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ORIGINAL PAPER

A Novel Magneto-Electron-Hole Model for Optical-Thermo-Diffusion Processes in Semiconducting Material with Variable Thermal Conductivity

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Abstract
A novel model is presented for understanding photothermal diffusion processes when the interaction between holes and electrons occurs during the study of semiconducting material. The thermal properties and optical absorption of silicon (Si) material are measured using the photothermal technique. The elastic-thermodiffusion (ETD) excitation under the influence of a fixed electromagnetic field is studied when the thermal conductivity depends on a gradient temperature (variable thermal conductivity). The governing equations are taken during thermoelastic deformation (TD) and electronic deformation (ED) in one-dimensional (1D). In the Laplace domain, the analytical dimensionless solutions of the distributions of the hole charge field carrier, mechanical, heat, and electrons charge carrier density (plasma) waves under some initial and boundary conditions are obtained. Algebraically, the complete solutions can be obtained when some numerical approximations in a closed-form during the inversion of the Laplace transform are used. The propagation waves under the effect of the magnetic field of heat, mechanical, hole, and plasma waves were examined graphically and explained with some comparisons when the thermal conductivity is changed.

Keywords Electrons and holes · Electromagnetic field · Thermal conductivity · Photo-excitation · Thermo-diffusion · Semiconductors

1 Introduction

Semiconductors are one of the important materials that have been recently discovered and studied, which provide a distinct set of physical properties that benefit workers in the research field. At the beginning of the last century, and based on the principles of thermoelastic theory, semiconductor materials were being studied as flexible materials. But in fact, semiconductor materials are not good conductors of electricity, such as aluminum, nor are they insulating materials such as glass. Where it was found that its resistance collapses with the gradual rise in temperatures, especially when laser beams or light beams (optical energy) fall on it. For this reason, it is necessary to take into account the study of thermal conductivity, especially which depends on temperature. Accordingly, studying the effect of thermal conductivity, especially the variable ones, is very important in understanding the physical properties and wave propagation of semiconductors. Therefore, the great industrial importance that uses semiconductors in its basic components, such as screens, solar cells, photovoltaic cells (renewable electrical

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energy), electrical circuits, and transistors, appeared in the modern electronic industries. As a result of the absorbed light energy and its thermal effect on the outer surface of the semiconductor, an excitation of the material occurs and two accompanying processes appear during it. The first process works to excite the free electrons and holes scattered through the lattice of the material, which leads to the appearance of a cloud called the carrying density of electrons (plasma) and holes, and all this happens during a process called electronic deformation (ED). In a microseconds the interaction between a plasma of electrons which called plasma waves and the hole charge carrier field during diffusion processes are occurred. The second process occurs when an increase in temperature causes the inner microparticles of the medium to vibrate in a process called thermoelastic deformation (TD).

With the beginning of interest in the theory of thermoelasticity, a traditional model appeared that does not correspond to physical facts. It carries with it many contradictions, including that the heat conduction equation does not contain elastic components and also assume that the heat equation is of the parabolic type, and this means that thermal waves will propagated at infinite speeds. Biot [1] presented the theory of thermodynamic thermoelasticity (CD) that resolved these contradictions when some elastic components were added to the heat equation as well as putting them on the hyperbolic form that shows that the speed of thermal wave propagation will be limited. Lord and Shulman (LS) [2] made some modifications to the CD model by adding a single relaxation time to the heat equation of for isotropic materials. The interaction between the elastic and heat quantities after adding two relaxation times was studied by Green and Lindsay (GL) [3]. The new model called the generalized thermoelasticity (GTE) theory. After that, during the past few years, many researchers have developed many models that have been interested in studying the theory of generalized thermoelasticity under the influence of many external fields such as the electromagnetic field and the effect of gravity, and also if the materials used are located in a rotating field [4–8]. Kumar et al. [9–13] studied many problems of electrostatic potential and threshold voltage according to the microstructures of thermoelastic materials.

The photothermal (PT) theory has recently been used to understand the physical properties of semiconductor media, in preparation for the use of these studies in modern technologies for the production of renewable and sustainable energy. Recently, many physical-mathematical models have been developed that describe the interference between PA theory and thermoelasticity (TE) theory. Gordon et al. [14] studied a model of the interference between the theory of TE and the PA theory during electronic deformation using optical spectroscopy. On the other hand, Maruszewski [15–17] utilized the classical model and its extended to describe the coupled between thermal, elastic during optical absorbed energy in the context of the thermodiffusive processes of a sample from semiconductors. Sharma et al. [18] developed and introduced a novel model describes the interaction between electrons and holes when used a plane harmonic waves technique for the elasto-thermodiffusive waves propagation in semiconductor medium. During a thermal diffusivity processes the PA theory and TE theory are used to describe the propagate of elastic-thermal-plasma waves of elastic semiconductor medium [19]. On the other said, the interaction between electrons and holes which distribute on the outer surface of semiconductor medium during photo-excited transport processes can be studied using the PT technique. The heat and mass diffusion is obtained by the PT mechanism of semiconductor medium [20]. Lotfy et al. [21–23] studied the applications of the photothermal theory during diffusion processes when the thermal conductivity is variable for the non-homogenous properties of polymer nano-composite semiconductor medium under the effect of magnetic field. On the other hand, the magneto-piezo-electric properties during photothermal excitation processes of refined multi dual phase-lags theory of hyperbolic two-temperature semiconductor material under the effect of laser pulse are studied by many researches [24–26]. The maps transforms have been used to introduce a new mathematical-physical model in the context of variable thermal conductivity [27]. The new model assumes that the thermal conductivity can be chosen as a linear function of temperature, and this assumption has been proven true for semiconductors [28]. Mahdy et al. [20, 29] studied the influence of volumetric heat source during a pulse heat flux when the thermal conductivity is change in the context of magneto-photothermal model and diffusion transport processes. Das et al. [30] investigated the magneto-thermoelastic analysis of semiconductor material using a thin circular. Masouleh et al. [31] studied the quality of light absorption of nano-excited semiconductor medium with the comparison of different plasmonic nanograting profiles. On the other hand, Wang et al. [32] used infrared Optical Wireless experimentally for silicon photonic integrated Circuit. Premaratne et al. [33] shown the technical and operational underpinnings of semiconductor material. Chander et al. [34–36] studied many applications of semiconductors during an electrical noise analysis when used a tunnel field effect transistor to improve the electrical characteristics of silicon. During previous studies, it was proven that the electrical, thermal and mechanical properties of semiconductors change according to the change in temperature. In all previous studies, the interference that occurs inside semiconductors between electrons and holes has been neglected during the thermal-diffusive processes.

In this article, the governing equations are taken in 1D deformation for semiconductor material. On the other hand, the overlapping between holes and electrons is obtained during a photogenerated processes of electron and hole charges. As a result of the gradient in the thermal effect resulting from the absorbed optical energy, it is possible to choose the thermal conductivity as a function of temperature. The medium is studied under the influence of external magnetic field during the elastic-electronics deformation with thermo-diffusion processes. A new mathematical-physical model can be created as a result of all the previous interactions. The plasma-hole and thermal-elastic waves for the main physical fields can be obtained analytically in Laplace domain. The initial and boundary conditions are taken at the free surface of the medium to determine the unknown parameters. The Laplace transform inversion is used to obtain the complete solutions of the main fields with approximate numerical methods. Finally, the plasma-hole and thermal-mechanical waves can be graphed and discussed. Some analytical comparisons are made under the impact of magnetic field for variable thermal conductivity.

2 Basic Equations

Considering the semiconductor medium is homogenous, linearity and has isotropic properties. The treatment considers a semiconductor elastic medium with isotropic and homogeneous electronic, thermal, and elastic properties [37]. Due to the thermal, elastic and electronic properties of the material which can be described during the coupled plasma-holes and generalized thermal-elastic equations in equilibrium state at a reference (absolute) temperature T_0(where $T-T_0$ is the temperature augments compared with natural state temperature T_0). The absolute temperature is the temperature at which the values of the physical properties of the elastic solid medium are chosen in dimensionless equations for the heat transfer, resistance, etc. For the case when the deformation is small, $\left|\frac{T-T_0}{T_0}\right| = 1$). In case of the excitation processes, the photo-generated holes and electrons carrier fields are obtained. To describe the problem, four quantities in 1D are be introduced. The first is the temperature distribution (thermal wave) $T\,(x,t)$, the second is the plasma (carrier) density$N(x,t)$, the third is the hole charge carrier$H(x,t)$which measures the concentration of holes and the last is the displacement distribution (elastic wave) $u(x,t)$, where t denotes to the time and $x$is the distance in the direction of x-axis. Consider the excited free holes and electrons create a free hole charge carrier and free charge carrier density when that the semiconductor medium is exposed to a beams light which fall on the outer surface. In the 1D deformation and in absence of the body force, the main governing equations can be written under the effect of magnetic field when the thermal conductivity depends on the temperature in the following form [14]:

$$\left.\begin{array}{c}\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial}{\partial x}\left[K\frac{\partial T}{\partial x}\right]+m_{nq}\frac{\partial^2 N}{\partial x^2}+m_{hq}\frac{\partial^2 H}{\partial x^2}-\rho\left(a_1^n\frac{\partial N}{\partial t}+a_1^h\frac{\partial H}{\partial t}\right)-\\ \left(1+\tau_q\frac{\partial}{\partial t}\right)\left[\frac{K}{k}\frac{\partial T}{\partial t}+\rho\,T_0\alpha_n\frac{\partial N}{\partial t}+\rho\,T_0\alpha_h\frac{\partial H}{\partial t}+T_0\gamma\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right]\\ =\left[\frac{\rho a_1^n}{t^n}N+\frac{\rho a_1^h}{t^h}H\right]\end{array}\right\}, \tag{1}$$

$$\left.\begin{array}{c}m_{qn}\frac{\partial^2 T}{\partial x^2}+D_n\rho\frac{\partial^2 N}{\partial x^2}-\rho\left(1-a_2^nT_0\alpha_n+t^n\frac{\partial}{\partial t}\right)\frac{\partial N}{\partial t}-\\ a_2^n\left[\frac{K}{k}\frac{\partial T}{\partial t}+\rho T_0\alpha_h\frac{\partial H}{\partial t}+T_0\gamma\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right]=-\frac{\rho}{t_1^n}\left(1+t^n\frac{\partial}{\partial t}\right)N\end{array}\right\}, \tag{2}$$

$$\left.\begin{array}{c}m_{qh}\frac{\partial^2 T}{\partial x^2}+D_h\rho\frac{\partial^2 H}{\partial x^2}-\rho\left(1-a_2^hT_0\alpha_h+t^h\frac{\partial}{\partial t}\right)\frac{\partial H}{\partial t}-\\ a_2^h\left[\frac{K}{k}\frac{\partial T}{\partial t}+\rho T_0\alpha_n\frac{\partial N}{\partial t}+T_0\gamma\frac{\partial}{\partial t}\frac{\partial u}{\partial x}\right]=-\frac{\rho}{t_1^h}\left(1+t^h\frac{\partial}{\partial t}\right)H\end{array}\right\}, \tag{3}$$

$$\rho\frac{\partial^2 u}{\partial t^2}=(2\mu+\lambda)\frac{\partial^2 u}{\partial x^2}-\gamma\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial T}{\partial x}-\delta_n\frac{\partial N}{\partial x}-\delta_h\frac{\partial H}{\partial x}+\vec{F}. \tag{4}$$

The constitutive equation in 1D (according to the coupled between the elastic-electrons-thermal-holes fields) which can describe the distribution of mechanical waves propagation, can be expressed as:

$$\sigma_{xx}=-\left(\gamma\left(1+\tau_\theta\frac{\partial}{\partial t}\right)T+\delta_nN+\delta_hH\right)+(2\mu+\lambda)e=\sigma. \tag{5}$$

In the above equations, the elastic parameters μ, λ are the Lame's counterparts of body. Where α_t denotes the thermal expansion linear coefficient and $\gamma=(3\lambda+2\mu)\alpha_t$refers to the volume thermal expansion. The specific heat is C_e and ρ is the density. The electrons and holes parameters are$\delta_n=(2\mu+3\lambda)d_n$, $\delta_h=(2\mu+3\lambda)d_h$, $d_n$and d_h which represent the electrons, holes elastodiffusive parameters, the coefficients of electronic and hole deformation respectively. The quantities m_{nq}, m_{qn}, m_{hq}, m_{qh} describe the Peltier-Dufour-Seebeck-Soret-like parameters and in general case, K is the thermal conductivity. The coefficients D_n and $D_h$are the diffusion of the electrons and holes. The thermal and elastic relaxation times are $\tau_q$and τ_θ. On the other hand, the life time of electrons and holes are t^n and t^h but the thermodiffusive parameters are α_h, α_n for holes and electrons respectively. The flux-like constants are a_{Qn}, a_{Qh}, a_Q, a_n, a_h, and the other notations can be expressed in the form, $a_1^n=\frac{a_{Qn}}{a_Q}$, $a_1^h=\frac{a_{Qh}}{a_Q}$, $a_2^n=\frac{a_{Qn}}{a_n}$, $a_2^h=\frac{a_{Qh}}{a_h}$ [18]. However, $\vec{F}$ is the Lorentz's force which measure the pressure of the magnetic field and the cubical dilatation (strain) in 1D is $\underline{e}=\frac{\partial u}{\partial x}$.

When an initial magnetic field $H=\left(0,H_0,0\right)$ fall on the free surface of the semiconductor medium, the induced magnetic field $\vec{h} = (0, h, 0)$is generated in the y-axis with induced electric field $E = (0, 0, E)$. In this case, the current density J is generated in z-direction. During the thermal-elastic-electronic properties, the electromagnetic fields equations can be considered according to the linearized Maxwell's equations which can be written in the context to slowly moving semiconductor elastic medium as:

$$\left.\begin{array}{l} \vec{J} = \text{curl } \vec{h}, \\ \text{curl } \vec{E} = -\mu_0 \dot{\vec{H}}, \\ \vec{E} = -\mu_0 \left(\dot{\vec{u}} \times \vec{H} \right), \\ \quad \text{div } \vec{h} = 0. \end{array}\right\}, \quad (6)$$

Where the electromagnetic constant is μ_0 which describe the magnetic permeability the dote notation is the time-differentiation. The unique component of the current density can be obtained from Eq. (5), which can be written as:

$$J_z = \frac{\partial h}{\partial x}. \quad (7)$$

The induced electric field and magnetic field can be rewritten in terms of displacement from Eq. (1) as follows:

$$\left.\begin{array}{l} E_z = -\mu_0 H_0 \dot{u}, \\ \quad h = -H_0 e. \end{array}\right\}. \quad (8)$$

In this case, the Lorentz's force can be formulated as:

$$\vec{F} = \mu_0 \left(\vec{J} \times \vec{H} \right) = \left(\mu_0 H_0^2 \frac{\partial^2 u}{\partial x^2}, 0, 0 \right) = (F, 0, 0). \quad (9)$$

The influence of heat conduction on the electrical resistivity of semiconductor medium can be studied when the thermal conductivity is taken into consideration. In this case, the thermoelectric energy conversion can be evaluated in a correct way [38, 39] when the thermal conductivity K can be chosen in a linear function (depends on) of temperature [38, 39]. However, for semiconductor material, the thermal conductivity can be represented as:

$$K(T) = K_0 \left(1 + K_1 T \right). \quad (10)$$

Where$K_1$is a arbitrary, small and negative. In case of $K_1 = 0$, the quantity K_0 represents the thermal conductivity when it not depends on the temperature [39]. For temperature distribution, the following map can be formulated as:

$$\hat{T} = \frac{1}{K_0} \int_0^T K(\vartheta) d\vartheta. \quad (11)$$

Using the differentiation properties, Eqs. (11) can be differentiated with respect to $x$and t, yields:

$$\left.\begin{array}{l} K_0 \frac{\partial \hat{T}}{\partial x} = K(T) \frac{\partial T}{\partial x}, \\ K_0 \frac{\partial \hat{T}}{\partial t} = K(T) \frac{\partial T}{\partial t}. \end{array}\right\}. \quad (12)$$

On the other hand, more differentiation properties can be constructed for Eqs. (12) as follow:

$$\left.\begin{array}{l} K_0 \frac{\partial \hat{T}}{\partial x} = K(T) \frac{\partial T}{\partial x} \Rightarrow \textit{differentiating by} \frac{\partial}{\partial x} \Rightarrow \\ \quad \frac{\partial}{\partial x}\left(K_0 \frac{\partial \hat{T}}{\partial x} \right) = \frac{\partial}{\partial x}\left(K(T) \frac{\partial T}{\partial x} \right) = \\ \quad K_0 \left(\frac{\partial^2 \hat{T}}{\partial x^2} \right) = \frac{\partial}{\partial x}\left(K_0 \left(1 + K_1 T \right) \frac{\partial T}{\partial x} \right) = \\ \quad K_0 K_1 \left\{ \left(\frac{\partial T}{\partial x} \right)^2 + \frac{\partial^2 T}{\partial x^2} \right\} = K_0 K_1 \frac{\partial^2 T}{\partial x^2} \end{array}\right\}, \quad (13)$$

$$\frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x} \right) = \frac{\partial}{\partial x}\left(K_0 \left(1 + K_1 T \right) \frac{\partial T}{\partial x} \right) = K_0 \frac{\partial^2 \hat{T}}{\partial x^2} + K_0 K_1 \left[\frac{\partial \hat{T}}{\partial x} \right]^2 = K_0 \frac{\partial^2 \hat{T}}{\partial x^2}. \quad (14)$$

$$\left.\begin{array}{l} \frac{K_0}{K} \frac{\partial \hat{T}}{\partial x} = \frac{K_0}{K_0 (1 + K_1 T)} \frac{\partial \hat{T}}{\partial x} = \left(1 + K_1 T \right)^{-1} \frac{\partial \hat{T}}{\partial x} = \left(1 - K_1 T + \left(K_1 T \right)^2 - \ldots\ldots \right) \frac{\partial \hat{T}}{\partial x} \\ \quad = \frac{\partial \hat{T}}{\partial x} - K_1 T \frac{\partial \hat{T}}{\partial x} + \left(K_1 T \right)^2 \frac{\partial \hat{T}}{\partial x} - \ldots\cdots = \frac{\partial \hat{T}}{\partial x} \end{array}\right\}. \quad (15)$$

In the above equations, the non-linear term is ignored according to the linearity. Using Eqs. (10)-(12) and (13)-(15) to convert the principle Eqs. (1) to (4) under the effect of magnetic field, yields:

$$\left.\begin{array}{l} \left(1 + \tau_\theta \frac{\partial}{\partial t} \right) \frac{\partial}{\partial x}\left[K_0 \frac{\partial \hat{T}}{\partial x} \right] + m_{nq} \frac{\partial^2 N}{\partial x^2} + m_{hq} \frac{\partial^2 H}{\partial x^2} - \rho \left(a_1^n \frac{\partial N}{\partial t} + a_1^h \frac{\partial H}{\partial t} \right) - \\ \quad \left(1 + \tau_q \frac{\partial}{\partial t} \right) \left[\frac{K_0}{k} \frac{\partial \hat{T}}{\partial t} + \rho\, T_0 \alpha_n \frac{\partial N}{\partial t} + \rho\, T_0 \alpha_h \frac{\partial H}{\partial t} + T_0 \gamma \frac{\partial}{\partial x} \frac{\partial u}{\partial t} \right] \\ \quad = \left[\frac{\rho a_1^n}{t^n} N + \frac{\rho a_1^h}{t^h} H \right] \end{array}\right\}, \quad (16)$$

$$\left.\begin{array}{l} \frac{m_{qn}}{K_1} \frac{\partial^2 \hat{T}}{\partial x^2} + D_n \rho \frac{\partial^2 N}{\partial x^2} - \rho \left(1 - a_2^n T_0 \alpha_n + t^n \frac{\partial}{\partial t} \right) \frac{\partial N}{\partial t} - \\ a_2^n \left[\frac{K_0}{k} \frac{\partial \hat{T}}{\partial t} + \rho T_0 \alpha_h \frac{\partial H}{\partial t} + T_0 \gamma \frac{\partial}{\partial x} \frac{\partial u}{\partial t} \right] = -\frac{\rho}{t_1^n} \left(1 + t^n \frac{\partial}{\partial t} \right) N \end{array}\right\}, \quad (17)$$

$$\left.\begin{array}{l} \frac{m_{qh}}{K_1} \frac{\partial^2 \hat{T}}{\partial x^2} + D_h \rho \frac{\partial^2 H}{\partial x^2} - \rho \left(1 - a_2^h\, T_0 \alpha_h + t^h \frac{\partial}{\partial t} \right) \frac{\partial H}{\partial t} - \\ a_2^h \left[\frac{K_0}{k} \frac{\partial \hat{T}}{\partial t} + \rho\, T_0 \alpha_n \frac{\partial N}{\partial t} + T_0 \gamma \frac{\partial}{\partial t} \frac{\partial u}{\partial x} \right] = -\frac{\rho}{t_1^h} \left(1 + t^h \frac{\partial}{\partial t} \right) H \end{array}\right\}, \quad (18)$$

$$\rho \frac{\partial^2 u}{\partial t^2} = (2\mu + \lambda) \frac{\partial^2 u}{\partial x^2} - \gamma \left(1 + \tau_\theta \frac{\partial}{\partial t} \right) \frac{\partial \hat{T}}{\partial x} - \delta_n \frac{\partial N}{\partial x} - \delta_h \frac{\partial H}{\partial x} + \mu_0 H_0^2 \frac{\partial^2 u}{\partial x^2}. \quad (19)$$

The governing main Eqs. (1) to (5) in 1D can easily be converted into a dimensionless (non-dimensional) forms.

The following dimensionless variables are presented which listed below as:

$$\left.\begin{array}{c} \left(x', u'\right) = \frac{\omega^*(x,u)}{C_T}, \left(t', \tau_q', \tau_\theta', t^{n\prime}, t^{h\prime}, t_1^{n\prime}, t_1^{h\prime}\right) = \omega^*\left(t, \tau_q, \tau_\theta, t^n, t^h, t_1^n, t_1^h\right), \\ \beta^2 = \frac{C_T^2}{C_L^2}, \sigma' = \frac{\sigma}{2\mu+\lambda}, N' = \frac{\delta_n(N)}{2\mu+\lambda}, C_T^2 = \frac{2\mu+\lambda}{\rho}, C_L^2 = \frac{\mu}{\rho}, \\ \omega^* = \frac{C_e(\lambda+2\mu)}{K_0}, \left(\delta_n', \delta_h'\right) = \frac{(\delta_n n_0, \delta_h h_0)}{\gamma T_0}, \left(T'\right) = \frac{\gamma(T)}{2\mu+\lambda}, H' = \frac{\delta_n(H)}{2\mu+\lambda}. \end{array}\right\}. \tag{20}$$

Where in the equilibrium case, the electrons concentration is n_0 and h_0 is holes concentration. The converted equations can be obtained in easily form when the dimensionless Eq. (20) is applied with ignored the primes, yields:

$$\left.\begin{array}{c} \left\{\left(1+\tau_\theta \frac{\partial}{\partial t}\right)\frac{\partial^2}{\partial x^2} - \left(1+\tau_q \frac{\partial}{\partial t}\right)\frac{\partial}{\partial t}\right\}\hat{T} + \left\{\alpha_1 \frac{\partial^2}{\partial x^2} - \alpha_2\left(1+\tau_q \frac{\partial}{\partial t}\right) - \alpha_3 \frac{\partial}{\partial t} - \alpha_4\right\}N + \\ \left\{\alpha_5 \frac{\partial^2}{\partial x^2} - \left(1+\tau_\alpha \frac{\partial}{\partial t}\right)\alpha_6 - \alpha_7\right\}H - \left(1+\tau_q \frac{\partial}{\partial t}\right)\varepsilon_1 \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}\right) = 0 \end{array}\right\}, \tag{21}$$

$$\left.\begin{array}{c} \left\{\frac{\partial^2}{\partial x^2} - \alpha_8 \frac{\partial}{\partial t}\right\}\hat{T} + \left\{\alpha_9 \frac{\partial^2}{\partial x^2} - \left(\alpha_{10} + t^n \frac{\partial}{\partial t}\right)\alpha_{11} + \left(1 + t^n \frac{\partial}{\partial t}\right)\frac{\alpha_{11}}{t^n}\right\}N- \\ \alpha_{12}\frac{\partial H}{\partial t} - \alpha_{13}\frac{\partial}{\partial x}\frac{\partial u}{\partial t} = 0 \end{array}\right\}, \tag{22}$$

$$\left.\begin{array}{c} \left\{\frac{\partial^2}{\partial x^2} - \alpha_{18} \frac{\partial}{\partial t}\right\}\hat{T} + \left\{\alpha_{14} \frac{\partial^2}{\partial x^2} - \left(\alpha_{15} + t^h \frac{\partial}{\partial t}\right)\alpha_{16}\frac{\partial}{\partial t} + \left(1 + t^h \frac{\partial}{\partial t}\right)\alpha_{17}\right\}H- \\ \alpha_{19}\frac{\partial N}{\partial t} - \alpha_{20}\frac{\partial}{\partial t}\frac{\partial u}{\partial x} = 0 \end{array}\right\}, \tag{23}$$

$$\left\{(1+R_H)\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial t^2}\right\}u - \left(1+\tau_\theta \frac{\partial}{\partial t}\right)\frac{\partial \hat{T}}{\partial x} - \frac{\partial N}{\partial x} - \alpha_{21}\frac{\partial H}{\partial x} = 0. \tag{24}$$

$$\sigma = \left(\frac{\partial u}{\partial x} - \left(\left(1+\tau_\theta \frac{\partial}{\partial t}\right)\hat{T} + N\right)\right) - H. \tag{25}$$

Where the pressure of magnetic field on the free surface of semiconductor medium is$R_H = \frac{\mu_0 H_0^2}{\rho C_T^2} = \frac{\vartheta_0^2}{C_T^2}$, where the velocity of wave represents $\vartheta_0 = H_0\sqrt{\frac{\mu_0}{\rho}}$and the other quantities are [40]:

$$\begin{array}{c} \alpha_1 = \frac{m_{nq}\alpha_t}{d_n\ K_0}, \alpha_2 = \frac{T_0\alpha_n}{C_e}, \alpha_3 = \frac{a_1^n}{C_e}, \\ \alpha_4 = \frac{a_1^n\gamma}{C_e\tau^n(2\mu+\lambda)}, \alpha_5 = \frac{\gamma m_{hq}\ h_0}{(2\mu+\lambda)K_0}, \alpha_6 = \frac{T_0\ \alpha_h\ K_0\ h_0}{C_e}, \\ \alpha_7 = \frac{a_1^h\gamma\omega^*}{t^h K_0}, \alpha_8 = \frac{a_2^n K_1}{m_{qn}}, \alpha_9 = \frac{D_n\rho\alpha_t}{m_{qn}\ d_n}, \\ \alpha_{10} = 1 - a_2^n T_0\alpha_n, \alpha_{11} = \frac{\alpha_t K_0}{m_{qn}\ d_n C_e}, \alpha_{12} = \frac{a_2^n\gamma h_0\alpha_h\omega^*}{m_{qn}}, \\ \alpha_{13} = \frac{a_2^n\gamma^2 T_0\omega^*}{\rho\ m_{qn}}, \alpha_{14} = \frac{D_n h_0\gamma}{C_T^2\ m_{qh}}, \alpha_{15} = 1 - a_2^h T_0\alpha_n, \\ \alpha_{16} = \frac{\gamma h_0\omega^*}{m_{qh}}, \alpha_{17} = \frac{\gamma h_0\omega^*}{m_{qh}\tau_1^h}, \alpha_{18} = a_2^h\frac{K_1}{m_{qh}}, \\ \alpha_{19} = \frac{a_2^h\gamma T_0\alpha_n(2\mu+\lambda)\omega^*}{m_{qh}\delta_n}, \alpha_{20} = \frac{a_2^h\gamma^2 T_0\ \omega^*}{m_{qh}\rho}, \alpha_{21} = \frac{\delta_h}{(2\mu+\lambda)}, \varepsilon_1 = \frac{T_0\gamma^2\omega^*}{\rho K_0}. \end{array}$$

The following initial conditions in equilibrium case are introduced to solve the problem mathematically which are chosen homogeneous as:

$$\begin{array}{c} u(x,t)|_{t=0} = \left.\frac{\partial u(x,t)}{\partial t}\right|_{t=0} = 0,\ T(x,t)|_{t=0} = \left.\frac{\partial T(x,t)}{\partial t}\right|_{t=0} \\ = 0,\ H(x,t)|_{t=0} = \left.\frac{\partial H(x,t)}{\partial t}\right|_{t=0} = 0,\ N(x,t)|_{t=0} = \left.\frac{\partial N(x,t)}{\partial t}\right|_{t=0} = 0. \end{array}$$

3 The Mathematical Solutions

In control system engineering, Laplace transform is used to convert the main Eqs. (21)-(25) from time domain to Laplace domain to solve some engineering problem mathematically. Laplace transform of the function $\mathbb{R}(x,t)$ can be written as:

$$L(\mathbb{R}(x,t)) = \overline{\mathbb{R}}(x,s) = \int_0^\infty \mathbb{R}(x,t)\exp(-st)dt. \tag{26}$$

The main Eqs. (21)-(25) under the Laplace transform can be rewritten as:

$$\left(q_1 D^2 - q_2\right)\overline{\hat{T}} + \left(\alpha_1 D^2 - q_3\right)\overline{N} + \left(\alpha_5 D^2 - q_4\right)\overline{H} - q_5 D\overline{u} = 0, \tag{27}$$

$$\left(D^2 - q_7\right)\overline{\hat{T}} + \left(\alpha_9 D^2 - q_6\right)\overline{N} - q_8\overline{H} - q_9 D\overline{u} = 0, \tag{28}$$

$$\left(D^2 - q_{10}\right)\overline{\hat{T}} + \left(\alpha_{14} D^2 - q_{11}\right)\overline{H} - q_{12}\overline{N} - q_{13}D\overline{u} = 0, \tag{29}$$

$$\left(D^2 - \alpha_1\right)\overline{u} - q_{14}D\overline{\hat{T}} - \xi D\overline{N} - \alpha_{21}^* D\overline{H} = 0, \tag{30}$$

$$\overline{\sigma}_{xx} = \alpha_{23}\left(D\overline{u} - \left(\left(1 + s\tau_\theta\right)\overline{\hat{T}} + \overline{N}\right)\right) - \overline{H}. \tag{31}$$

Where,$D = \frac{d}{dx}$,$q_1 = (1+\tau_\theta s)$, $\alpha_1 = \frac{s^2}{(1+R_H)}$,$q_2 = (1+\tau_q s)s$, $q_3 = \alpha_2(1+\tau_q s) + \alpha_3 s + \alpha_4$

$$\begin{array}{c} q_4 = \left(1+\tau_q s\right)\alpha_6 + \alpha_7, q_5 = \left(1+\tau_q\ s\right)\varepsilon_1\ s, q_6 = \left(\alpha_{10} + t^n s\right)\alpha_{11} \\ -(1+t^n s)\frac{\alpha_{11}}{t^n}, q_7 = \alpha_8\ s, q_8 = \alpha_{12}s, q_9 =, \alpha_{13}\ s, q_{10} = \alpha_{18}s, q_{11} \\ = \left(\alpha_{15} + t^h s\right)\alpha_{16}s - \left(1 + t^h s\right)\alpha_{17}, q_{12} \\ = \alpha_{19}s, q_{13} = \alpha_{20}s, q_{14} = \frac{1+\tau_\theta s}{1+R_H}, \\ \alpha_{21}^* = \frac{\delta_h}{(1+R_H)(2\mu+\lambda)}, \xi = \frac{1}{(1+R_H)}. \end{array}$$

The system Eqs. (27)-(30) can be eliminated to obtain the Ordinary differential equation for the main quantities $\hat{T}, \overline{u}, \overline{N}$ and $\overline{H}$, therefore [41]:

$$\left(D^8 - \prod\nolimits_1 D^6 + \prod\nolimits_2 D^4 - \prod\nolimits_3 D^2 + \Pi_3\right)\left\{\overline{H}, \overline{N}, \overline{\hat{T}}, \overline{u}\right\}(x,s) = 0. \tag{32}$$

The mathematical computer programmer is used to evaluate the main coefficients of Eq. (32) which are represented as:

$$\left.\begin{array}{c}\Pi_1 = \frac{-1}{(\alpha_9\alpha_{14}q_1-\alpha_1\alpha_{14}-\alpha_5\alpha_9)}\Big(- s^2\alpha_9\alpha_{14}q_1 + s^2\alpha_1\alpha_{14} + \alpha_5\alpha_9 \\ + \alpha_1\alpha_{14}q_9q_{14} + \alpha_5\alpha_9q_{13}q_{14} - \alpha_9\alpha_{12}q_1q_{13} - \alpha_9\alpha_{14}q_5q_{14} - \alpha_1\alpha_{12}q_9 \\ + \alpha_1\alpha_{12}q_{13} + \alpha_1\alpha_{14}q_7 + \alpha_5\alpha_9q_{11} + \alpha_9\alpha_{12}q_5 - \alpha_9\alpha_{14}q_2 - \alpha_9q_1q_{10} \\ - \alpha_{14}q_1q_6 - \alpha_{14}q_1q_9 - \alpha_1q_8 + \alpha_1q_{10} + \alpha_5q_6 + \alpha_5q_9 - \alpha_5q_{12} - \alpha_5q_{13} \\ + \alpha_9q_4 + \alpha_{14}q_3\Big).\end{array}\right\}, \tag{33}$$

$$\left.\begin{array}{c}\Pi_2 = \frac{1}{(\alpha_9\alpha_{14}q_1-\alpha_1\alpha_{14}-\alpha_5\alpha_9)}\Big(- s^2\alpha_1\alpha_{14}q_7 - s^2\alpha_5\alpha_9q_{11} + s^2\alpha_{14}\alpha_9q_2 \\ + s^2\alpha_9q_1q_6 + s^2\alpha_1q_8 - s^2\alpha_1q_{10} - s^2\alpha_5q_6 + s^2\alpha_5q_{12} - s^2\alpha_9q_4 - s^2\alpha_{14}q_3 \\ - \alpha_1\alpha_{12}q_7q_{13} + \alpha_1\alpha_{12}q_9q_{11} + \alpha_1q_8q_{13}q_{14} - \alpha_1q_9q_{10}q_{14} - \alpha_5q_6q_{13}q_{14} + \\ \alpha_5q_9q_{12}q_{14} + \alpha_9\alpha_{12}q_2q_{13} - \alpha_9\alpha_{12}q_5q_{11} - \alpha_9\alpha_4q_{13}q_{14} + \alpha_9q_5q_{10}q_{14} + \\ \alpha_{12}q_1q_6q_{13} - \alpha_{12}q_1q_9q_{12} - \alpha_{14}q_3q_9q_{14} + \alpha_{14}q_5q_6q_{14} - \alpha_1q_7q_{10} + \alpha_1q_8q_{11} - \\ \alpha_5q_6q_{11} + \alpha_5q_7q_{12} - \alpha_5q_9q_{11} + \alpha_9q_2q_{10} - \alpha_9q_4q_{11} + \alpha_{12}q_3q_9 - \alpha_{12}q_3q_{13} - \\ \alpha_{12}q_5q_6 + \alpha_{12}q_5q_{12} + \alpha_{14}q_2q_9 - \alpha_{14}q_3q_7 - \alpha_{14}q_5q_7 + q_1q_6q_{10} - q_1q_8q_{12} - \\ q_1q_8q_{13} + q_1q_9q_{10} + q_3q_8 - q_3q_{10} - q_4q_6 - q_4q_9 + q_4q_{12} + q_5q_8 + q_4q_{13} - q_5q_{10}\Big)\end{array}\right\}, \tag{34}$$

$$\left.\begin{array}{c}\Pi_3 = \frac{-1}{(\alpha_9\alpha_{14}q_1-\alpha_1\alpha_{14}-\alpha_5\alpha_9)}\Big(s^2\alpha_1q_7q_{11} - s^2\alpha_1q_8q_{11} + s^2\alpha_5q_6q_{11} \\ - s^2\alpha_5q_7q_{12} - s^2\alpha_9q_8 - s^2\alpha_2q_{10} - s^2q_1q_6q_{10} + s^2q_1q_8q_{12} - s^2q_3q_8 \\ + s^2q_4q_6 - s^2q_4q_{12} - \alpha_{12}q_2q_6q_{13} + \alpha_{12}q_2q_9q_{11} + \alpha_{12}q_3q_7 - q_3q_8q_{13}q_{14} \\ + q_3q_9q_{10}q_{14} + q_4q_6q_{13}q_{14} - q_4q_9q_{12}q_{14} - q_5q_6q_{10}q_{14} + q_5q_8q_{12}q_{14} \\ - q_2q_6q_{10} + q_2q_8q_{12} + q_2q_8q_{13} - q_2q_9q_{10} + q_3q_7q_{10} - q_3q_8q_{11} + q_4q_6q_{11} \\ - q_4q_7q_{12} - q_4q_7q_{13} + q_4q_9q_{11} + q_5q_7q_{10} - q_5q_8q_{11}\Big)\end{array}\right\}, \tag{35}$$

$$\prod_4 = \frac{\left(s^2q_2q_6q_{10} - q_2q_3q_{12}s^2 - s^2q_3q_7q_{10} + s^2q_3q_3q_{11} - s^2q_4q_6q_{11} + s^2q_4q_7q_{12}\right)}{\left(\alpha_9\alpha_{14}q_1 - \alpha_1\alpha_{14} - \alpha_5\alpha_9\right)}. \tag{36}$$

To solve Eq. (32) the factorization method is utilized. Therefore, Eq. (32) can be factorized as:

$$\left(D^2 - m_1^2\right)\left(D^2 - m_2^2\right)\left(D^2 - m_3^2\right)\left(D^2 - m_4^2\right)\left\{\overline{\hat{T}}, \overline{u}, \overline{N}, \overline{H}\right\}(x, s) = 0. \tag{37}$$

Where $m_i^2 (i = 1, 2, 3, 4)$ are the equation roots which are taken at $x \to \infty$ as positive and real. Due to the linearity, the solutions of Eq. (37) can be formulated as [42, 43]:

$$\overline{\hat{T}}(x, s) = \sum_{i=1}^{4} \mathrm{B}_i(s) e^{-m_i x}. \tag{38}$$

The other linear solutions for the other main quantities $\overline{N}, \overline{u}, \overline{H}$and $\overline{\sigma}$ can be formulated as:

$$\overline{N}(x, s) = \sum_{i=1}^{4} \mathrm{B}'_i(s) e^{-m_i x} = \sum_{i=1}^{4} H_{1i} \mathrm{B}_i(s) e^{-m_i x}, \tag{39}$$

$$\overline{u}(x, s) = \sum_{i=1}^{4} B_i''(s)\ \exp\left(-m_i x\right) = \sum_{i=1}^{4} H_{2i}\ B_i(s)\ \exp\left(-m_i x\right), \tag{40}$$

$$\overline{H}(x, s) = \sum_{i=1}^{4} \mathrm{B}_i'''(s) \exp\left(-m_i x\right) = \sum_{i=1}^{4} H_{4i} \mathrm{B}_i(s) \exp\left(-m_i x\right), \tag{41}$$

$$\overline{\sigma}(x, s) = \sum_{i=1}^{4} \mathrm{B}''''_i(s) \exp\left(-m_i x\right) = \sum_{i=1}^{4} H_{4i} \mathrm{B}_i(s) \exp\left(-m_i x\right). \tag{42}$$

The relation between the unknown quantities $\mathrm{B}'_i, \mathrm{B}''_i, \mathrm{B}'''$,$\mathrm{B}''''_i$and B_i, $i = 1, 2, 3, 4$ can be obtained from the system of Eqs. (27)-(30) as:

$$\mathrm{B}'_i = H_{1i}\mathrm{B}_i, B''_i = H_{2i}\mathrm{B}_i, \mathrm{B}'''_i = H_{3i}\mathrm{B}_i, \tag{43}$$

where

$$H_{1i} = \frac{c_1 m_i^4 + c_2 m_i^2 + c_3}{c_4 m_i^4 + c_2 m_i^2 + c_6},\ H_{3i} = \frac{\left(m_i^2 q_1 - q_2\right)}{q_5 m_i} + \frac{\left(m_i^2 \alpha_5 - q_4\right) H_{2i}}{q_5 m_i} + \frac{\left(m_i^2 \alpha_1 - q_3\right) H_{1i}}{q_5 m_i},$$

$$H_{2i} = -\frac{-\left(m_i^2 q_1 - q_2\right) q_9 m_i - q_5 m_i \left(m_i^2 - q_7\right)}{-\left(m_i^2 \alpha_5 - q_4\right) q_9 m_i + q_5 q_8 m_i} - \frac{\left(-\left(m_i^2 \alpha_1 - q_3\right) q_9 m_i - q_5 m_i \left(m_i^2 \alpha_9 - q_6\right)\right) H_{3i}}{-\left(m_i^2 \alpha_5 - q_4\right) q_9 m_i + q_5 q_8 m_i},$$

$$H_{4i} = \alpha_{23}\left(m_i H_{2i} - \left(\left(1 + s\tau_\theta\right) H_{1i} + 1\right) - \alpha_{22} H_{3i}\right).$$

$$\begin{gathered} c_1 = \alpha_{14}q_1q_9 - \alpha_5q_9 - \alpha_5q_{13} + \alpha_{14}q_5, \\ c_2 = \alpha_5q_7q_{13} + \alpha_5q_9q_{11} - \alpha_{14}\left(q_2q_9 + q_5q_7\right) - q_1q_8q_{13} \\ -q_1q_9q_{10} + q_4\left(q_9 + q_{13}\right) + q_5q_8 - q_5q_{10}, \\ c_3 = q_2q_8q_{13} + q_2q_9q_{10} - q_4q_7q_{13} - q_4q_9q_{11} + q_5\left(q_7q_{10} - q_8q_{11}\right), \\ c_4 = \alpha_1\alpha_{14}q_9 - \alpha_5\alpha_9q_{13} + \alpha_9\alpha_{14}q_5, c_5 = -\alpha_1q_8q_{13} - \alpha_1q_9q_{10} + \alpha_5q_6q_{13} \\ +\alpha_5q_9q_{12} + \alpha_9q_4q_{13} - \alpha_9q_5q_{10} - \alpha_{14}q_3q_9 - \alpha_{14}q_5q_6\Big), \\ c_6 = q_3q_8q_{13} + q_3q_9q_{10} - q_4q_6q_{13} - q_4q_9q_{12} + q_5\left(q_6q_{10} - q_8q_{12}\right). \end{gathered}$$

To determine the unknown parameters$\mathrm{B}_i(s)$ some boundary conditions are applied at the free surface of the semiconductor when $x = 0$. The traction-free is applied as mechanical condition, thermal load is applied also which can be expressed after performing the Laplace transform as [44–49]:

$$\left.\sigma(0, t) = 0 \Rightarrow \overline{\sigma} = \sum i = 1^4 H_{4i}\mathrm{B}_i = 0, T(0, t) = T_0 f(s) \Rightarrow \overline{T} = \sum i = 1^4 \mathrm{B}_i = \tfrac{T_0}{s}. \right\}. \tag{44}$$

On the other hand, the plasma and holes conditions can be formulated during the recombination transport processes and diffusive optical excitation at the free surface of the semiconductor medium $x = 0$. In this case, these conditions can be formulated as:

$$\left.\begin{array}{c} N(0,s)=\frac{\tilde{s}n_0}{D_e}\Rightarrow \overline{N}=\sum i=1^4 H_{1i}\mathrm{B}_i(s)=\frac{\tilde{s}n_0}{D_e}, H(0,s) \\ =h_0\Rightarrow \overline{H}=\sum i=1^4 H_{3i}\mathrm{B}_i(s)=h_0. \end{array}\right\}. \tag{45}$$

Where $D_e$is the electron charge diffusion coefficient, $f(s)$ is the Heaviside unit step function and $\tilde{s}$ is the recombination velocity. Solving the system of Eqs. (44) and (45), the parameters$\mathrm{B}_i(s)$ can be obtained algebraically.

4 Inversion Processes of the Laplace Transforms

The inversion of Laplace transforms can be applied using an accurate and efficient numerical approach according to Riemann-sum approximate which based on Fourier series expand according to Honig and Hirdes technique [50]. However, the physical fields in complete form in the time domain can be obtained according to Laplace transform invers, where the invers of the function $\overline{\Omega}(x,s)$ can be expressed in the form [51]:

$$\Omega\left(x,t'\right)=L^{-1}\left\{\overline{\Omega}(x,s)\right\}=\frac{1}{2\pi i}\int_{n-i\infty}^{n+i\infty}\exp\left(st'\right)\overline{\Omega}(x,s)ds. \tag{46}$$

Expand the function $\Omega(x,t')$ which can be defined on $[0,2t']$, according to the Fourier series the function $\Omega(x,t')$ can be expand as [51]:

$$\Omega\left(x,t'\right)=\frac{e^{nt'}}{t'}\left[\frac{1}{2}\overline{\Omega}(x,n)+\mathrm{Re}\sum_{k=1}^{N}\overline{\Omega}\left(x,n+\frac{ik\pi}{t'}\right)(-1)^n\right]. \tag{47}$$

Where $n\in R$, $i=\sqrt{-1}$ (imaginary number unit) and *Re* reprsents the real part. In closed form, the sufficient integer N can be chosen which refers to the number of terms, and the term $nt'\approx 4.7$(for quicker convergence)[50].

5 Validation

5.1 The Thermoelasticity Models

When the effects carrier density and the holes charge field are ignored ($_{\text{i.e.}}$ $N=0$, $H=0$), the generalized thermoelasticity theory with different models is obtained. In this case, the Eqs. (16)-(19) can be rewritten as [39–44]:

$$\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial}{\partial x}\left[K_0\frac{\partial\hat{T}}{\partial x}\right]=\left(1+\tau_q\frac{\partial}{\partial t}\right)\left[\frac{K_0}{k}\frac{\partial\hat{T}}{\partial t}+T_0\gamma\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right]=0, \tag{48}$$

$$\frac{m_{qn}}{K_1}\frac{\partial^2\hat{T}}{\partial x^2}-a_2^n\left[\frac{K_0}{k}\frac{\partial\hat{T}}{\partial t}+T_0\gamma\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right]=0, \tag{49}$$

$$\rho\frac{\partial^2 u}{\partial t^2}=(2\mu+\lambda)\frac{\partial^2 u}{\partial x^2}-\gamma\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial\hat{T}}{\partial x}+\mu_0H_0^2\frac{\partial^2 u}{\partial x^2}. \tag{50}$$

Applying the same technique, the main thermoelastic quantities are obtained. On the other hand, the thermoelasticity models according to the different relaxation times can be obtained as follows: when $0\le\tau_\theta<\tau_q$, the dual phase lag (DPL) model is observed, when $\tau_\theta=0$ and $0<\tau_q$ the Lord and Şhulman (LS) model is appeared and finally, when $\tau_\theta=\tau_q=0.0$, the coupled thermoelasticity (CT) model is obtained.

5.2 The Photo-Thermoelasticity Model

When the holes charge carrier field is neglected i.e. $H=0$, in this case the photo-thermoelasticity model is appeared and the main Eqs. (21)-($_{24}$) are rewritten as [39–41]:

$$\left.\begin{array}{c} \frac{\rho a_1^n}{t^n}N=\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial}{\partial x}\left[K_0\frac{\partial\hat{T}}{\partial x}\right]+m_{nq}\frac{\partial^2 N}{\partial x^2}-\rho a_1^n\frac{\partial N}{\partial t}- \\ \left(1+\tau_q\frac{\partial}{\partial t}\right)\left[\frac{K_0}{k}\frac{\partial\hat{T}}{\partial t}+\rho\, T_0\alpha_n\frac{\partial N}{\partial t}+T_0\gamma\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right] \end{array}\right\}, \tag{51}$$

$$\left.\begin{array}{c} \frac{m_{qn}}{K_1}\frac{\partial^2\hat{T}}{\partial x^2}+D_n\rho\frac{\partial^2 N}{\partial x^2}-\rho\left(1-a_2^n\,T_0\alpha_n+t^n\frac{\partial}{\partial t}\right)\frac{\partial N}{\partial t}- \\ a_2^n\left[\frac{K_0}{k}\frac{\partial\hat{T}}{\partial t}+T_0\gamma\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right]=-\frac{\rho}{t_1^n}\left(1+t^n\frac{\partial}{\partial t}\right)N \end{array}\right\}, \tag{52}$$

$$\rho\frac{\partial^2 u}{\partial t^2}=(2\mu+\lambda)\frac{\partial^2 u}{\partial x^2}-\gamma\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial\hat{T}}{\partial x}-\delta_n\frac{\partial N}{\partial x}+\mu_0H_0^2\frac{\partial^2 u}{\partial x^2}. \tag{53}$$

5.3 The Impact of Variable Thermal Conductivity

When the chosen constant $K_1=0$, in this case the thermal conductivity is constant $K=K_0$, and the heat conduction equation can be written as [48]:

$$\left.\begin{array}{c} K\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial^2 T}{\partial x^2}+m_{nq}\frac{\partial^2 N}{\partial x^2}+m_{hq}\frac{\partial^2 H}{\partial x^2}-\rho\left(a_1^n\frac{\partial N}{\partial t}+a_1^h\frac{\partial H}{\partial t}\right)- \\ \left(1+\tau_q\frac{\partial}{\partial t}\right)\left[\rho\, C_e\frac{\partial T}{\partial t}+\rho\, T_0\alpha_n\frac{\partial N}{\partial t}+\rho\, T_0\alpha_h\frac{\partial H}{\partial t}+T_0\gamma\frac{\partial}{\partial x}\frac{\partial u}{\partial t}\right] \\ =\left[\frac{\rho a_1^n}{t^n}N+\frac{\rho a_1^h}{t^h}H\right] \end{array}\right\}. \tag{54}$$

5.4 The Pressure Force of Magnetic Field

When the pressure force of magnetic field (magnetic intensity) is neglected ($H_0=0$) the equation of motion in 1D can be rewritten as:

$$\rho\frac{\partial^2 u}{\partial t^2}=(2\mu+\lambda)\frac{\partial^2 u}{\partial x^2}-\gamma\left(1+\tau_\theta\frac{\partial}{\partial t}\right)\frac{\partial\hat{T}}{\partial x}-\delta_n\frac{\partial N}{\partial x}. \tag{55}$$

Furthermore, algebraically the temperature distribution can be obtained from the map transform as [49]:

$$\hat{T} = \frac{1}{K_0}\int_0^T K_0\left(1 + K_1 T\right)dT = T + \frac{K_1}{2}T^2 = \frac{K_1}{2}\left(T + \frac{1}{K_1}\right)^2 - \frac{1}{2K_1}. \tag{56}$$

$$T = \frac{1}{K_1}\left[\sqrt{1 + 2K_1\hat{T}} - 1\right] \iff \overline{T} = \frac{1}{K_1}\left[\sqrt{1 + 2K_1\hat{\overline{T}}} - 1\right]. \tag{57}$$

6 Numerical Results and Discussions

The Nano-composite polymer semiconductor material such as silicon (Si) is used to discuss this problem numerically to obtain the behavior of wave distributions of the main physical filed T, σ, $H$and graphically. Silicon is a material that is available in nature and is economically inexpensive and has many uses in the modern electronic industries and plasma physics. In this simulation, the physical constants of Si (as the input parameters) are used in SI unit with helping the computer software program (Matlab 2018b) to show the output wave propagations of physical fields. The input parameters of Si is shown in the following Table 1 [52–54]:

Table 1 the input parameters of Si medium

Unit	Symbol	Si
N/m^2	λ	6.4×10^{10}
	μ	6.5×10^{10}
kg/m^3	ρ	2330
K	T_0	800
$sec(s)$	τ	$5\text{x}10^{-5}$
m^2/s	D_e	2.5×10^{-3}
m^3	d_n	$-9\text{x}10^{-31}$
H/m	μ_0	$4\pi\times10^{-7}$
K^{-1}	α_t	$4.14\text{x}10^{-6}$
$Wm^{-1}K^{-1}$	k	150
$J/(kgK)$	C_e	695
m/s	$\tilde{s}$	2
H/m	μ_0	$4\pi\times10^{-7}$
vk^{-1}	m_{qn}	1.4×10^{-5}
	m_{nq}	1.4×10^{-5}
	m_{qh}	-0.004×10^{-6}
	m_{hq}	-0.004×10^{-6}
m^2s^{-1}	D_n	0.35×10^{-2}
m^2s^{-1}	D_h	0.125×10^{-2}
m^2/s	α_n	1×10^{-2}
m^2/s	α_h	5×10^{-3}

6.1 The Impact of Variable Thermal Conductivity

The changes in investigated physical fields against the horizontal distance x according to different values of thermal conductivity are shown in the first category (Fig. 1). In this category, the dimensionless with real part for studied physical fields x are made in very small time $t=0.0001\,s$under the effect of external magnetic field when the interaction between electrons and holes are occurred. The none-composite semiconductor polymer material subjected to Si medium is used. In this the kind if materials, thermal conductivity can be taken in variable case which depends on the temperature ($K(T)=K_0(1+K_1T)$), where the values of K_1 can be taken in the range $-10^{-3}\le K_1\le 10^{-2}$ may be negative [38]. According to the value of K_1 two cases are investigated during the DPL model. The classical case can be obtained in case of $K_1=0.0$, this case describes the independent temperature of thermal conductivity. On the other hand, when $K_1=-0.03$ and $K_1=-0.06$ its describe the case when the thermal conductivity of Si medium depends on the gradient temperature. The thermal wave distributions are shown in the first subfigure, which satisfy the thermal shock condition at $x=0$. The thermal waves start at positive value with increasing in the magnitude to reach the maximum value near the surface due to the thermal effect of light and pressure force of magnetic field. Far from the surface, it converges from the zero line to arrive the steady state. The mechanical wave can be described by the normal stress distribution which it illustrated in the second subfigure. At the surface, the traction free is satisfied for the mechanical waves which start from the zero point Due to the pressure of magnetic force, the mechanical wave increases near the surface hence it decreases far away the surface before converge to zero line with the increasing in distance. In the third subfigure, the hole charge density distribution is described which it satisfies the recombination hole condition. Due to magnetic and thermal pressures the hole density distribution decreases sharply in the first range and increases again to reach the maximum value with a wave behavior. The electrons (carrier) density distribution is illustrated in the fourth subfigure, due to optical stress and magnetic field the electrons density satisfies the plasma (recombination) condition at the surface. The electrons density increases in the beginning to reach the maximum value near the surface. The electrons density decreases in the second range smoothly to reach the minimum with wave behavior before the equilibrium state converge according to elastic polymer semiconductors characteristics. In general, the thermal wave and plasma (electrons density propagation)wave increase in the beginning due to the thermal effect of light beams (electronic and thermoelastic deformation) and the magnetic pressure until reach the maximum point. Far away from the surface, the thermal wave and electrons density propagation

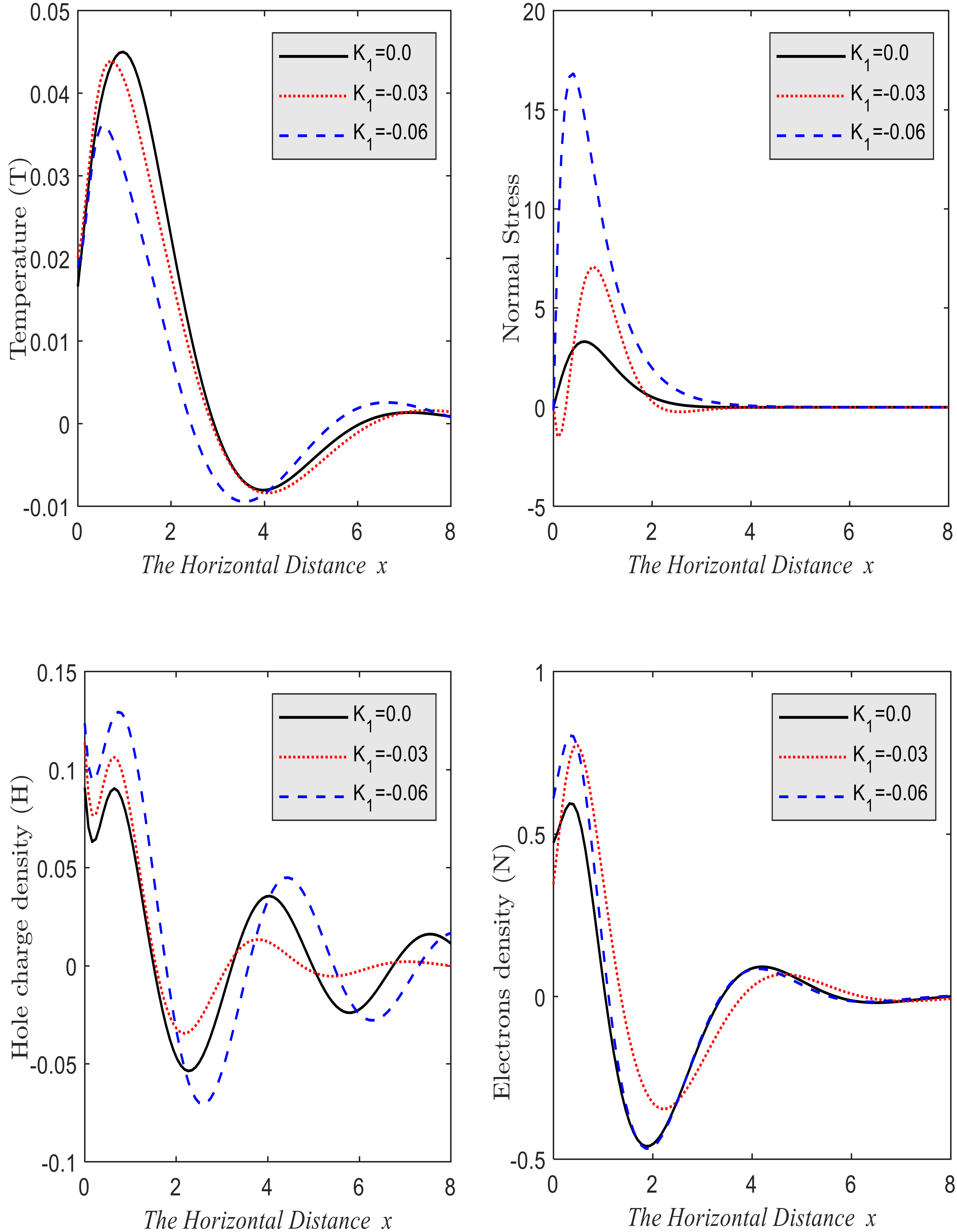

Fig. 1 the variation of the main physical field distributions against the distance ***x*** with variable thermal conductivity under the effect of magnetic field according to DPL model for Si medium

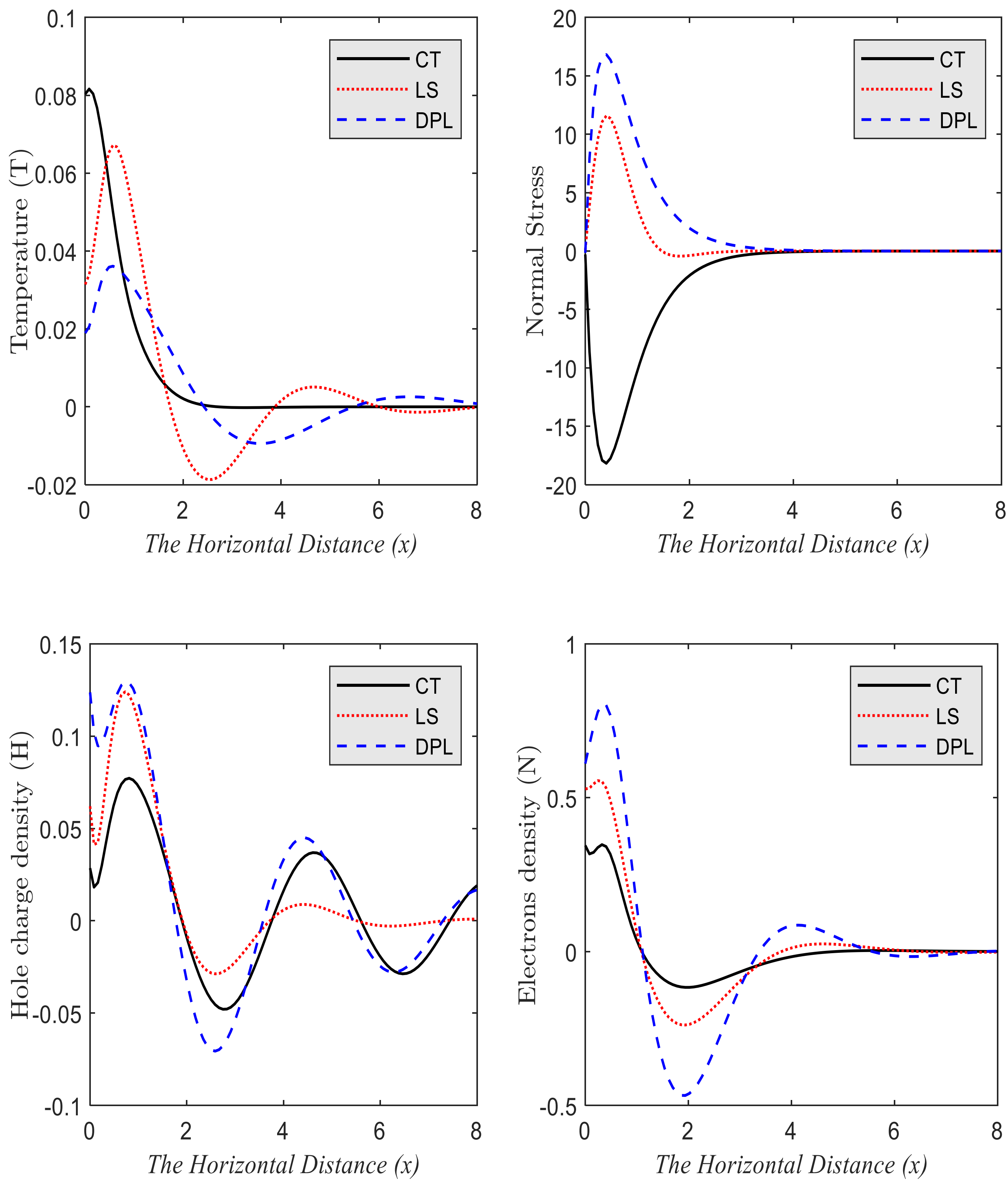

Fig. 2 the variation of the physical field distributions against the distance x under the impact of magnetic field according to the photo-thermoelasticity models for Si medium when $K_1 = -0.06$

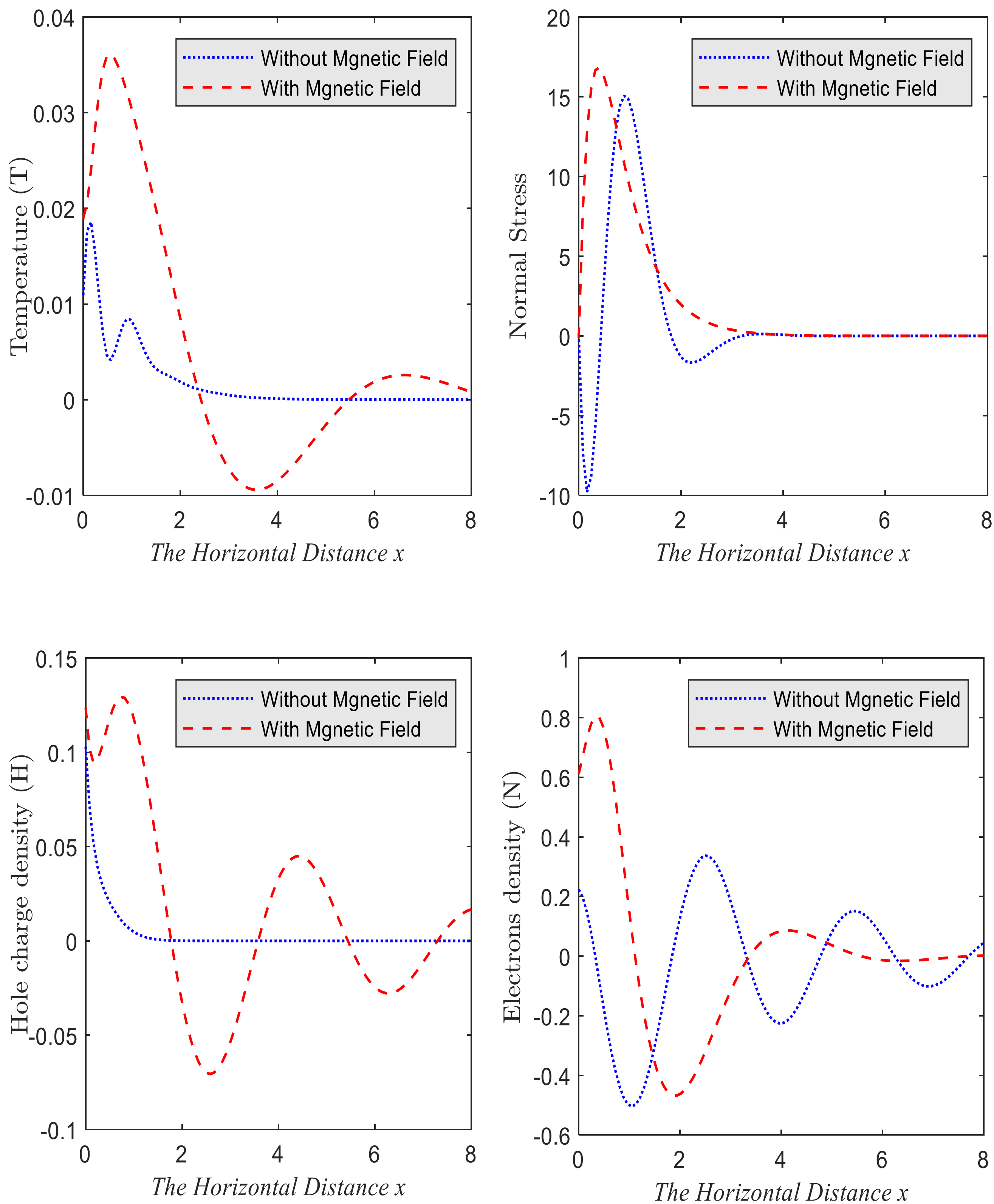

Fig. 3 the variation of the physical field distributions against the distances x without and with magnetic field of Si medium according to DPL theory when $K_1 = -0.06$

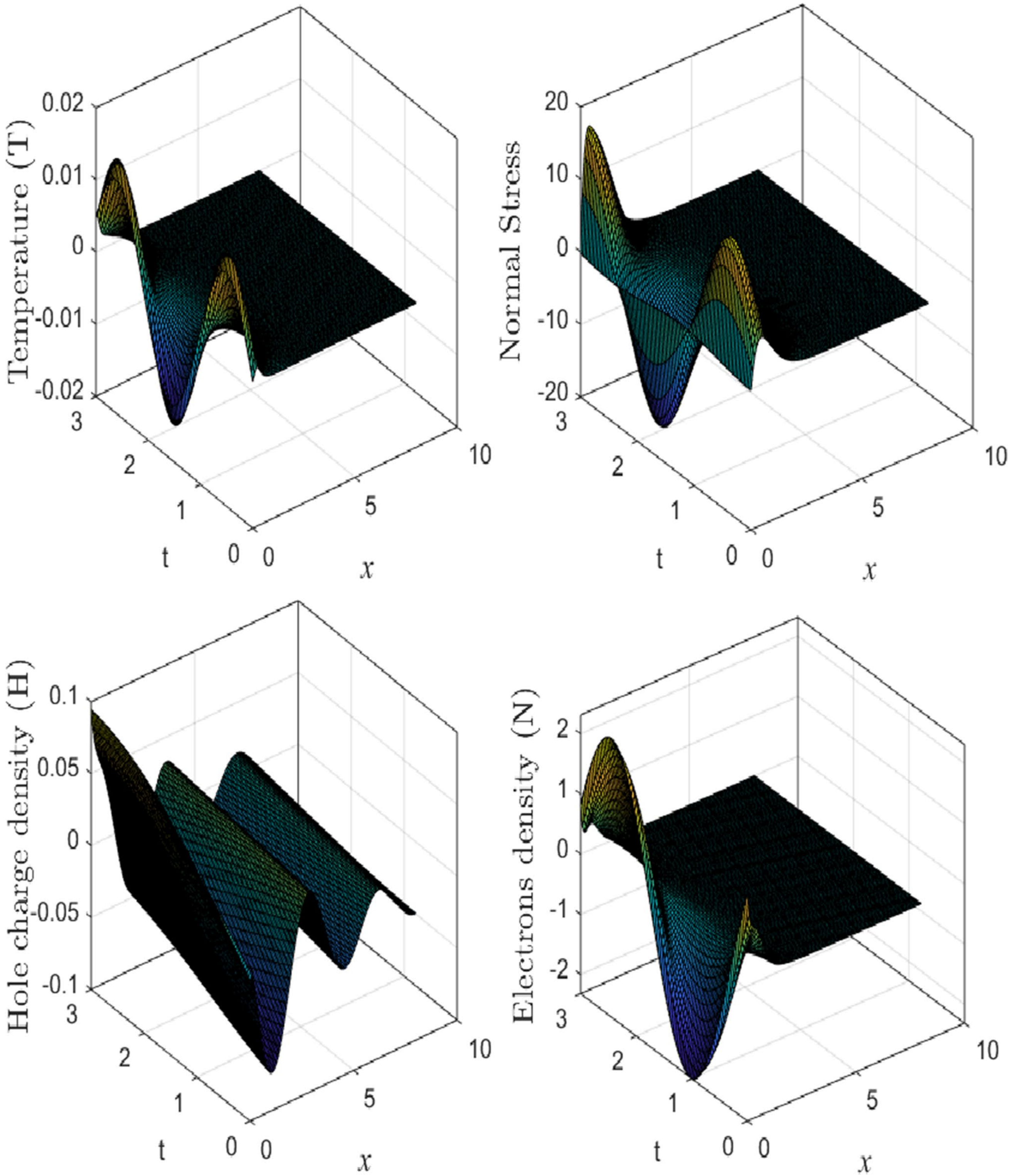

Fig. 4 The 3D plot with the variation of the main fields distributions verses the time and the distances *x*of Si under the effect of magnetic field according to DPL model when $K_1 = -0.06$

decreases gradually with exponential behavior for all three cases which agree with the experimental results [55].

6.2 The Thermoelasticity Models

The second category describe the variation the physical fields against the horizontal distance according to the vary in thermal relaxation times, this numerical results are shown in Fig. 2. For very small time, the input parameters of Si medium are used under the impact of magnetic field pressure when the thermal conductivity depends on temperature $K_1 = -0.06$. Three models of photo-thermoelasticity are illustrated according to differences in thermal memories CT model, LS model as well as DPL model. An increase in the value of the relaxation times leads to fundamental differences in the behavior of the wave distribution. However, a small change in thermal relaxation times have a significant effects on all physical fields.

6.3 The Effect of Magnetic Field

The various uses of the magnetic field are very useful for understanding the properties of the internal structure of most materials under recent studies. Accordingly, many modern applications appeared in the physical sciences, engineering and medicine. The third Fig. 3 illustrates the impact of external magnetic field with compressive force on the main fields against the distance. For very small time, the Si medium is used to study the magnetic pressure during the holes-electronics-elastic deformation according to DPL model when $K_1 = -0.06$. The two cases are studied, the first case when the magnetic field is absent (without magnetic field). On the other hand, the second case is described under the impact of the magnetic field (with magnetic field). The effect of magnetic field on semiconductor materials is shown by observing the propagation behavior of waves. The presence of the magnetic field on the medium leads to a difference in wave propagation distributions.

6.4 The 3D Plot

For the constant values of relaxation times according to DPL model and when the thermal conductivity is variable when $K_1 = -0.06$ and in the presence of the magnetic field, Fig. 4 illustrate the changes in wave propagation behavior as functions of distance and time in 3D plots. From this figure, it is clear that the propagation of waves vanishes (limited propagation speeds) with the increase in the value of time and distance.

7 Conclusion

The photo-generated diffusion processes when the interactions between the holes and the electrons are occurred, are investigated under the impact of magnetic field. The governing equations are studied in 1D with dimensionless quantities when the thermal conductive of semiconductor medium depends on temperature gradient. Few previous studies have taken into account the overlap between the holes and electrons under the effect of magnetic field according to variable thermal conductivity due to the complexity of the model. The thermal relaxation times are very important when the wave propagations of physical fields are investigated with a finite velocity wave. On the other hand, Due to the presence of magnetic field the wave distribution is attached to the surface. The vary in the thermal conductivity parameters leads to a great influence on the distribution of different physical domains. This investigation may be very useful for researches in the development of quality semiconductor fabrication and its physical and engineering applications. Semiconductors are the brains of modern electronics industrial. Many modern electronics industries which depend on the gradient of temperature have a various uses of clean energy, electric circuits in aircraft, electronic devices, healthcare, military systems and solar cells.

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