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Photo-thermoelastic interactions in a 2D semiconducting medium

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Abstract. Photo-thermoelastic interactions in a two-dimensional semiconductor medium are studied by using mathematical methods in the context of coupled thermoelastic theory and plasma waves with one thermal relaxation time. The Laplace-Fourier transformations and eigenvalues approach are used to obtain the general solutions for any set of boundary conditions. The medium is initially assumed to be at rest and due to a moving thermal source with a constant speed, which are traction free. A semiconductor medium like silicon has been considered. In the conclusion, the outcomes are represented graphically to show the influences of heat source speed and the relaxation time. The eigenvalues approach gives the analytical solution without any assumed restriction on the actual physical quantities.

Introduction

Essentially, the investigation of a semiconducting with band gap energy E_g is lighted by a laser radiation with energy E higher than E_g, and followed by an electron excitement procedure that will take place. Electron can be transferred to the level of energy from the valence band ($E - E_g$, whereas E is the incident photon energy) above the conduction band edge only if $E > E_g$. The photoexcited free carriers will relaxes to one of the unfilled levels nearby the conductance band bottom during the non-radiative transitions. After that, a process of recombination will occur during the formation of the pairs of electron-hole. There is electron-hole plasma prior to the recombination process.

To overcome the first shortcoming in the theory of uncoupled thermoelasticity, Biot [1] presented the theory of coupled thermoelasticity that it provided two inconsistent phenomena with the physical observations. By postulating a new law of thermal conduction to replace the classical Fourier law, the theory of generalized thermoelasticity has been presented by Lord and Shulman [2] with one relaxation time. By using two relaxation time, Green and Lindsay [3] established the second theory of generalized of thermoelasticity.

During the last twenty-five years, great efforts have been carried out to investigate the structure of microelectronic and semiconductors through photoacoustic (PA) and photothermal (PT) technology [4,5] recently, both PA and PT technologies are considered as standard modes which are highly sensitive to photoexcited carrier dynamics. According to Mandelis and Hess [6], the absorption laser beam with modulated intensity leads to the generation of photo carriers, namely hole-electron pairs, *i.e.*, the carrier-diffusion waves or plasma waves, that play a dominant role in the experiments of PT and PA for most semiconductors. Both thermal and elastic waves are produced as a contribution of the plasma waves depth dependence that generates periodic heat and mechanically vacillations. The various effects of electronic deformation and thermoelasticity in a neglected semiconductor medium of a coupled system of thermoelastic equations and plasma have been analyzed by numerous researchers [7–12]. Rosencwaig and Opsal [13] studied the depth profiling of a photo-thermal wave in silicon [14]. As significant part of the properties of solid matter, researchers [15–28] investigated various problems by analytical and numerical methods. Moreover, Song *et al.* [29] studied the vibrations under the theory of generalized thermoelasticity subjected to optically excited semiconductor micro-cantilevers. They studied the reflections of the wave in a semiconductor plate under photo-thermal and generalized thermoelastic theories [30,31]. Abbas [32] investigated the dual-phase-lag model on photo-thermal interaction

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in an infinite semiconducting material containing a cylindrical hole. Abbas and Hobiny [33] studied the photo-thermal wave in an unbounded semiconductor material with a cylindrical hole. Abbas *et al.* [34–37] investigated the photo-thermal wave in one-dimensional semiconducting material. In the Laplace domain, the eigenvalues techniques give analytical solutions without any constraint on the factual physical quantity assumptions.

In this paper, however, the investigation is based on the thermoelastic and plasma waves with the Lord-Shulman model; the photo-thermoelastic interactions in a 2D semiconducting medium are investigated. Based on the eigenvalue techniques and Fourier-Laplace transformations, the governing relations are processed by using the numerical and analytical methods. The numerical computations are made for a silicon-like semiconducting material, and the outcomes are represented graphically.

Mathematical model

Mostly, the transport process theoretical analysis in a semiconductor material involves the coupling of elastic, plasma and thermal waves with one another. For a homogeneous, elastic and isotropic semiconducting medium, the basic equations of motion, plasma and the conduction of heat in the context of the Lord and Shulman model can be introduced by [2,11,38–40]

$$(\lambda+\mu)u_{j,ij}+\mu u_{i,jj}-\gamma_n N_{,i}-\gamma_t \Theta_{,i}=\rho\frac{\partial^2 u_i}{\partial t^2}\,, \tag{1}$$

$$D_e N_{,jj}=\frac{\partial N}{\partial t}+\frac{N}{\tau}-\vartheta\frac{\Theta}{\tau}\,, \tag{2}$$

$$K\Theta_{,jj}=-\frac{E_g}{\tau}N+\left(1+\tau_o\frac{\partial}{\partial t}\right)\left(\rho c_e\frac{\partial\Theta}{\partial t}+\gamma_t T_o\frac{\partial u_{j,j}}{\partial t}-Q\right). \tag{3}$$

The relations of stress and strain tensor can be given by

$$\sigma_{ij}=\mu(u_{i,j}+u_{j,i})+(\lambda u_{k,k}-\gamma_n N-\gamma_t\Theta)\delta_{ij}. \tag{4}$$

There are two cases:

i) (LS) refers to the Lord and Shulman's model,

$$\tau_o>0;$$

ii) (CT) refers to the classical thermoelastic model

$$\tau_o=0,$$

where $\Theta=T-T_o$, T_o is the reference temperature, Q is the moving heat source, $N=n-n_o$, n_o is the equilibrium carrier concentration, $\delta_E=E-E_g$, E_g is the semiconductor energy gap, E is the excitation energy, ρ is the medium density, σ_{ij} are the components of stresses, u_i are the components of displacement K is the thermal conductivity, c_e is the specific heat at constant strain, λ,μ are the Lamé's constants, $\gamma_n=(3\lambda+2\mu)d_n$, d_n is the coefficient of electronic deformation, D_e is the coefficient of carrier diffusion, $\gamma_t=(3\lambda+2\mu)\alpha_t$, α_t is the coefficient of linear thermal expansion, τ is the photogenerated carrier lifetime and $\vartheta=\frac{\partial n_o}{\partial\Theta}$ is the thermal activation coupling parameter [41], $i,j,k=1,2,3$, $\boldsymbol{r}$ is the vector of position, t is the time and (for semiconductor $10^{-12}\le\tau_o\le 10^{-10}s$) where τ_o is the thermal relaxation times. We consider a semiconducting half-space ($x\ge 0$) with the x-axis pointing into the semiconducting medium. The components of variables can be defined as

$$N=N(x,y,t),\quad \Theta=\Theta(x,y,t),\quad \boldsymbol{u}=(u,v,0),\quad v=v(x,y,t),\quad u=u(x,y,t). \tag{5}$$

Therefore, eqs. (1)–(4) can be expressed as

$$(\lambda+2\mu)\frac{\partial^2 u}{\partial x^2}+(\lambda+\mu)\frac{\partial^2 v}{\partial x\partial y}+\mu\frac{\partial^2 u}{\partial y^2}-\gamma_n\frac{\partial N}{\partial x}-\gamma_t\frac{\partial\Theta}{\partial x}=\rho\frac{\partial^2 u}{\partial t^2}\,, \tag{6}$$

$$(\lambda+2\mu)\frac{\partial^2 v}{\partial y^2}+(\lambda+\mu)\frac{\partial^2 u}{\partial x\partial y}+\mu\frac{\partial^2 v}{\partial x^2}-\gamma_n\frac{\partial N}{\partial y}-\gamma_t\frac{\partial\Theta}{\partial y}=\rho\frac{\partial^2 v}{\partial t^2}\,, \tag{7}$$