

# Frequency and Mass Dependent Acoustoelectric Phenomenon in Piezoelectric Semiconductors

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## ABSTRACTS

The phenomenon of acoustoelectric effect is similar to that of self focusing of an optical beam. A phenomenological approach has been used to determine the change in collision frequency, which is greater than change in electron mass for all acoustic wave frequencies and temperatures. It has been shown that both change in collision frequency and electron mass both increase rapidly and then increase slowly and show saturation at high frequency. It is also shown that at the low temperature, the frequency for saturation and mass with respect to the carrier concentration was found to be very small.

**Keywords :** Self Focusing, Phenomenological Approach, Acoustoelectric Phenomenon

## I. INTRODUCTION

When an acoustic wave of frequency  $\omega$  propagates through semiconductors, interaction between electrons and acoustic phonons takes place<sup>1-5</sup> and a fraction of the total number of electrons follow the acoustic phonons. The effective mass of the acoustic phonon may be taken as  $m \approx \frac{K_0 T_0}{v_s^2}$  where  $K_0$  is the

Boltzmann constant,  $T_0$  is the lattice temperature and  $v_s$  the sound velocity in the medium. Due to this, piezoelectric semiconductors can exhibit harmonic generation<sup>6,7</sup> because of interaction between the acoustic and electric fields, which contribute to the non linearity in electron mass and collision frequency. The average momentum and temperature of electrons can be determined by momentum and energy balance equation.

$$\frac{d(mv)}{dt} = -eE_a - \nu m v \dots\dots\dots (1)$$

$$\frac{d}{dt} \left( \frac{3K_0 T}{2} \right) = -eR_e E_a R_e v - \left\langle \frac{d\zeta}{dt} \right\rangle_{\text{dissipation}} \dots\dots\dots (2)$$

Where  $E_a$  is the electric field associated with the acoustic wave.  $-e$  is the electronic charge,  $m$  is mass,  $v$  is the velocity,  $n$  is the collision frequency,  $T$  is the electron temperature. For non linearity in electron mass and collision frequency at room temperature as well as low temperature, we consider only acoustic phonon associated with acoustic wave scattering, for which the collision frequency  $n$  is given by<sup>9</sup>

$$\nu = \nu_0 \left( \frac{3K_0 T}{2\zeta} \right)^{\frac{1}{2}} \dots\dots\dots (3)$$

Where  $\nu_0$  is the equilibrium collision frequency and  $\zeta = \frac{3K_0 T}{2}$ ,  $T$  is the electron temperature. The rate of energy loss to acoustic modes in simple mode is given by<sup>10</sup>

$$\left\langle \frac{d\zeta}{dt} \right\rangle = \frac{4C^2 m^{\frac{5}{2}} (2K_0 T)^{\frac{3}{2}}}{\pi^{\frac{3}{2}} h^4 \rho} \left(1 - \frac{T_0}{T}\right) \dots\dots\dots (4)$$

Where, C is the acoustic deformation potential constant,  $\rho$  is the density of the medium, h is Planck's constant, The average value of the electron

$$\text{mass is } m = \frac{2 \left\langle \frac{\zeta}{K_0 T_0} \right\rangle + \frac{E_g}{K_0 T_0}}{W} \dots\dots\dots (5)$$

Where  $E_g$  is the energy band gap and  $W = \frac{(4P\pi)^2}{3h^2 K_0 T_0}$  is a constant. For a piezoelectric solid, there is an additional contribution to the internal energy from the polarization fields, which accompany the lattice displacement.

This additional energy is given by the product of electric displacement and electric field as  $\frac{1}{2} \bar{D} \cdot \bar{E}$ .

The stress tensor<sup>11</sup> for the medium is then

$$T = C \bar{S} - e_p \bar{E} \dots\dots\dots (6)$$

Equation (6) follows from the Maxwell's relations for the displacement field given by

$$\bar{D} = \varepsilon \bar{E} + 4\pi\beta \bar{S} \dots\dots\dots (7a)$$

$$I = ne\mu \bar{E} - eD_n \nabla_n \dots\dots\dots (7b)$$

$$\nabla \cdot I = -e \frac{\partial n}{\partial t} \dots\dots\dots (7c)$$

Where  $\bar{D}$  is the electric displacement,  $\bar{S}$  is the strain, I is the current density,  $D_n = \frac{\mu K_0 T}{e}$  is the diffusion coefficient,  $\mu = \frac{e}{m\nu}$  is the electron mobility, b and e are the piezoelectric and dielectric constants of the semiconductor respectively. The electric field and carrier concentration can be expressed as<sup>12</sup>

$$E = E_a \exp\{i(\omega t - qx)\} \dots\dots\dots (8a)$$

$$n = n_0 + n_a \exp\{i(\omega t - qx)\} \dots\dots\dots (8b)$$

Here it has been assumed that the acoustic wave is propagating along the x axis in the semiconductor. Solving (7) and (8) along the Maxwell's equations, the following expression for  $E_a$  is obtained.

$$E_a = -4\pi \frac{\beta}{\varepsilon} \frac{(1 + i \frac{\omega}{\omega_D}) S_a}{1 + i(\frac{\omega}{\omega_D} + \frac{\omega_c}{\omega})} \dots\dots\dots (9)$$

Where  $\omega_c = 4\pi n_0 e \frac{\mu}{\varepsilon}$  is the carrier relaxation

frequency,  $\omega_D = \frac{v_s^2}{D}$  is the diffusion frequency and

$S_a = i q U_a$  where q is the wave number and  $U_a$  the lattice displacement.

Using the expression for the acoustic flux given by  $\phi_a = \rho v_s \omega^2 U_a U_a^* / 2$  and from equation (9), we obtain the following expression

$$E_a E_a^* = (2h\beta / e)^2 \frac{2\phi_a \{1 + (\frac{\omega}{\omega_D})^2\}}{\rho \hbar^2 v_s^3 \{1 + \frac{\omega}{\omega_D} + \frac{\omega_c}{\omega_D}\}} \dots\dots\dots (10)$$

Where  $E_a$  and  $E_a^*$  is the Electric field of acoustic wave? To obtain the expression for the ratio between the temperatures of the electron and the lattice in the steady state, for the case of  $n^2 \ll w^2$  using equation (4), in equation (1) and equation (2) as

$$\frac{T}{T_0} - 1 = \frac{\Delta T}{T_0} = \left(\frac{\pi}{2K_0 T_0}\right)^{\frac{3}{2}} \cdot \frac{e^2 \hbar^4 \rho E_a E_a^*}{8\nu C^2 m^{\frac{7}{2}}} \dots\dots\dots (11)$$

Where T temperature of electron and  $T_0$  is temperature of the lattice.

Using equation (11) in (3) and (5), the expression for the electron mass and collision frequency can be written, respectively as

$$m = m_0 + m_2 E_a E_a^* \dots\dots\dots (12a)$$

$$\text{And } \nu = \nu_0 + \nu_2 E_a E_a^* \dots\dots\dots (12b)$$

Where  $\nu_0$  and  $m_0 = (3 + \frac{E_g}{K_0 T_0})/W$  are unperturbed parts of the collision frequency and mass of the electron respectively and

$$m_2 = \left( \frac{\pi}{2K_0 T_0} \right)^{\frac{3}{2}} \frac{3e^2 \hbar^4 \rho}{8C^2 \nu_0 m^{7/2} W} \dots\dots\dots (13a) \text{ and}$$

$$\nu_2 = \left( \frac{\pi}{2K_0 T_0} \right)^{3/2} \frac{e^2 \hbar^4 \rho}{16C^2 m^{7/2}} \dots\dots\dots (13b)$$

## II. DISCUSSIONS

To have numerical appreciations of the result obtained in the equation (12a) and (12b) respectively, using equation (10), (13a) and (13b), we made calculations to study change  $\Delta m = m - m_0$  in electron mass and  $\Delta n = n - n_0$  in collision frequency. We present here numerical result for the typical case of n-Cadmium sulphide at two different temperatures.

The relative change in mass  $\frac{\Delta m}{m_0}$  and collision

frequency  $\frac{\Delta \nu}{\nu_0}$  with respect to the acoustic wave

frequency at  $T=300K$  with the following parameters chosen are  $m_0 = 1.913 \times 10^{-25}g$ , energy band gap  $E_g = 2.6 eV$ , dielectric constant  $\epsilon = 5.4$ , density of medium  $r = 4.84 gcm^{-3}$ , sound velocity  $v_s = 4.2 \times 10^5 cm/s$ , acoustic deformation constant  $C = 10 eV$ , mobility  $m = 340 cm^2/Vs$ , piezoelectric constant  $b = 6.54 \times 10^4 esu/cm^2$  and carrier concentration  $n_0 = 1.0 \times 10^{14} cm^{-3}$ .

The relative change in the  $m$  and  $n$  with the CdS and at  $T = 100 K$  with the following parameters  $E_g =$

$2.5 eV$ ,  $m_0 = 1.45 \times 10^{-28}g$ ,  $\epsilon = 9.35$ ,  $r = 4.8 gcm^{-3}$ ,  $C$ ,  $b$  and  $n_0$  having the same values in the earlier case. The flux associated with acoustic wave has been taken as  $0.5 Wcm^{-2}s$  for the both cases.

It has been seen that both the change in mass and change in collision frequency increases rapidly with increasing acoustic wave frequency in the range  $w < (n_0 w_D)^{1/2}$  while in the vicinity of  $w = (n_0 w_D)^{1/2}$ , they increase slowly and show saturation at very high frequencies. The change in mass as well as collision frequency is found to be larger at low temperatures. The relative change in collision frequency is much higher than in mass for all values of  $w$  and  $T$ . It is also noted that at low temperature, the frequency for the saturation in mass and collision frequency is lowered. The change in mass and collision frequency with respect to the carrier concentration was found to be very small. In fact, the non linear effects of the acoustic waves are similar to that of electromagnetic waves (self focussing of laser beam).

We believe that this simple theory will be useful in the theoretical field of non linear acoustics in semiconductors.

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