Computers, Materials & Continua
DOI:10.32604/cmc.2021.015223
Article

The Hyperbolic Two Temperature Semiconducting Thermoelastic Waves by Laser Pulses

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Received: 11 November 2020; Accepted: 05 January 2021

Abstract: A novel model of a hyperbolic two-temperature theory is investigated to study the propagation the thermoelastic waves on semiconductor materials. The governing equations are studied during the photo-excitation processes in the context of the photothermal theory. The outer surface of o semiconductor medium is illuminated by a laser pulse. The generalized photo-thermoelasticity theory in two dimensions (2D) deformation is used in many models (Lord–Shulman (LS), Green–Lindsay (GL) and the classical dynamical coupled theory (CD)). The combinations processes between the hyperbolic two-temperature theory and photo-thermoelasticity theory under the effect of laser pulses are obtained analytically. The harmonic wave technique is used to obtain the exact solutions of the main physical fields under investigation. The mechanical, thermal and recombination plasma loads are applied at the free surface of the medium to obtain the complete solutions of the basic physical fields. Some comparisons are made between the three thermoelastcity theories under the electrical effect of thermoelectric coupling parameter. The influence of hyperbolic two-temperature, two-temperature and one temperature parameters on the distributions of wave propagation of physical fields for semiconductor silicon (Si) medium is shown graphically and discussed.

Keywords: Photo-thermo-elasticity theory; semiconductors; laser pulses; hyperbolic two temperature; harmonic waves; thermo-elastic waves

1 Introduction

In the first half of the last century, many authors used the generalized thermoelasticity theory to describe the elastic and thermal waves in elastic material such as semiconductors (semi-insulating). In this case, the semiconductor materials have been studied as an elastic media only. But at the end of the last century, various scientists studied the semiconductor materials especially the inner structures of them during the microelectronics processes. In this study, the photothermal (PT) technique is used to describe the wave propagation of the semiconductor material in the context of photo-acoustic (PA) modern technology. In modern studies the heat conduction effect for semiconductor solid materials is very important when the change of mass and heat transport (thermal diffusivity) occur. The diffusion of heat and mass clearly happens in semiconductor materials when the PT and PA in modern technology are taken into consideration in the context of sensitive to photo-excited transport processes [1,2]. The thermal excitation of the laser pulses causes the electrons to move rapidly and plasma waves (carrier density) are generated in semiconductor materials. This process is very important in microelectronic devices industry during the waves of plasma and elastic-thermal created. A non-Gaussian laser beam is used in this problem to heat the semiconductor plane surface.

Biot [3] developed the coupled thermoelasticity theory (CD theory) when motived the law of Fourier heat conduction that became appropriate for modern engineering applications spicily in high temperature case. But in low temperature case, the thermoelastic models are physically unacceptable and cannot obtain equilibrium state. Lord et al. [4] (LS) inserted one relaxation time and Green et al. [5] (GL) inserted two relaxation times in the heat conduction equation (Fourier's law of heat conduction) to overcome this contradiction. Many scientists developed many works with some applications in the generalized thermoelasticity theory when used these theories (CD, LS and GL) [6–10].

When an intracavity sample of semiconductor is exposed to laser pulses or beams of laser light sources for photoacoustic spectroscopy analysis in this case, the photothermal theory is introduced [11–14]. Experimentally the electrical resistance of semiconductor materials depends on the temperature increasing. Due to the thermal wave an elastic vibration and thermoelatic deformation (TE) is occurred in the medium, in this case the thermoelastic mechanism during photothermal processes will generate [15]. In the context of photo-excited transport processes the free carriers (carrier density) appear this process is the electronic deformation (ED) [16]. During the two processes TE and Ed, the coupled between plasma and thermo-elastic waves are obtained in a semiconductor medium [17,18]. In modern technology (renewable energy), a semiconductor material industry is widely used specially in solar cells. When the inner structure of semiconductor material is taken into consideration a two different temperatures (the conductive temperature (ϕ) and the thermo-dynamical temperature (T)) should study. The system two temperature theory is investigated during structural stability and convergence by Quintanilla et al. [19]. Youssef et al. [20,21] developed a novel technique when used two-temperature theory in the context of the linear generalized thermoelasticity. Lotfy et al. [22–30] used the photo-thermoelasticty theory during TE and ED deformation when used pulse heat flux and gravity field in the context of two-temperature theory with many external fields and various thermal memories. Mondal et al. [31,32] used the memory dependent and fractional derivative during piezo-thermoelastic medium to study Photo-thermo-elastic wave propagation in semiconductor medium.

Recently, Youssef et al. [33] investigated a new model in generalized thermoelsticity theory when they introduced the theory of hyperbolic two-temperature. Ezzat [34] developed the hyperbolic two-temperature theory to study thermal-plasma-elastic wave propagation in organic semiconductor material. Hobiny [35] studied the influence of the hyperbolic two-temperature theory for Photo-thermal waves in a semiconducting medium without energy dissipation. Abbas et al. [36,37] used the hyperbolic two-temperature during the interaction between photo-thermal waves in a cylindrical cavity of semiconductor medium. Many authors developed many models in thermoelasticity theory [38,39].

The basic goal of the investigation is solving a new mathematical model in the context of the 2D deformation processes for hyperbolic two-temperature theory. The problem is studied in photo-thermoelasticity (coupled between plasma and thermal waves) theory of a thin film semiconductor material which exposed to laser pulses. The photo-excitation transport processes occur due to the thermal effect of laser pulses. The problem is studied when using three models of thermoelasticity theory. The harmonic waves (normal mode analysis) expressions are used to obtain the analytical solutions and exact expressions of the main physical quantities. The effects of the hyperbolic two-temperature parameters, thermoelectric (electrical) parameters and the relaxation times (thermal memories) on some physical quantities are obtained. The obtained results have been depicted by simulation (using Si material) graphically and theoretical discussed.

2 Basic Equations

In the present work, a theoretical dissuasion during the heat transport process when the inner structure of semiconductor is taken into consideration. The interaction between plasma-thermal and elastic waves altogether are generated in the context of the own temperature (the hyperbolic two-temperature). The system of equations in this work depend on four main variable quantities, the carrier density $N(\vec{r},t)$ which describe the plasma wave, the thermal wave or thermodynamic temperature distribution $T(\vec{r},t)$, the conductive temperature $(\phi(\vec{r},t))$ and the elastic waves (displacement distribution) $\vec{u}(\vec{r},t)$. In this problem, the vector $\vec{r}$ is the position vector and t is the time during the heat flux located, the two-temperature influence appear for a linear, homogeneous and isotropic semiconductor medium. In 2D deformation the variables x and in the xz-plane are taken into account. When the semiconductor surface is excited that it exposed to a laser pulses [40] with the heat input function Q as follows (see the schematic Fig. 1):

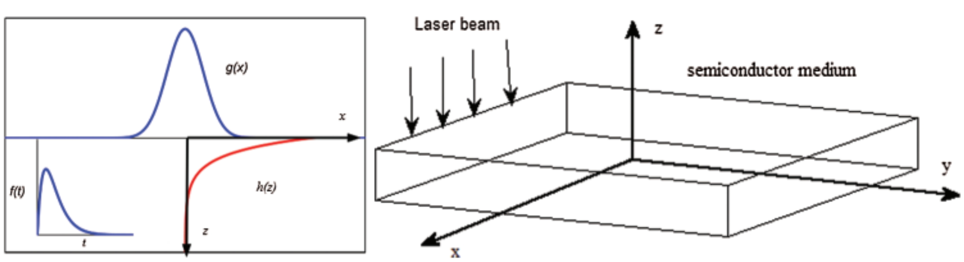
$$Q = I_0 f(t)\, g(z)\, h(x)\,. \tag{1}$$

The function $f(t)$ expresses the temporal profile which can be represented as,

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

The pulse Gaussian spatial profile $g(z)$ for the laser beam in z-direction is:

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



Spatial profile and temporal of the pulse Geometry of the problem

Figure 1: Schematic representation of the problem (a) spatial profile and temporal of the pulse (b) geometry of the problem

The laser pulse causes a heat deposition $h(x)$ which it decays exponentially and propagates in the semiconductor medium as the follows:

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

Using Eqs. (2)–(4) and substitution in Eq. (1), yields:

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

The laser constants I_0, t_0, a and γ' represent the absorbed energy, the pulse rise time, the radius of the laser beam and the absorption heating energy at the medium depth (z) respectively.

When the external surface of semiconductor is exposed to thermal effect due to the laser pulses the net charge carrier density is generated. During the excitation transport heat, the coupled plasma, thermal and elastic equations can be obtained in the context of the hyperbolic two temperature theory in the absence of heat source as the form [5,20,41,42]:

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

$$\rho C_e \left(n_1 + n_0 \tau_0 \frac{\partial}{\partial t}\right) \frac{\partial \mathrm{T}\left(\vec{r}, t\right)}{\partial t} = k \nabla^2 \phi\left(\vec{r}, t\right) + \frac{E_g}{\tau} N\left(\vec{r}, t\right) + \gamma T_0 \left(n_1 + n_0 \tau_0 \frac{\partial}{\partial t}\right)\left(\frac{\partial}{\partial t} \nabla \cdot \vec{u}\left(\vec{r}, t\right) - \rho Q\right), \tag{7}$$

$$\rho \frac{\partial^2 \vec{u}\left(\vec{r}, t\right)}{\partial t^2} = \mu \nabla^2 \vec{u}\left(\vec{r}, t\right) + (\mu + \lambda) \nabla\left(\nabla \cdot \vec{u}\left(\vec{r}, t\right)\right) - \gamma \left(1 + \nu_0 \frac{\partial}{\partial t}\right) \nabla \mathrm{T}\left(\vec{r}, t\right) - \delta_n \nabla N\left(\vec{r}, t\right). \tag{8}$$

The hyperbolic two temperature theory which it describes the coupled between the heat conduction and the thermo-dynamical temperatures can be written in the following form [40]:

$$\ddot{T} - \ddot{\phi} = -\beta \nabla^2 \phi. \tag{9}$$

where β is arbitrary positive constant and it expresses the hyperbolic two-temperature parameter and $\nabla\phi$ represents the gradient in heat conduction flux.

In the above equations, κ is a non-zero coupling parameter which expresses about the thermal activation $\left(\kappa = \frac{\partial N_0}{\partial T} \frac{T}{\tau}\right)$ in equilibrium carrier concentration N_0 at the temperature T (high temperature) [43–45]. The elastic Lame's constants are λ and μ, but $\gamma = (3\lambda + 2\mu)\alpha_T$ and α_T represents the linear thermal expansion coefficient. The other constants, D_E, τ, E_g, ρ, k, C_e, δ_n and T_0 express about the carrier diffusion coefficient, the lifetime during the photo-generated carrier processes, the energy gap, the density of the material, the heating conductivity, the specific heat coefficient, the deformation potential difference with valence band and the absolute temperature respectively. The thermal memories constants (the thermal relaxation time) are ν_0 and τ_0. The parameters n_0, n_1 are chosen in dimensionless according to the thermoelasticity theories [43,44]. In this investigation all main variables are analyzed the xz-plane, in this case the displacement vector can be taken the components form as $\vec{u} = (u_x, 0, u_z)$, where the two components of displacement are $u_x(x, z, t)$ and $u_z(x, z, t)$.

The constitutive (stress–strain) relation during the coupled processes can be represented in 2D as:

$$\sigma_{xx} = (2\mu+\lambda)\frac{\partial u_x}{\partial x} + \lambda\frac{\partial u_z}{\partial z} - (3\lambda+2\mu)(\alpha_T\left(\left(1+\nu_0\frac{\partial}{\partial t}\right)T + d_n N\right), \tag{10}$$

$$\sigma_{zz} = (2\mu+\lambda)\frac{\partial u_z}{\partial z} + \lambda\frac{\partial u_x}{\partial x} - (3\lambda+2\mu)\left(\alpha_T\left(1+\nu_0\frac{\partial}{\partial t}\right)T + d_n N\right), \tag{11}$$

$$\sigma_{xz} = \mu\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right). \tag{12}$$

3 Formulation of the Problem

The dimensionless displacement (u_x and u_z) can be represented in terms of the scalar and vector potentials $\Pi(x, z, t)$ and $\psi(x, z, t)$ functions as follows:

$$u_x = \frac{\partial \Pi}{\partial x} + \frac{\partial \psi}{\partial z}, \qquad u_z = \frac{\partial \Pi}{\partial z} - \frac{\partial \psi}{\partial x}.$$

In the other hand, the all quantities can be introduced in non-dimensional quantities for simplicity as follows:

$$\left(x', z', u'_x, u'_z\right) = \frac{(x, z, u_x, u_z)}{C_T t^*}, \quad \left(t', \upsilon'_0, \tau'_0\right) = \frac{(t, \upsilon_0, \tau_0)}{t^*}, \quad \left(T', \phi'\right) = \frac{\gamma\,(T, \phi)}{2\mu+\lambda},$$
$$\sigma'_{ij} = \frac{\sigma_{ij}}{\mu}, \quad N' = \frac{\delta_n N}{2\mu+\lambda}, \quad \left(\Pi', \psi'\right) = \frac{(\Pi, \psi)}{(C_T t^*)^2}, \quad Q' = \frac{Q}{T_0 C_e t^*}. \tag{13}$$

Therefore, the dimensionless Eq. (13) and the scalar and vector potential function (9) can be used in the governing Eqs. (6)–(12), yields (in this case, the primes are dropped for convenient):

$$\left(\nabla^2 - q_1^* - q_2^*\frac{\partial}{\partial t}\right)N + \varepsilon_3 T = 0, \tag{14}$$

$$\nabla^2\varphi - \left(n_1 + n_0\tau_0\frac{\partial}{\partial t}\right)\frac{\partial T}{\partial t} + \varepsilon_2 N + \varepsilon_1\left(n_1 + n_0\tau_0\frac{\partial}{\partial t}\right)\frac{\partial}{\partial t}\nabla^2\Pi = \varepsilon_1\left(n_1 t + n_0\tau_0\left\{1 - \frac{t}{t_0}\right\}\right)\frac{Q}{t}, \tag{15}$$

$$\left(\nabla^2 - \frac{\partial^2}{\partial t^2}\right)\Pi - \left(1+\nu_0\frac{\partial}{\partial t}\right)T - N = 0, \tag{16}$$

$$\left(\nabla^2 - \beta^2\frac{\partial^2}{\partial t^2}\right)\psi = 0, \tag{17}$$

$$\ddot{T} - \ddot{\phi} = -a\nabla^2\phi. \tag{18}$$

where,

$$q_1^* = \frac{k t^*}{D_E \rho \tau C_e}, \quad q_2^* = \frac{k}{D_E \rho C_e}, \quad \varepsilon_1 = \frac{\gamma^2 T_0 t^{*2}}{k\rho}, \quad \varepsilon_2 = \frac{\alpha_T E_g t^*}{d_n \rho \tau C_e}, \quad \varepsilon_3 = \frac{d_n k \kappa t^*}{\alpha_T \rho C_e D_E},$$
$$C_T^2 = \frac{2\mu+\lambda}{\rho}, \quad C_L^2 = \frac{\mu}{\rho}, \quad \beta^2 = \frac{C_T^2}{C_L^2}, \quad \delta_n = (2\mu+3\lambda)\,d_n, \quad t^* = \frac{k}{\rho C_e C_T^2}, \quad a = \frac{\beta}{C_L^2}.$$

Where, ε_1, ε_2 and ε_3 are parameters which describe the thermal-elastic, thermal-energy and thermal-electric coupling parameters respectively, d_n is the coefficient of electronic deformation.

The constitutive (stress–strain) relations can be obtained in dimensionless form as:

$$\sigma_{xx} = \frac{(2\mu+\lambda)}{\mu}\frac{\partial^2\Pi}{\partial x^2} + \frac{\lambda}{\mu}\frac{\partial^2\Pi}{\partial z^2} + 2\frac{\partial^2\psi}{\partial x\partial z} - \frac{(2\mu+\lambda)}{\mu}\left(\left(1+\nu_0\frac{\partial}{\partial t}\right)T + N\right), \tag{19}$$

$$\sigma_{zz} = \frac{(2\mu+\lambda)}{\mu}\frac{\partial^2\Pi}{\partial z^2} + \frac{\lambda}{\mu}\frac{\partial^2\Pi}{\partial x^2} - 2\frac{\partial^2\psi}{\partial x\partial z} - \frac{(2\mu+\lambda)}{\mu}\left(\left(1+\nu_0\frac{\partial}{\partial t}\right)T + N\right), \tag{20}$$

$$\sigma_{xz} = \frac{\partial^2\psi}{\partial z^2} + 2\frac{\partial^2\Pi}{\partial x\partial z} - \frac{\partial^2\psi}{\partial x^2}. \tag{21}$$

4 Solution of the Problem

Using the harmonic wave technique (normal mode method) to discuss the wave propagation of the main quantities, which it can be expressed in the xz-plane as follows:

$$\left[\Pi, \psi, \phi, T, \sigma_{ij}, N\right](x,z,t) = \left[\tilde{\Pi}(x), \tilde{\psi}(x), \tilde{\phi}(x), \tilde{T}(x), \tilde{\sigma}_{ij}(x), \tilde{N}(x)\right]\exp(\omega t + ibz), \tag{22}$$

where ω, i, b and $(\tilde{\Pi}(x), \tilde{\psi}(x), \tilde{\phi}(x), \tilde{T}(x), \tilde{\sigma}_{ij}(x), \tilde{N}(x))$ represent the angular frequency (constant of a complex time), the imaginary unit, the number of wave in z-direction and the amplitudes of the main quantities ($\Pi(x)$, $\psi(x)$, $\phi(x)$, $T(x)$, $\sigma_{ij}(x)$, $N(x)$) respectively.

Applying the normal mode (harmonic wave technique) which defined in Eq. (22) on the main Eqs. (14)–(18), the system of non-homogeneous ordinary deferential equations (ODE):

$$\left(D^2 - \alpha_1\right)\tilde{N} + \varepsilon_3\tilde{T} = 0, \tag{23}$$

$$\left(D^2 - b^2\right)\tilde{\phi} - \omega^*\tilde{T} + \varepsilon_2\tilde{N} + \alpha_2\left(D^2 - b^2\right)\tilde{\Pi} = g(z,t)\exp\left(-\gamma' x\right), \tag{24}$$

$$\left(D^2 - \alpha_3\right)\tilde{\Pi} - \alpha_7\tilde{T} - \tilde{N} = 0, \tag{25}$$

$$\left(D^2 - \alpha_4^2\right)\tilde{\psi} = 0, \tag{26}$$

$$\left(D^2 - A_1\right)\tilde{\phi} + \beta^*\tilde{T} = 0. \tag{27}$$

In the other hand, the constitutive (stress–strain) relations (19)–(21) when the normal mode analysis is applied yields:

$$\tilde{\sigma}_{xx} = \left(\alpha_5 D^2 - \alpha_6 b^2\right)\tilde{\Pi} + 2ibD\tilde{\psi} - \alpha_5\left(\alpha_7\tilde{T} + \tilde{N}\right), \tag{28}$$

$$\tilde{\sigma}_{zz} = \left(-\alpha_5 b^2 + \alpha_6 D^2\right)\tilde{\Pi} - 2ibD\tilde{\psi} - \alpha_5\left(\alpha_7\tilde{T} + \tilde{N}\right), \tag{29}$$

$$\tilde{\sigma}_{xz} = 2ibD\tilde{\Pi} - \left(D^2 + b^2\right)\tilde{\psi}. \tag{30}$$

where,

$$D=\frac{d}{dx},\quad \alpha_1=b^2+q_1^*+\omega q_2^*,\quad \alpha_2=\varepsilon_1\omega\left(n_1+n_0\tau_0\omega\right),\quad \alpha_3=b^2+\omega^2,\quad \alpha_4^2=b^2+\omega^2\beta^2,$$

$$A_1=b^2+\beta^*,\quad \beta^*=\frac{\omega^2}{a},\quad \omega^*=\omega\left(n_1+n_0\tau_0\omega\right),\quad \alpha_5=\frac{(2\mu+\lambda)}{\mu},\quad \alpha_6=\frac{\lambda}{\mu},\quad \alpha_7=1+\nu_0\omega,$$

$$g(z,t)=\varepsilon_1\left(n_1t+n_0\tau_0\left\{1-\frac{t}{t_0}\right\}\frac{I_0\gamma'}{2\pi a^2t_0^2}\exp\left(-\frac{z^2}{a^2}-\frac{t}{t_0}+\omega t+ibz\right)\right). \tag{31}$$

Solving the system of Eqs. (23)–(25) and (27) by eliminate $\tilde{\Pi}(x),\tilde{\phi}(x),\tilde{T}(x)$, and $\tilde{N}(x)$, the non-homogeneous six-order ODE in $\tilde{\theta}(x)$ can be obtained as:

$$\left[D^6-ED^4+FD^2-G\right]\tilde{\theta}(x)=L_1g(z,t)\exp\left(-\gamma'x\right). \tag{32}$$

where the coefficients of Eq. (32) are:

$$E=\left[\left(\alpha_1+\alpha_3+b^2\right)\beta^*+\left(\alpha_1+\alpha_3+A_1\right)\omega^*-\varepsilon_2\varepsilon_3-\alpha_2\left(\alpha_1^*+\alpha_7\left(A_1+b^2\right)\right)\right]\Big/A_2, \tag{33}$$

$$F=\left[\left(\alpha_1\alpha_3+\left(\alpha_1+\alpha_3\right)b^2\right)\beta^*+\left(\alpha_1A_3+\alpha_3A_1\right)\omega^*-\varepsilon_2\varepsilon_3A_3-\alpha_2\left(\alpha_1^*A_1+b^2A_4\right)\right]\Big/A_2, \tag{34}$$

$$G=\left[\alpha_1\alpha_3b^2\beta^*+\alpha_1\alpha_3A_1\omega^*-\varepsilon_2\varepsilon_3\alpha_3A_1-\alpha_2\alpha_1^*A_1b^2\right]\Big/A_2. \tag{35}$$

The other constants are:

$$L_1=\gamma'^6-\left(\alpha_1+\alpha_3+A_1\right)\gamma'^4+\left(\alpha_1A_1+\alpha_3A_1+\alpha_1\alpha_3\right)\gamma'^2-\alpha_1\alpha_3A_1,$$

$$\alpha_1^*=\alpha_1\alpha_7+\varepsilon_3,\quad A_2=\beta^*+\omega^*-\alpha_2\alpha_7,\quad A_3=\alpha_3+A_1,\quad A_4=\left(\alpha_1^*+\alpha_7A_1\right).$$

The factorization of six-order homogenous ODE (32) can be expressed as:

$$\left(D^2-k_1^2\right)\left(D^2-k_2^2\right)\left(D^2-k_3^2\right)\tilde{T}(x)=0. \tag{36}$$

But the characteristic equation six-order homogenous ODE (36) which it has the roots $k_n^2\,(\mathrm{Re}\,(k_n)>0,\ n=1,2,3)$ can be taken the following form:

$$\pi^6-E\pi^4+F\pi^2-G=0 \tag{37}$$

In the other hand, the characteristic equation of the six-order non-homogenous ODE (32) and homogenous ODE (26) can be rewritten the same equation as the follows:

$$\left(D^2-k_1^2\right)\left(D^2-k_2^2\right)\left(D^2-k_3^2\right)\left(D^2-k_4^2\right)\left(\tilde{T},\tilde{\psi}\right)=L_1g(z,t)\exp\left(-\gamma'x\right). \tag{38}$$

where k_4^2 represents the real root of Eq. (26).

The solution of the eighth-order non-homogenous ODE Eq. (38) takes the following form:

$$\tilde{T}(x)=\sum_{n=1}^{3}\Re_n(b,\omega)\exp\left(-k_nx\right)+L_2\exp\left(-\gamma'x\right). \tag{39}$$

where, $L_2 = \dfrac{L_1 g(z,t)}{\left[\gamma'^6 - E\gamma'^4 + F\gamma'^2 - G\right]}$.

By the same way,

$$\tilde{\Pi}(x) = \sum_{n=1}^{3} \Re'_n(b,\omega)\exp(-k_n x) + L_3\exp\left(-\gamma' x\right), \tag{40}$$

$$\tilde{N}(x) = \sum_{n=1}^{3} \Re''_n(b,\omega)\exp(-k_n x) + L_4\exp\left(-\gamma' x\right), \tag{41}$$

$$\tilde{\phi}(x) = \sum_{n=1}^{3} \Re'''_n(b,\omega)\exp(-k_n x) + L_5\exp\left(-\gamma' x\right), \tag{42}$$

$$\tilde{\psi}(x) = \Re_4(b,\omega)\exp(-k_4 x). \tag{43}$$

where, $L_3 = L_2\dfrac{\left(\alpha_7\gamma'^2 - \alpha_1^*\right)}{\left(\gamma'^2 - \alpha_1\right)\left(\gamma'^2 - \alpha_3\right)}$, $L_4 = \dfrac{-\varepsilon_3 L_2}{\left(\gamma'^2 - \alpha_1\right)}$, $L_5 = -\dfrac{\beta^* L_2}{\gamma'^2 - A_1}$ and the parameters $\Re_n$, $\Re'_n$, $\Re''_n$, $\Re'''_n$ and $\Re_4$ are unknown which they depend on b and ω.

The displacement components in terms of the amplitude of the scalar and vector potential functions can be rewritten as:

$$\tilde{u}_x(x) = D\tilde{\Pi} + ib\ \tilde{\psi}, \tag{44}$$

$$\tilde{u}_x(x) = -\sum_{n=1}^{3} \Re'_n(b,\omega) k_n e^{-k_n x} - \gamma' L_3\exp\left(-\gamma' x\right) + ib\Re_4(b,\omega)\exp(-k_4 x), \tag{45}$$

$$\tilde{u}_z(x) = ib\quad \tilde{\Pi} - D\tilde{\psi}, \tag{46}$$

$$\tilde{u}_z(x) = ib\left\{\sum_{n=1}^{3} \Re'_n(b,\omega) e^{-k_n x} + L_3\exp\left(-\gamma' x\right)\right\} + \Re_4(b,\omega) k_4\exp(-k_4 x). \tag{47}$$

Using Eqs. (39)–(42) into Eqs. (23)–(25) and (27) to obtain the main relations between the unknown parameters $\Re_n$, $\Re'_n$, $\Re''_n$ and $\Re'''_n$ which they can written as follows:

$$\Re'_n(b,\omega) = \frac{\left(\alpha_7 k_n^2 - \alpha_1^*\right)}{\left(k_n^2 - \alpha_1\right)\left(k_n^2 - \alpha_3\right)}\Re_n(b,\omega), \quad n = 1,2,3. \tag{48}$$

$$\Re''_n(b,\omega) = \frac{-\varepsilon_3}{\left(k_n^2 - \alpha_1\right)}\Re_n(b,\omega), \quad n = 1,2,3, \tag{49}$$

$$\Re'''_n(b,\omega) = -\frac{\beta^*}{k_n^2 - A_1}\Re_n(b,\omega), \quad n = 1,2,3, \tag{50}$$

Therefore, the other physical quantities can be represented in terms of the unknown parameters $\Re_n$ as follows:

$$\tilde{\Pi}(x) = \sum_{n=1}^{3} \frac{\left(\alpha_7 k_n^2 - \alpha_1^*\right)}{\left(k_n^2 - \alpha_1\right)\left(k_n^2 - \alpha_3\right)} \Re_n \exp(-k_n x) + L_3 \exp\left(-\gamma' x\right), \tag{51}$$

$$\tilde{N}(x) = \sum_{n=1}^{3} \frac{-\varepsilon_3}{\left(k_n^2 - \alpha_1\right)} \Re_n \exp(-k_n x) + L_4 \exp\left(-\gamma' x\right), \tag{52}$$

$$\tilde{\phi}(x) = \sum_{n=1}^{3} \frac{-\beta^*}{k_n^2 - A_1} \Re_n \exp(-k_n x) + L_5 \exp\left(-\gamma' x\right), \tag{53}$$

$$\tilde{\sigma}_{xx} = \sum_{n=1}^{3} h_n \Re_n \exp(-k_n x) + \chi_1 \exp\left(-\gamma' x\right) - 2ibk_4 \Re_4 \exp(-k_4 x), \tag{54}$$

$$\tilde{\sigma}_{zz} = \sum_{n=1}^{3} h_n' \Re_n \exp(-k_n x) + \chi_2 \exp\left(-\gamma' x\right) + 2ibk_4 \Re_4 \exp(-k_4 x), \tag{55}$$

$$\tilde{\sigma}_{xz} = \sum_{n=1}^{3} h_n'' \Re_n \exp(-k_n x) + \chi_3 \exp\left(-\gamma' x\right) - \left(k_4^2 + b^2\right) \Re_4 \exp(-k_4 x), \tag{56}$$

$$\tilde{u}_x(x) = -\sum_{n=1}^{3} \frac{k_n\left(\alpha_7 k_n^2 - \alpha_1^*\right)}{\left(k_n^2 - \alpha_1\right)\left(k_n^2 - \alpha_3\right)} \Re_n e^{-k_n x} - \gamma' L_3 \exp\left(-\gamma' x\right) + ib\Re_4 e^{-k_4 x}, \tag{57}$$

$$\tilde{u}_z(x) = \sum_{n=1}^{3} \frac{ib\left(\alpha_7 k_n^2 - \alpha_1^*\right)}{\left(k_n^2 - \alpha_1\right)\left(k_n^2 - \alpha_3\right)} \Re_n e^{-k_n x} + ibL_3 \exp\left(-\gamma' x\right) + k_4 \Re_4 e^{-k_4 x}. \tag{58}$$

Where, $h_n = \frac{\left(\alpha_7 k_n^2 - \alpha_1^*\right)\left(\alpha_5 k_n^2 - \alpha_6 b^2\right)}{\left(k_n^2 - \alpha_1\right)\left(k_n^2 - \alpha_3\right)} - \alpha_5\left(\alpha_7 - \frac{\varepsilon_3}{\left(k_n^2 - \alpha_1\right)}\right)$, $h_n'' = -2ibk_n$, $\chi_3 = -2ib\gamma' L_3$, $h_n' = -\frac{\left(\alpha_7 k_n^2 - \alpha_1^*\right)\left(\alpha_5 b^2 - \alpha_6 k_n^2\right)}{\left(k_n^2 - \alpha_1\right)\left(k_n^2 - \alpha_3\right)} - \alpha_5\left(\alpha_7 - \frac{\varepsilon_3}{\left(k_n^2 - \alpha_1\right)}\right)$, $\chi_1 = \left(\alpha_5 \gamma'^2 - \alpha_6 b^2\right) L_3 - \alpha_5(\alpha_7 L_2 + L_4)$, $\chi_2 = \left(\alpha_6 \gamma'^2 - \alpha_5 b^2\right) L_3 - \alpha_5(\alpha_7 L_2 + L_4)$.

5 Boundary Conditions

In this section, some boundary conditions are applied at the free surface of the semi-infinites semiconducting ζ medium to obtain the unknown parameters $\Re_n\,(n = 1, 2, 3, 4)$ when the positive exponentials unlimited when x tends to infinity. The problem is studied in the hyperbolic two temperature theory with laser pulses that generate thermal, elastic, plasma effects in the context of the photothermal transport during recombination processes.

(I) Mechanical loads at the surface:

i) At surface $x = 0$, the traction can be chosen as loaded with force p_1 in the normal direction as:

$$\sigma_{xx}(0, z, t) = -p_1 \exp(\omega t + ibz). \tag{59}$$

ii) But, the traction is free for half-space surface as:

$$\sigma_{xz}(0, z, t) = 0. \tag{60}$$

(II) Isolated thermal boundary:
The thermal boundary at the free surface $x = 0$ can be chosen as thermally insulated:

$$\frac{\partial T(0, z, t)}{\partial x} = 0. \tag{61}$$

(III) Diffusion recombination boundary:
During the photothermal transport processes, the carrier's diffusion occur in the context of the limited recombination processes (possibility), in this case the condition can be chosen as:

$$\frac{\partial N(0, z, t)}{\partial x} = \frac{s}{D_e} N. \tag{62}$$

With applying the above boundary conditions in harmonic wave technique, the following expressions in terms of the parameters $\Re_n$ can be obtained as:

$$\sum_{n=1}^{3} h_n \Re_n - 2ibk_4 \Re_4 = -(p_1 + \chi_1), \tag{63}$$

$$\sum_{n=1}^{3} h_n'' \Re_n - \left(k_4^2 + b^2\right) \Re_4 = -\chi_3, \tag{64}$$

$$\sum_{n=1}^{3} k_n \Re_n = -\gamma' L_2, \tag{65}$$

$$\sum_{n=1}^{3} \frac{-\varepsilon_3 k_n}{(k_n^2 - \alpha_1)} \Re_n = -\left(\frac{s}{D_e} N + \gamma' L_4\right). \tag{66}$$

Using Cramer's rule for the above Eqs. (63)–(66), the four unknown parameters $\Re_n$ can be determinate at $x = 0$. In this case, the complete solutions of physical quantities can be obtained in time-space domain.

6 Validation

6.1 Two Temperature Theory

To obtain the two-temperature thermoelasticity theory in classical model, Eq. (9) can be rewritten in the following form [46]:

$$T - \phi = -\beta \nabla^2 \phi. \tag{67}$$

where, $\beta > 0$ is the two temperature parameter and the problem can be studied in photo-thermoelasticity theory with laser pulses in two temperature field.

6.2 One Temperature Theory

To obtain the one-temperature theory when the two temperatures are identical (conductive temperature and the thermodynamic temperature) when $\beta = 0$, in this case the heat conduction Eq. (7) can be rewritten in the following form [22]:

$$\rho C_e \left(n_1 + n_0\tau_0 \frac{\partial}{\partial t}\right) \frac{\partial \mathrm{T}}{\partial t} = k\nabla^2 T + \frac{E_g}{\tau} N + \gamma T_0 \left(n_1 + n_0\tau_0 \frac{\partial}{\partial t}\right) \left(\frac{\partial}{\partial t} \nabla \cdot \vec{u} - \rho Q\right). \tag{68}$$

6.3 Laser Pulses Effect

When the heat input function Q is neglected, then the problem is studied in photo-thermoelasticty theory with hyperbolic two temperature theory, in this case the heat Eq. (7) can be written as [47]:

$$\rho C_e \left(n_1 + n_0\tau_0 \frac{\partial}{\partial t}\right) \frac{\partial T}{\partial t} = k\nabla^2 \phi + \frac{E_g}{\tau} N + \gamma T_0 \left(n_1 + n_0\tau_0 \frac{\partial}{\partial t}\right) \frac{\partial \nabla \cdot \vec{u}}{\partial t}. \tag{69}$$

6.4 The Thermoelasticity Theory without Photothermal Excitation

When the carrier density effects $N(\vec{r}, t)$ (free electrons) which describe the plasma wave is neglected (i.e., $N = 0$), in this case the main governing equation can be expressed in the generalized thermoelasticity theory in hyperbolic two temperature theory with laser pulses [37].

6.5 The Generalized Photo-Thermoelasticity Theory

In generalized photo-thermoelasticity theory in this problem three theories can be obtained as follows:

(i) When $n_1 = 1$, $n_0 = 0$, $\nu_0 = \tau_0 = 0$, the CD theory can be discussed [3].
(ii) When $n_1 = n_0 = 1$, $\nu_0 = 0$, $\tau_0 > 0$, the LS theory can be discussed [4].
(iii) When $n_1 = 1$, $n_0 = 0$, $\nu_0 \geq \tau_0 > 0$, the GL theory can be discussed [5].

7 Numerical Results and Discussions

To investigate the obtained results theoretically, the physical properties and physical constants in SI unit of silicon (Si) as a semiconductor elastic material is used. Silicon (Si) constants are used to make the numerical simulation and discussed the computational results. The MATLAB (2018) is used to complete the numerical simulation; the constants of Si are shown in Tab. 1 as [46,47]:

In the above computations, $\omega = \omega_0 + i\xi$ ($\omega_0 = -0.03$) for small time $t = 0.0005$ s and $\xi = 0.01$, the exponential function can be expressed as $e^{\omega t} = e^{\omega_0 t}(\cos \xi t + i \sin \xi t)$ where $i = \sqrt{-1}$ represents the imaginary unit. The obtained results are calculated when the wave number is $b = 1.0$ and load force is $p_1 = 1$, the distributions of physical quantities are taken for the real part in this problem.

Table 1: The physical constants of Si

Unit	Symbol	Value
N/m^2	λ , μ	3.64×10^{10}, 5.46×10^{10}
kg/m^3	ρ	2330
K	T_0	800
sec	τ	5×10^{-5}
m^3	d_n	-9×10^{-31}
m^2/s	D_E	2.5×10^{-3}
eV	E_g	1.11
K^{-1}	α_t	4.14×10^{-6}
$Wm^{-1}K^{-1}$	k	150
$J/(kgK)$	C_e	695
m/s	s	2
ps	t_0	9
μm	a	100
m^{-1}	γ'	10^{-3}
J	I_0	10^5

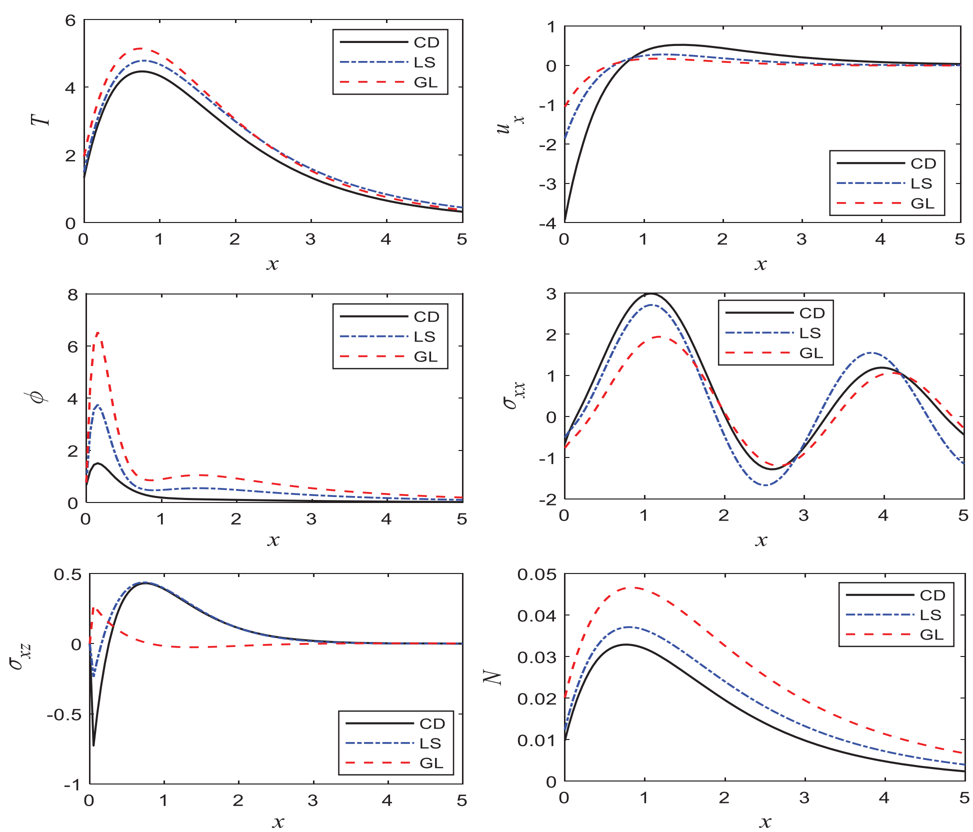


Figure 2: The variation of main physical fields against the horizontal distance under generalized three theories when $\varepsilon_3 = -5$ with laser pulses in hyperbolic two temperature field

Fig. 2 shows the wave propagation of the main physical fields (thermo-dynamical temperature T, the horizontal displacement u_x, heat conduction temperature ϕ, the normal and tangent stresses (σ_{xx}, σ_{xz}) and carrier density N) against the horizontal distance x at the plane $z = -1$. A three theories of generalized photo-thermoelasticity are applied, the coupled model (CD theory (solid lines)), the Lord-Şhulman model (LS theory (dashed-dotted lines)) with one thermal memory (relaxation time) when $\tau_0 = 0.00002$ s, and generalized theory Green-Lindsay model (GL theory (dashed lines)) with two thermal memories when $\tau_0 = 0.00002$ s, $\nu_0 = 0.00003$ s. In these figures, the real dimensionless forms are applied for main fields in hyperbolic two temperature field under the influence of laser pulse at $\varepsilon_3 = -5$. From the subfigures in Fig. 2, all physical fields satisfy the thermal, mechanical and plasma conditions at the boundary surface. All waves' distributions start from minimum values and increases in the first range near the boundary surface due to the effect of laser pulses. The distributions of waves are damped which have an exponential wave form with a finite speed with the increasing in the horizontal distance due to the effect of hyperbolic two temperature parameter.

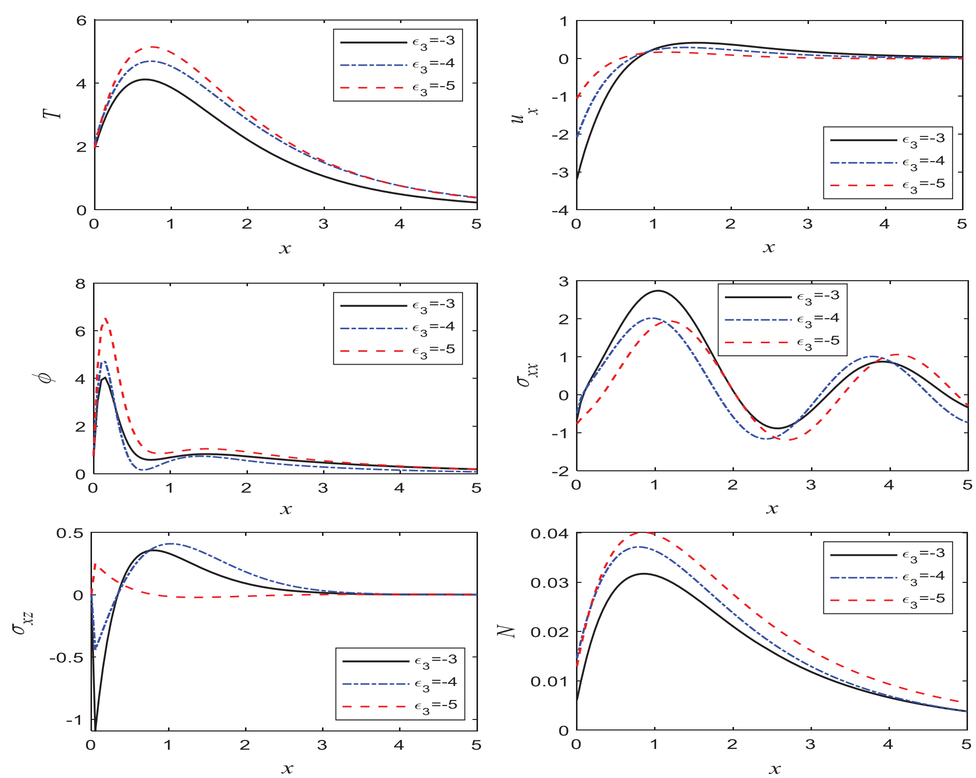


Figure 3: The variation of main physical fields against the horizontal distance under generalized Gl theory with laser pulses in hyperbolic two temperature field and different thermoelectric coupling parameter

The second category (Fig. 3) displays the variation of main physical fields with the horizontal distance under the effect of different three negative values of thermoelectric coupling parameter in hyperbolic two temperature field with laser pulse under GL theory. From the second figure, the wave propagation distributions coincide with the increasing of distance x at infinity due to a finite speed of waves. The thermoelectric coupling parameters have a great significant effect of all physical field distributions. The amplitude of most wave propagations increases when the value of the thermoelectric coupling parameters decreases.

Fig. 4 represents the comparison between the main physical fields under investigation three cases, the first case when the thermodynamic temperature T is equal to the conductive temperature ϕ (one-temperature (OT)) in the absence of heat supply which it expresses by the solid lines. The second case represents the classical two temperature parameter (CTT) in absence of heat supply which it represents by dashed-dotted lines. But the third case represents hyperbolic two temperature (HTT) case which it expresses by dashed lines. All obtained results are made when $\varepsilon_3 = -5$ under the influence of laser pulses under in GL model. A clear significant difference is obtained in three different cases.

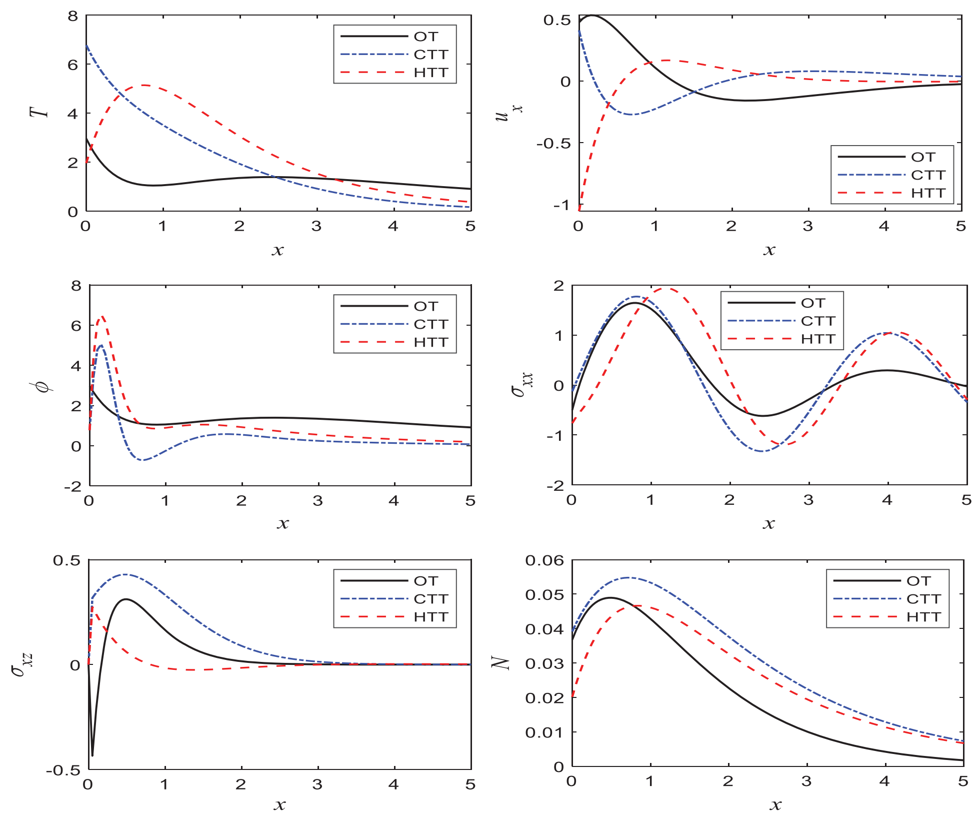


Figure 4: The variation of main physical fields against the horizontal distance under generalized Gl theory with laser pulses in one temperature, two temperature and hyperbolic two temperature when $\varepsilon_3 = -5$

The forth category (Fig. 5) shows that the variations of the basic physical fields against the horizontal distance in two cases, the first when the problem is studied without laser pulse (WOLP) which it represents by solid lines. The second case when the problem is investigated under the effect of laser pulse (WLP), all computationals are carried out in GL photo-thermoelasticity theory in hyperbolic two temperature field when $\varepsilon_3 = -5$. The influence of laser pulses clearly shows in the amplitude of the wave propagation. The values of the amplitude of physical quantity are greater under the influence of laser pulse (WLP) than without the effect of laser pulse

(WOLP) due to the physical properties of semiconductor materials (laser with thermal effect causes photo-excited electrons).

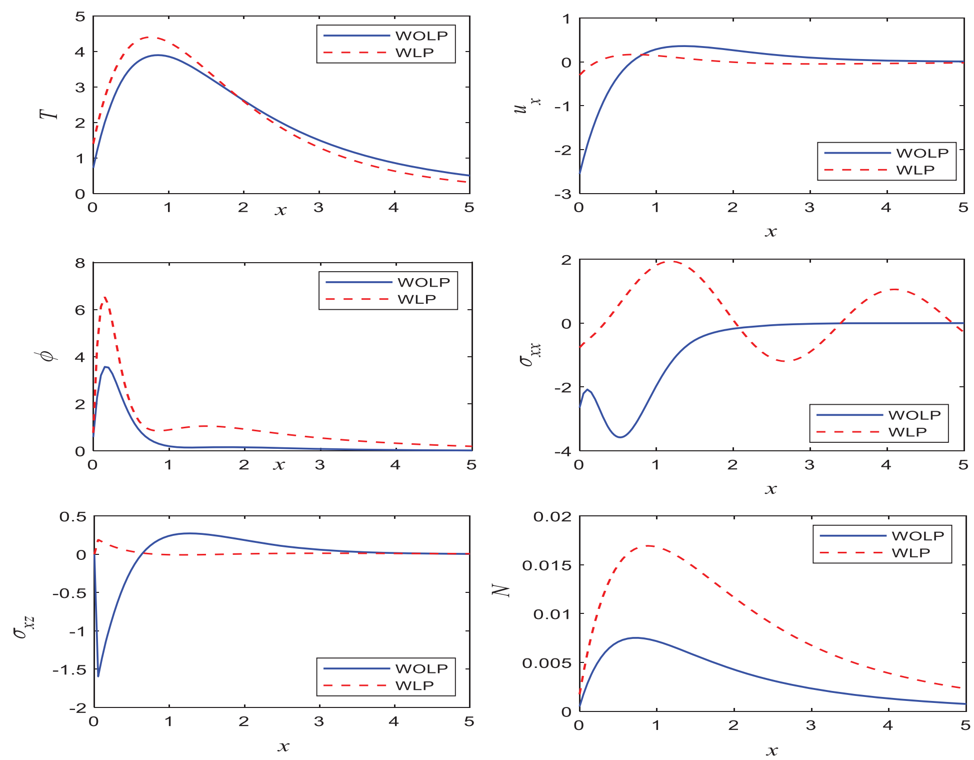


Figure 5: The variation of main physical fields against the horizontal distance under generalized Gl theory with and without laser pulses in hyperbolic two temperature field when $\varepsilon_3 = -5$

8 Conclusion

In the present problem, the coupled between the plasma, elastic and thermal waves is investigated in generalized photo-thermoelasticity theory in the context of the hyperbolic two temperature theory with the effect of laser pulses of a 2D deformation semiconductor wafer. The harmonic wave analysis is used to obtain the physical fields analytically, therefore they are illustrated graphically and discussed. The influences of the thermal memories time, the thermoelectric coupling parameters, three theories of thermodynamic-conduction temperatures (OT, CTT and HTT) and laser pulses effect are discussed. From the above investigations, some important results are obtained as follows:

1. The wave propagation of all physical fields decreases exponentially when the horizontal distance x increases.
2. The thermal memories according to the thermoelasticity theories have a great influence of all the physical field distributions.
3. The thermoelectric coupling parameters have a significant effect in all physical fields under the hyperbolic two temperatures theory due to the effect of laser pulse.
4. The hyperbolic two-temperature in generalize photo-thermoelasticity theory is more effective for discus the wave propagation on the distribution of field quantities when study the

behavior of the inner structure of the semiconductor elastic solid body more real than the two temperature theory and one-temperature with laser pulses.

5. The laser pulses in the hyperbolic two temperature theory is important phenomena which it has a great influence on the distribution of field quantities.

Acknowledgement: This paper was funded by the deputyship for Research & Innovation Ministry of Education in Saudi Arabia through the project number (IFP-2020-08).

Funding Statement: The authors extend their appreciation to the deputyship for Research & Innovation Ministry of Education in Saudi Arabia for funding this research work through the project number (IFP-2020-08).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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