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Propagation of Thermo-Elastodiffusive Surface Acoustic Waves in Semiconductors

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The paper is aimed at to investigate the propagation of thermoelastic diffusive surface waves in homogenous isotropic, thermally conducting semiconductor, half space materials. The secular equations governing the phase velocity, attenuation coefficient and other characteristics of the thermoelastic (ET) and elastodiffusive (EN) waves have been obtained. The waves are found to be dispersive in character and attenuated in space. The secular equations have been solved numerically for silicon (Si) semiconductor to obtain the profile of phase velocity and attenuation coefficient. The numerically simulated results have also been presented graphically.

Key Words: Semiconductors, Electrons, Holes, Surface waves, Silicon.

INTRODUCTION

Semiconductors have some useful properties and are being extensively used in electronic circuits. For instance, transistor-a semiconductor device is fast replacing bulky vacuum tubes in almost all applications. During the last decades, the acousto electric interaction has been used in a number of different devices such as acoustic amplifiers, acousto electric convolvers and acoustic coupled transport devices. Recent developments in synthesized semiconductor super lattices with high quality hetero structures have been found to be useful in a new generation of high performance devices such as the High Electron Mobility Transistor. The physics of surface phenomenon, especially of surface waves has been very rapidly developed during the last decades. Maruszewski[1,2] presented the theoretical consideration and developments of the simultaneous interactions of elastic, thermal and diffusion of charge carrier's fields in semiconductors. Maruszewski[2], Sharma and Thakur[3] formulated the problem of interaction of various fields mathematically and studied relaxation effect on thermodiffusive waves. Some researches[4-6] modified Fourier law of heat conduction and constitutive relations so as to obtain a hyperbolic equation for heat conduction.

In the present article, the effect of life and relaxation times of carrier fields on the characteristics of ET and EN waves in semiconductor half space has been investigated.

FORMULATION OF THE PROBLEM

We consider a homogeneous isotropic, thermally conducting, elastic semiconductor medium initially under the undeformed state at uniform temperature (T_0). We take the origin of coordinate system oxyz on the top plane surface and z-axis pointing normally into the halfspace, which is thus represented by $z \geq 0$. We assume that the surface $z = 0$ is stress free, thermally insulated or isothermal and there is no flow of electrons and holes across it or equilibrium state of charge carrier fields is set up on the surface. We choose x-axis along the direction of wave propagation so that all particles on a line parallel to y-axis are equally displaced. In linear theory of thermoelasticity in semiconductors, the nondimensional governing field equations for temperature $T(x,z,t)$, displacement vector $\vec{u}(x,z,t)=(u,0,w)$, electron and hole charge carrier fields $N(x,z,t)$ and $P(x,z,t)$ respectively, in the absence of body forces, and heat sources, are as[3]

$$\nabla^2\phi - \ddot{\phi} - \overline{\lambda_n} N - \overline{\lambda_p} P - \theta = 0, \tag{1}$$

$$-\varepsilon_T \nabla^2(\dot{\phi}+t^Q\ddot{\phi})+\varepsilon^{nq}\nabla^2 N-\left\{\frac{\alpha_0^n\partial^2}{\partial t^2}+\left(a_0{}^n+\alpha_0^n\right)\frac{\partial}{\partial t}+\frac{a_0^n}{t_n^+}\right\}N$$

$$+\varepsilon^{pq}\nabla^2 P-\left\{\frac{\alpha_0^p\partial^2}{\partial t^2}+\left(a_0{}^p+\alpha_0^p\right)\frac{\partial}{\partial t}+\frac{a_0^p}{t_p^+}\right\}P+\nabla^2\theta-\left(\dot{\theta}+t^Q\ddot{\theta}\right)=0,$$

$$-\varepsilon_n\varepsilon_T\nabla^2\dot{\phi}+\nabla^2 N-\frac{K}{\rho C_e D^n}\left[\frac{1}{t_n^+}+\left(1-\frac{\epsilon_n\alpha_0^n D^n}{k}-\frac{t^n}{t_n^+}\right)\frac{\partial}{\partial t}+\frac{t^n\partial^2}{\partial t^2}\right]N$$

$$-\varepsilon_n\alpha_0^p\dot{P}-\varepsilon_n\dot{\theta}+\varepsilon^{qn}\nabla^2\theta=0,$$

$$-\varepsilon_p\varepsilon_T\nabla^2\dot{\phi}+\nabla^2 P-\frac{K}{\rho C_e D^p}\left[\frac{1}{t_p^+}+\left(1-\frac{\epsilon_p\alpha_0^p D^p}{k}-\frac{t^p}{t_p^+}\right)\frac{\partial}{\partial t}+\frac{t^p\partial^2}{\partial t^2}\right]P$$

$$-\varepsilon_p\alpha_0^n\dot{N}-\varepsilon_p\dot{\theta}+\varepsilon^{qp}\nabla^2\theta=0,$$

$$\nabla^2\psi=\frac{1}{\delta^2}\psi$$

Where symbols used in eq. 1 have yheir usual meanings as defined by Sharma and Thakur[3]. The last eq. of (1) corresponds to purely transverse waves, which get decoupled from rest of the motion and are not affected by the thermal and charge carrier fields. These waves travel with nondimensional velocity (δ) without dispersion, attenuation and damping. The non-dimensional boundary conditions[3] at the surface $z = 0$ are

$$\left(1-2\delta^2\right)u_{,x}+\left(1-\delta^2\right)w_{,z}-\overline{\lambda_n}N-\overline{\lambda_p}P-T=0 \tag{2.1}$$

$$u_{,z}+w_{,x}=0 \tag{2.2}$$

$$T_{,3}+h_T T+\varepsilon^{nq}\left(N_{,3}+h_n N\right)+\varepsilon^{pq}\left(P_{,3}+h_p P\right)=0 \tag{2.3}$$

$$\varepsilon^{qn}\left(T_{,3}+h_T\frac{\varepsilon_n}{\varepsilon^{qn}}T\right)+N_{,3}+h_n\bar{\varepsilon}'_{nq}N=0 \tag{2.4}$$

$$\varepsilon^{qp}\left(T_{,3}+h_T\frac{\varepsilon_p}{\varepsilon^{qp}}T\right)+P_{,3}+h_p\bar{\varepsilon}'_{pq}p=0 \tag{2.5}$$

$$h_T=\frac{K^S c_1}{K\omega^*},\quad h_n=\frac{a_0{}^n s^n}{\varepsilon^{nq}c_1},\quad h_p=\frac{a_0{}^p s^p}{\varepsilon^{pq}c_1},\quad \bar{\varepsilon}_{nq}=\frac{m^{nq}}{\rho D^n a_1{}^n},\quad \bar{\varepsilon}_{pq}=\frac{m^{pq}}{\rho D^p a_1{}^p}$$

$$\tau_1^n=\left(t^n+i\omega^{-1}\right),\tau_1^p=\left(t^p+i\omega^{-1}\right),\bar{\varepsilon}'_{nq}=-i\omega\bar{\varepsilon}_{nq}\tau_1^n,\ \bar{\varepsilon}'_{pq}=-i\omega\bar{\varepsilon}_{pq}\tau_1^p$$

Here ε_T is thermoelastic coupling parameter, k is the thermal diffusivity, K^S, s^n and s^p are respectively, the surface heat conduction coefficient and surface recombination velocities.

Secular equations

ET-surface waves

Let us now consider the case of the propagation of the ET surface wave, when complete equilibrium state of electron and hole concentration is established the system become charge free. In case of thermoelastic (ET) waves concerning the reciprocal dynamical interactions of the elastic and thermal fields and omit the electron and hole fields $(N=0=P,\varepsilon_n=\varepsilon_p=0,\varepsilon^{qn}=0=\varepsilon^{qp}=\overline{\lambda_n}=\overline{\lambda_p})$, the secular equation governing the interaction is given by

$$\begin{aligned}(\beta^2+k^2)^2\left[m_1^2+m_1m_2+m_2^2-\alpha^2\right]-4k^2\beta\, m_1m_2\left(m_1+m_2\right)\\=h_T\left[(\beta^2+k^2)^2\left(m_1+m_2\right)-4k^2\beta\left(m_1m_2+\alpha^2\right)\right]\end{aligned} \tag{3}$$

EN- surface waves

If we confine our discussion to the propagation of EN-waves concerning the reciprocal dynamical interactions of the elastic and electron diffusion fields and omit the thermal and hole fields $(P=\theta=0,\ \varepsilon_T=0=\varepsilon^{nq},\ \alpha_0{}^n=0=a_0{}^n)$, then the secular equation governing the interaction is obtained as

$$(\beta^2 + k^2)^2 \left[m_1^2 + m_1 m_3 + m_3^2 - \alpha^2\right] - 4\beta k^2 \varepsilon^{nq} m_1 m_3 (m_1 + m_3)$$
$$= h_n \left[(\beta^2 + k^2)^2 (m_1 + m_3) - 4\beta k^2 \varepsilon^{nq} (m_1 m_3 + \alpha^2)\right] \quad (4)$$

where $\beta^2 = k^2\left(1 - \frac{c^2}{\delta^2}\right)$ (5)

Eq. 3 is of the similar type as obtained and discussed by Lockett[7], Chadwick and Windle[8], Chadwick and Aitkin's[9] and Nayfeh and Nasser[10], in the context of generalized and conventional coupled thermoelasticity. The secular eq. 4 also has similar form and structure as that of eq. 3 and hence can be discussed on the same lines to obtain the complete information regarding wave number, frequency, phase velocity and attenuation coefficient along with other characteristics of the waves they contain in semiconducting materials.

RESULTS AND DISCUSSION

In order to illustrate the analytical development the numerical simulations of the secular equation (4) are carried out for silicon semiconductor in case of thermally insulated surface conditions. The physical data of silicon semiconductor material is given in Sharma and Thakur[3]. Here the considered non-dimensional values of life time $t_n^+ = 0.00796, 0.000796, 0.0000796$ corresponding to their respective dimensional values $t_n^+ = 10^{-14} s, 10^{-15} s, 10^{-16} s$ of charge carriers. Fig. 1 represents the non-dimensional phase velocity profile for elastodiffusive (EN) waves under insulated surface conditions with wave number and lifetime of charge carrier field. It is observed that the lifetime of charge carriers has a significant effect on phase velocity of EN waves. The amplitude of phase velocities amplitude starts from a high value (V = *ca.* 6) and decrease sharply in $0 \leq k \leq 1.2$ before these profiles become smoothen and steady for all wave numbers $k \geq 1.2$. The phase velocity profile corresponding to $t_n^+ = 10^{-16} s$ has comparatively high amplitude to that of all other cases in the all other in the wave number range $k \geq 1.2$. Some crosses over points among various profiles have also been noticed in the range $0 \leq k \leq 1.2$. The attenuation profiles for elastodiffusive (EN) waves in case of insulated surface conditions are represented in Fig. 2 with wave number. The amplitude of attenuation corresponding to the lifetime $t_n^+ = 10^{-15} s$ of charge carriers is maximal as compared to that at other values of lifetime of carrier's fields. The behaviour of attenuation profile is observed to be more or less as Gaussian in $0 \leq k \leq 2$ but linear and stable afterwards.

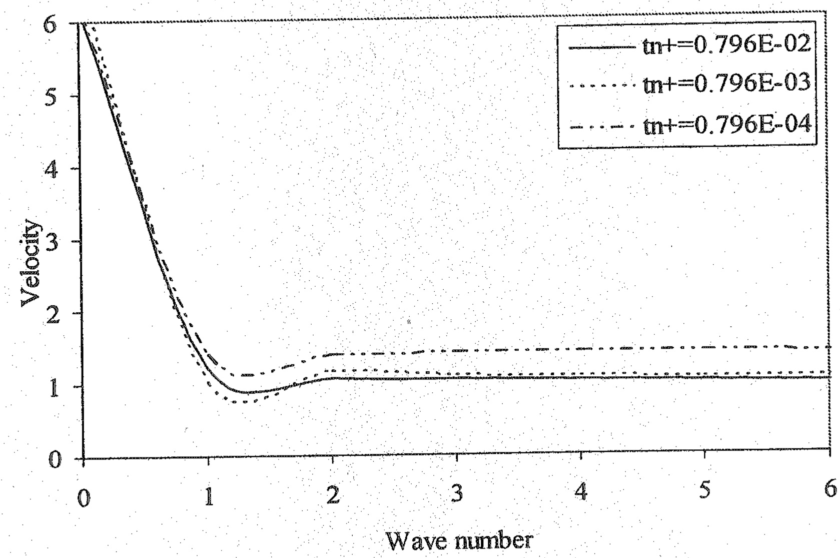

Fig. 1. Phase velocity profiles of elastodiffusive (EN) insulated waves

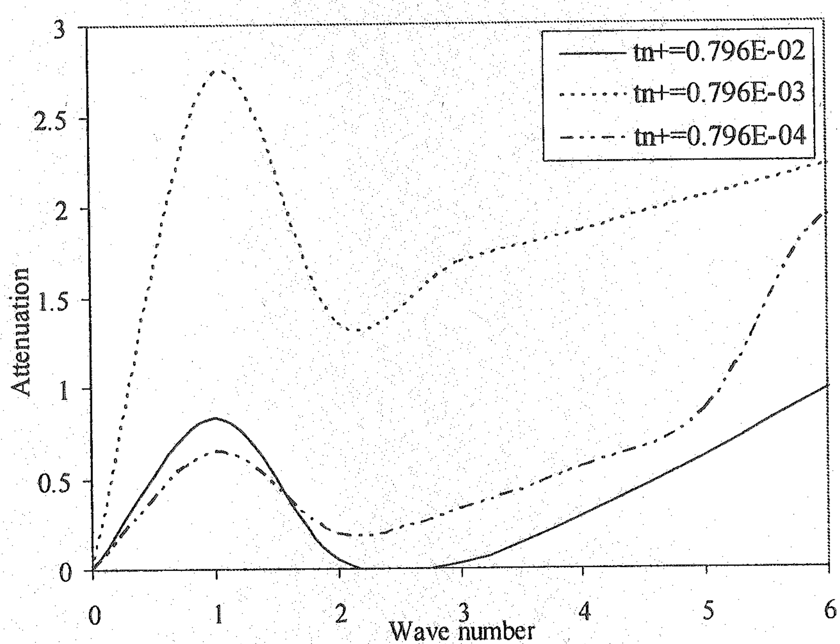

Fig. 2. Attenuation coefficient profiles of elastodiffusive (EN) insulated waves

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