the absorption coefficient of an acoustic wave is directly related to σ^1 through the relation [7]

$$\frac{\alpha}{\frac{2N_0 m}{\tau_0 \rho u}\left(\frac{C}{mv^2}\right)\frac{\omega_C^4}{\omega_P^4}} = \alpha_0 = R_e[\sigma^1]^{-1}$$

where $\omega_P = (4\pi N_0 e^2/m)^{1/2}$ is the plasma frequency. The symbol Re stands for the real part and α_0 is the dimensionless measure of the absorption coefficient of acoustic wave.

We have computed σ^1 and hence α_0 numerically.

Discussion

The solid curves in Fig. 1 show the variation of α with ql for various values of temperature, when scattering by both acoustic and optical phonon is taken into account. To emphasize the effect of including optical phonon scattering on absorption we also show the variation of α with ql by the dotted curves when only acoustic phonon scattering is taken into account. It is seen from fig. 1 that absorption coefficient increases with decreasing temperature for a given frequency. One also notes that the effect of including optical phonon scattering is to decrease α in the limit $q\text{l} << 1$ while in the limit $q\text{l} \geq 1$ it leads to increased value of absorption coefficient.

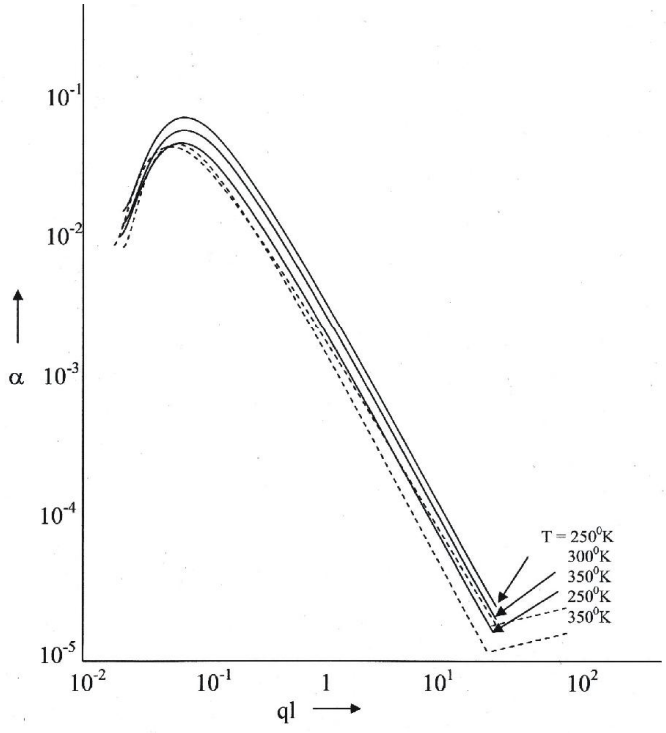

Fig. 5.1. Variation of absorption coefficient α with ql has been shown for various values of temperature. The dotted curve is only for acoustic phonon scattering while continuous curve is for mixed scattering.

The variation of absorption coefficient with ql (Fig. 1) shows a peak in the absorption of acoustic wave which can be explained as follows. In the hydrodynamic limit, *i.e.*, for relatively lower frequencies (ql << 1…) the deformation potential coupling which is proportion to ql is very small and thus absorption coefficient is very small. In the high frequency limit, *i.e*., for ql >> 1, as pointed out by Pippard, the acoustic wave-electron interaction is limited only to those electrons for which the component of velocity along the direction of propagation of sound is equal to the sound velocity. Thus the absorption of acoustic wave by electrons for ql >> 1 is again very small despite larger value of deformation potential coupling in this region of frequency. Therefore the absorption coefficient versus ql plot should have a maximum somewhere between these two limits.

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