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Response of a semiconducting infinite medium under two temperature theory with photothermal excitation due to laser pulses

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ABSTRACT

A novel model of two-dimensional deformations for two-temperature theory at the free surface under the excitation of thermoelastic wave by pulsed laser for a semi-infinite semiconducting medium is studied. The effect of mechanical force during a photothermal process is investigated. The mathematical methods of the Lord–Shulman (LS includes one relaxation time) and Green–Lindsay (GL with two relaxation times) theories as well as the classical dynamical coupled theory (CD) are used. An exact expression for displacement components, force stresses, carrier density and distribution of temperature are obtained using the harmonic wave analysis. Combinations of two-temperature and photothermal theories are obtained analytically. Comparisons of the results are made between the three theories also. The effects of thermoelectric coupling parameter, two-temperature parameter on the displacement component, force stress, carrier density, and distribution of temperature for silicon (Si) medium have been illustrated graphically. The variations of the considered variables with the horizontal distance have been discussed.

1. Introduction

Biot [1] introduced the theory of coupled thermoelasticity (CD theory) based on the classical Fourier heat conduction law. This prediction may be suitable for most engineering applications. But for some cases, like a short-pulse laser heating process or under low temperature operating conditions, the conventional thermoelastic model is physically unacceptable because during short work time the thermal conditions cannot obtain equilibrium. Two well-known generalized thermoelastic models that drew attention of researchers are Lord-Shulman [2] model with one relaxation time and Green-Lindsay [3] model with two relaxation times, in those models the thermal relaxation times parameters are introduced in the Fourier's law of heat conduction. Many researchers and many works have been done under these theories [4–6]. These theories eliminate the paradox of infinite velocity of heat propagation and are termed generalized theories of thermoelasticity.

Excitation of thermal wave by pulsed laser in semiconductor materials is very important in industry (microelectronic devices) and technology of pulsed laser. The waves are created when ultra-short-pulsed laser heated a material. The high-density energy flux and ultra-short period laser beam have introduced situations where very large thermal gradients or an ultra-high heating rate may exist on the medium at the boundaries. When the laser pulse is used to heat a metal film, the thermal wave generate due to thermal expansion near the surface. In this phenomenon, we are using a non-Gaussian laser beam to heat the bounding plane surface. Moreover, in the case of ultra-short pulsed lasers heating, some researchers studied two important effects. The first one is the non-Fourier's effect in heat conduction which is modification of the Fourier heat conduction theory to account for the effect of mean free time in the energy carrier's collision process causing a photothermal processing [7,8]. The second is the dissipation of the stress wave due to coupling between temperature and strain rate, which causes transform of mechanical energy associated with the stress wave to the thermal energy of the material.

Gordon et al. [9] introduced the theory of photothermal, when used a laser-based apparatus on an intra cavity sample. Later, Kreuzer [10] used laser light sources to show sensitive analysis by photoacoustic spectroscopy. After that the photothermal heating methods of a semiconductor have been used to introduce stress-induced, thermal change, velocity of sound, bulk flow velocities. Specific heats cause changes in physical properties of the medium [11–13]. The study of semiconductor materials depends on the resistance of electrical conduction. It is known that, the resistance of the semiconductors decreases as temperature increases. The propagation of a thermal wave causes elastic vibrations in the medium, this process called thermoelastic mechanism of photothermal generation [14]. On the other hand, the free carriers directly produced by the photo-excited are called the electronic deformation in the elastic sample [14]. The above two ways

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describe the interaction between the plasma, thermal, and elastic wave equations during a photothermal process for a semiconductor medium [15]. As a result of technological developments in semiconductor industry, semiconductor materials are widely used in solar cells, modern electronic devices etc.

Chen and Gurtin [16] and Chen et al. [17,18] developed the deformable body using the theory of heat conduction, based on two different temperatures, the conductive temperature (ϕ) and the thermo dynamical temperature (T). In case of no heat supply, these two temperatures are equal. The spatial behavior, structural stability and convergence of the two temperature theory are developed by Quintanilla and Tien [19]. Youssef [20] introduced new model of the generalized thermoelasticity with two temperature theory. Later, Youssef et al. [21,22] studied various problems using the two temperature theory. Different theories with two temperature theory are used to investigate other areas in generalized thermoelasticity. Also the interactions between the plane waves in elastic medium and the theory of two temperatures for different theories have been considered by Othman and Lotfy [23–25]. The normal mode method for two-temperature theory in generalized rotation-magneto-thermoelasticity in 2D problem is widely used in many researches, see for example [26–30].

The main goal of this work is solving the 2-D deformation problem for two-temperature theory of a thin film semiconducting medium subjected to laser pulse. The photothermal process with the three theories at the free surface is taken into consideration. The harmonic wave method is used to obtain the analytical solution of two-temperature theory under a photothermal process. The used method showed the exact expression of some physical fields. Also, the influences of thermoelastic coupling, thermoelectric parameters and the relaxation times in this phenomenon on some physical quantities are studied. The effect of these forces has been depicted graphically. Comparisons between the results of LS theory with and without two temperature parameter are also discussed.

2. Basic equations

In this work, we present a theoretical description by taking into consideration the heat transport process in a semiconductor involved some quasi-particles (phonons, holes,... etc.). The coupled plasma waves, thermal waves and elastic waves altogether are produced by the interactions between these particles. A lot of these interactions have its own temperature (one-temperature is the light absorbed by the medium and converted into heat). We present a theoretical description by writing the system of equations for this phenomenon. The basic variable quantities are the carrier density $N(\vec{r}, t)$, the distribution of temperature $T(\vec{r}, t)$, and the elastic displacement $\vec{u}(\vec{r}, t)$, $\vec{r}$ is the position vector at time t. To study this phenomenon, we suggest that the heat flux located at the surface causes two temperatures effects.

Assume that the medium is linear, homogeneous and has isotropic properties. Choose the space variables x and z (the variables in this problem will be described in the xz-plane) to express the medium state at time t.

The semiconductor surface is illuminated by a laser pulse [31] given by the heat input as follows:

$$Q = I_0 f(t) g(z) h(x). \tag{1}$$

The temporal profile $f(t)$ is presented as,

$$f(t) = \frac{t}{t_0^2} \exp\left(-\frac{t}{t_0}\right). \tag{2}$$

The pulse is also assumed to have a Gaussian spatial profile in z

$$g(z) = \frac{\gamma'}{2\pi r^2} \exp\left(-\frac{z^2}{r^2}\right). \tag{3}$$

The heat deposition due to the laser pulse is assumed to decay exponentially within the semiconductor,

$$h(x) = \gamma' \exp(-\gamma' x). \tag{4}$$

Substituting from Eqs. (2)–(4) in Eq. (1), we obtain:

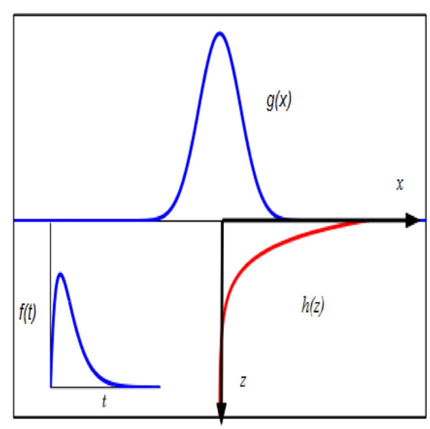
$$Q = \frac{I_0 \gamma' t}{2\pi r^2 t_0^2} \exp\left(-\frac{z^2}{r^2} - \frac{t}{t_0} - \gamma' x\right), \tag{5}$$

where I_0 is the absorbed energy, t_0 is the pulse rise time, r is the radius of the beam and γ' is the absorption depth (z) of heating energy (see schematic representation of the problem).

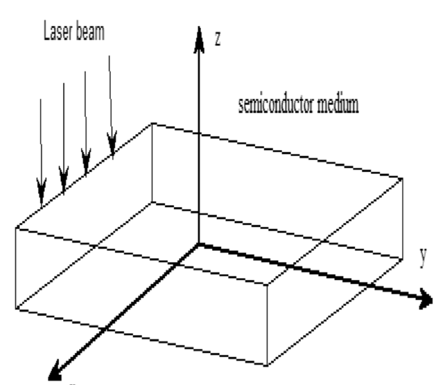
In thermal case of the medium generation a net charge carrier density assuming that it remains is a constant. So as to keep the equations linear in N and T, we assume that the transport heat coefficients are also independent of N and T. Then, the coupled plasma, thermal and elastic heat transport equations can be given below (the novel model under two temperature theory) as a vector form as in [5,20,32,33],

$$\frac{\partial N(\vec{r}, t)}{\partial t} = D_E \nabla^2 N(\vec{r}, t) - \frac{N(\vec{r}, t)}{\tau} + \kappa\, T(\vec{r}, t), \tag{6}$$

But, waves of thermal and elastic generated by conversion of light into heat is qualified by elastic field and coupled thermal diffusion (thermal wave, plasma wave, assuming that the heat flux is continues). We can use the two-temperature approach to analyze the thermal wave propagation in semiconductors. Then the equations take the form:



Spatial profile and temporal of the pulse



Geometry of the problem