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Review Article

Photo Thermal Diffusion of Excited Nonlocal Semiconductor Circular Plate Medium with Variable Thermal Conductivity

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To examine the effects of the nonlocal thermoelastic parameters in a nanoscale semiconductor material, a novel nonlocal model with variable thermal conductivity is provided in this study. The photothermal diffusion (PTD) processes in a chemical action are utilized in the framework of the governing equations. When elastic, thermal, and plasma waves interact, the nonlocal continuum theory is used to create this model. For the main formulations to get the analytical solutions of the thermal stress, displacement, carrier density, and temperature during the nanoscale thermo-photo-electric medium, the Laplace transformation approach in one dimension (1D) of a thin circular plate is utilized. To create the physical fields, mechanical forces and thermal loads are applied to the semiconductor's free surface. To acquire the full solutions of the research areas in the time-space domains, the inverse of the Laplace transform is applied with several numerical approximation techniques. Under the impact of nonlocal factors, the principal physical fields are visually depicted and theoretically explained.

1. Introduction

Nanotechnology is currently and in the future will be one of the most crucial cornerstones of human existence. This significant technology is expanding quickly, and several scientists are engaged in this fascinating sector. Several of the physical characteristics of elastic materials may vary depending on the temperature. Many difficulties arise in researching elastic materials without taking varying heat conductivity into account. When thermal conductivity varies, particularly in response to temperature, it becomes essential. Thermo-diffusion is the relationship between mass diffusion and changing thermal conductivity. Thermo-diffusion happens when particles move from an area of greater concentration to an area of lower concentration as a result of a temperature change. Modern engineering has several uses for the study of thermal conductivity in the presence of mass diffusion, particularly in the aerospace, electronics, and integrated circuit industries. High-performance nanostructures, such as nanotubes, nanofilms, and nanowires, have been extensively used as resonators, probes, sensors, transistors, actuators, etc. with the fast development of nanomechanical electromechanical systems (NEMS) technologies. It is crucial to comprehend the precise characterizations of these nanostructures' thermal and mechanical characteristics.

Semiconductor materials (such as silicon) are an excellent research subjects for this phenomenon, particularly when subjected to laser or falling light beams. On the surface, the excited electrons will produce a charge known as free carriers (plasma waves). According to the quantity of light descending, the plasma density is employed to regulate the diffusion [1–3]. Numerous publications [4–6] failed to take into account the coupling between thermal-elastic waves and plasma waves during the deformation process in semiconductor materials. Recently, several authors employed photoacoustic spectroscopy to detect photothermal events when a laser beam struck a semiconductor [7, 8]. Semiconductors' temperature, carrier intensity, and thermal diffusion are measured using the photothermal phenomena [9–13]. When thermal waves propagate, generating elastic oscillation, and plasma waves are formed by photo-excited free carriers, directly creating a periodic elastic deformation as well [14–16], the interaction between the elastic-thermal-plasma waves occurs. Without considering the impact of changing thermal conductivity, several issues in generalized thermoelasticity have been explored [17–25]. Later, a lot of writers studied generalized thermoelasticity in many areas using variable thermal conductivity. The thermal-mechanical behavior of the medium may be affected by the deformation of elastic media depending on temperature [26–28]. Abbas [29–33] studied many problems of the fiber-reinforced anisotropic thermoelastic medium in two dimensions with fractional transient heating according to many mathematical methods.

The nonlocal thermoelastic model with variable thermal conductivity (which may be considered as a linear function of temperature) is utilized in the current study using a theoretical method. The process of photo-thermal-diffusion interactions in semiconductor nanoscale media is investigated. The variation in temperature caused by the light beam impacting the nonlocal semiconductor medium is the basis for the variable thermal conductivity. The chemical diffusion method enables photothermal transfer (mass diffusion). When the Laplace transform domain in cylindrical coordinates is utilized, the analytical solutions of the basic fields are found. The numerical techniques provide analytical solutions in the Laplace domain without any presumptive limitations on the real physical values. Finally, with changes in nonlocal parameters and changing thermal conductivity, the numerical calculations of the important physical quantities distribution are graphically shown and discussed. The numerical findings presented in the current study have applications in solid mechanics, acoustics, material science, and engineering for earthquakes.

2. Formulation of the Problem and Basic Equations

The four important variables in this problem, respectively, are $u(r,t)$, $T(r,t)$, $N(r,t)$, and $C(r,t)$ which stand in for the displacement (elastic waves), temperature (thermal or heat waves), carrier density (plasma waves), and diffusive material concentration (mass diffusion). When the thermal activation coupling value κ for the nonlocal medium is nonzero, the photothermal diffusion transport process takes place. It makes use of cylindrical coordinates (r,ψ,z). When a very thin circular plate is taken into account, all quantities are independent of ψ and z because of the symmetry of the axis z. Elastic-plasma-thermal-diffusion wave overlapping processes' governing equations are presented as [34, 35], the photo-electronic equation is as follows:

$$\frac{\partial N(r,t)}{\partial t} = D_E N_{,\mathrm{ii}}(r,t) - \frac{N(r,t)}{\tau} + \kappa T(r,t). \tag{1}$$

Equations for thermal diffusion in the photothermal diffusion process transport are as follows:

$$\left(KT_{,i}(r,t)\right)_{,i} = \frac{\partial}{\partial t}\left(\frac{K}{k}T(r,t) + \beta_1 T_0 u_{,i}(r,t) + cT_0 C\right) - \frac{E_g}{\tau}N(r,t). \tag{2}$$

If there is no body force, the equations of motion for nonlocal medium may be expressed as follows[34]:

$$\rho\left(1-\xi^2\nabla^2\right)\frac{\partial^2 u_i}{\partial t^2} = \mu u_{i,\mathrm{jj}}(r,t) + (\mu+\lambda)\,u_{i,\mathrm{jj}}(r,t) - \beta_1 T_{,i}(r,t) - \beta_2 C_{,i}(r,t) - \delta_n N_{,i}(r,t). \tag{3}$$

The length-related elastic nonlocal parameter is represented by $\xi = ae_0/l$ (l is the external characteristic length scale, a is the internal characteristic length, and e_0 is nondimensional material property).

The mass diffusion equation is expressed as follows [35]:

$$D_c\beta_2 e_{\mathrm{nn,ii}} + D_c cT_{,\mathrm{ii}}(r,t) + \left(\frac{\partial}{\partial t} + \tau_d\frac{\partial^2}{\partial t^2}\right)C(r,t) = D_c bC_{,\mathrm{ii}}(r,t). \tag{4}$$

The change in thermal conductivity is K of the nonlocal semiconductor medium and $\beta_2 = (3\lambda+2\mu)\alpha_c$ where α_c is the coefficient of linear diffusion. On the other hand, the transport heat coefficients for the nonlocal medium are independent of N, C and T [36–38].

The strain-stress combinations are as follows:

$$\begin{aligned}
\left(1-\xi^2\nabla^2\right)\sigma_{\mathrm{rr}} &= 2\mu\frac{\partial u}{\partial r} + \lambda e - \beta_1\left(T-T_0\right) - \beta_2 C + (3\lambda+2\mu)d_n N,\\
\left(1-\xi^2\nabla^2\right)\sigma_{\psi\psi} &= 2\mu\frac{u}{r} + \lambda e - \beta_1\left(T-T_0\right) - \beta_2 C + (3\lambda+2\mu)d_n N,\\
\left(1-\xi^2\nabla^2\right)\sigma_{\mathrm{zz}} &= \lambda e - \beta_1\left(T-T_0\right) - \beta_2 C + (3\lambda+2\mu)d_n N,\ \sigma_{r\psi} = \sigma_{z\psi} = \sigma_{rz} = 0.
\end{aligned} \tag{5}$$

The nonlocal semiconductor medium's chemical potential equation is

$$P = -\beta_2 e_{\mathrm{nn}} + bC - c\left(T - T_0\right). \tag{6}$$

where P is the chemical potential per unit mass.

It is possible to choose a material's variable thermal conductivity K, which may be estimated as a linear function of temperature [26]:

$$K(T) = K_0(1 + qT), \tag{7}$$

where q is a negative parameter and K_0 is a thermal conductivity when $q = 0$ (the nonlocal medium is independent of temperature).

The map of temperature can be taken in the following form [27]:

$$\Theta = \frac{1}{K_0}\int_0^T K(\mathfrak{R})d\mathfrak{R}. \tag{8}$$

Differentiating both sides of equation (7) relative to x_i, we get

$$\left.\begin{aligned} K_0\Theta_{,i} &= K(T)T_{,i}, \\ K_0\Theta_{,ii} &= \left(K(T)T_{,i}\right)_{,i}. \end{aligned}\right\} \tag{9}$$

Another form of equation (9) when the nonlinear terms are neglected can be obtained as follows:

$$\begin{aligned} K_0\Theta_{,\mathrm{ii}} &= K_{,i}T_{,i} + KT_{,\mathrm{ii}} = K_0\left(1 + K_1T\right)_{,i}T_{,i} + KT_{,\mathrm{ii}} \\ &= K_0K_1\left(T_{,i}\right)^2 + KT_{,\mathrm{ii}} = KT_{,\mathrm{ii}}. \end{aligned} \tag{10}$$

The time-differentiation is done in the same manner to both sides of equation (7), resulting in:

$$K_0\frac{\partial\Theta}{\partial t} = K(T)\frac{\partial T}{\partial t}. \tag{11}$$

Using equation (8) and differentiating equation (1) by $\partial/\partial x_i$, yields:

$$\frac{\partial}{\partial t}N_{,i} = D_E\left(N_{,\mathrm{mm}}\right)_{,i} - \frac{1}{\tau}N_{,i} + \frac{\kappa K_0}{K}\Theta_{,i}. \tag{12}$$

The other form of the quantity $\kappa K_0/K\Theta_{,i}$ with neglected the nonlinear term can be represented as follows:

$$\left.\begin{aligned} &\frac{\kappa K_0}{K_0\left(1 + K_1T\right)}\Theta_{,i} = \kappa\left(1 + K_1T\right)^{-1}\Theta_{,i} = \kappa\left(1 - K_1T + \left(K_1T\right)^2 - \ldots\right)\Theta_{,i} = \\ &\kappa\Theta_{,i} - \kappa K_1T\Theta_{,i} + \left(K_1T\right)^2\Theta_{,i} - \ldots = \kappa\Theta_{,i}. \end{aligned}\right\} \tag{13}$$

Equation (1) results when equation (13) is applied:

$$\frac{\partial}{\partial t}N_{,i} = D_E\left(N_{,\mathrm{mm}}\right)_{,i} - \frac{1}{\tau}N_{,i} + \kappa\Theta_{,i}. \tag{14}$$

Integrating equation (14), yields:

$$\frac{\partial N}{\partial t} = D_E N_{,\mathrm{ii}} - \frac{1}{\tau}N + \kappa\Theta. \tag{15}$$

Under the influence of mapping, the heat (thermal) diffusion equation (2) have the following form:

$$\Theta_{,\mathrm{ii}} = \frac{1}{k}\frac{\partial\Theta_i}{\partial t} + \frac{\beta_1T_0}{K_0}\frac{\partial u_{,i}}{\partial t} + \frac{cT_0}{K_0}\frac{\partial C_i}{\partial t} - \frac{E_g}{K_0\tau}N_i. \tag{16}$$

The nonlocal motion equation (3) under the temperature map may be simplified as follows:

$$\begin{aligned} \rho\left(1 - \xi^2\nabla^2\right)\frac{\partial^2 u_i}{\partial t^2} &= \mu u_{i,\mathrm{jj}} + (\mu + \lambda)u_{i,\mathrm{jj}} \\ &\quad - \beta_1\Theta_{,i} - \beta_2C_{,i} - \delta_nN_{,i}. \end{aligned} \tag{17}$$

The equation for mass diffusion equation (4) may be expressed as follows:

$$\begin{aligned} &D_c\beta_2e_{\mathrm{nn,ii}} + \frac{D_ccK_0}{K}\Theta_{,\mathrm{ii}}(r,t) + \left(\frac{\partial}{\partial t} + \tau_d\frac{\partial^2}{\partial t^2}\right)C(r,t) \\ &= D_cbC_{,\mathrm{ii}}(r,t). \end{aligned} \tag{18}$$

The term $D_ccK_0/K\Theta_{,ii}(r,t)$ can be represented with neglected nonlinear terms in the following form:

$$\left.\begin{aligned} &\frac{D_ccK_0}{K}\Theta_{,\mathrm{ii}} = \frac{D_ccK_0}{K_0\left(1 + K_1T\right)}\Theta_{,\mathrm{ii}} = D_cc\left(1 + K_1T\right)^{-1}\Theta_{,\mathrm{ii}} = D_cc\left(1 - K_1T + \left(K_1T\right)^2 - \ldots\ldots\right)\Theta_{,\mathrm{ii}} = \\ &D_cc\left(1 - K_1T + \left(K_1T\right)^2 - \ldots\ldots\right)\Theta_{,\mathrm{ii}} = D_cc\Theta_{,\mathrm{ii}} - D_ccK_1T\Theta_{,\mathrm{ii}} + D_cc\left(K_1T\right)^2\Theta_{,\mathrm{ii}} - \ldots\ldots = D_cc\Theta_{,\mathrm{ii}}, \end{aligned}\right\} \tag{19}$$

In this case, equation (18) can be rewritten as follows:

$$D_c\beta_2 e_{\mathrm{nn,ii}} + D_c c\Theta_{,\mathrm{ii}}(r,t) + \left(\frac{\partial}{\partial t} + \tau_d \frac{\partial^2}{\partial t^2}\right)C(r,t) = D_c b C_{,\mathrm{ii}}(r,t). \tag{20}$$

The strain in cylindrical 1D form can be represented as follows:

$$e_{\mathrm{rr}} = \frac{\partial u}{\partial r}, e_{\psi\psi} = \frac{u}{r}, e_{r\psi} = e_{\psi z} = e_{\mathrm{zz}} = e_{\mathrm{rz}} = 0, e = \frac{1}{r}\frac{\partial(\mathrm{ru})}{\partial r}\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}. \tag{21}$$

By doing the analysis in the radial direction (r), the problem will be solved in 1D, with the displacement vector having the form $\vec{u} = (u,0,0), u(r,t)$.

The main governing equations in 1D (radial) are reduced as follows:

$$\frac{\partial N}{\partial t} = D_E\left(\frac{\partial^2 N}{\partial r^2} + \frac{1}{r}\frac{\partial N}{\partial r}\right) - \frac{N}{\tau} + \kappa\Theta, \tag{22}$$

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)\Theta = \frac{1}{k}\frac{\partial\Theta}{\partial t} + \frac{\beta_1 T_0}{K_0}\frac{\partial e}{\partial t} + \frac{cT_0}{K_0}\frac{\partial C}{\partial t} - \frac{E_g}{K_0\tau}N. \tag{23}$$

Taking the divergence on both sides of equation (17), yields:

$$\rho\left(1 - \xi^2\nabla^2\right)\frac{\partial^2 e}{\partial t^2} = (2\mu+\lambda)\nabla^2 e - \beta_1\nabla^2\Theta - \beta_2\nabla^2 C - \delta_n\nabla^2 N. \tag{24}$$

The equation for mass diffusion may be shortened to

$$D_c\beta_2\nabla^2 e + D_c c\nabla^2\Theta + \left(\frac{\partial}{\partial t} + \tau_d\frac{\partial^2}{\partial t^2}\right)C - D_c b\nabla^2 C = 0. \tag{25}$$

For simplicity, the dimensionless variables will be represented as follows: $(r', u', \xi') = (r,u,\xi)/C_T t^*$, $(t', \tau_0', \tau_d') = (t,\tau_0,\tau_d)/t^*$, $\Theta' = \beta_1\Theta/2\mu+\lambda$, $\sigma_{\mathrm{jj}}' = \delta_{\mathrm{ij}}\sigma_{\mathrm{ij}}/2\mu+\lambda$, $C' = \beta_2 C/2\mu+\lambda$, $N' = \delta_n N/2\mu+\lambda$, $P' = P/\beta_2$, and $T' = \beta_1(T-T_0)/2\mu+\lambda$.

According to dimensionless variables, the governing equations (22)–(25) and the chemical potential equation have the following form (drop the dash):

$$\begin{aligned}
&\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} - q_1 - q_2\frac{\partial}{\partial t}\right)N + \varepsilon_3\Theta = 0,\\
&\nabla^2\Theta - \frac{\partial}{\partial t}\left(\Theta + \varepsilon_1 e + \varepsilon_4 C\right) + \varepsilon_2 N = 0,\\
&\nabla^2(e - \Theta - C - N) - \left(1 - \xi^2\nabla^2\right)\frac{\partial^2 e}{\partial t^2} = 0,\\
&\nabla^2(e + q_4\Theta - q_3 C) + q_5\left(\frac{\partial}{\partial t} + \tau_d\frac{\partial^2}{\partial t^2}\right)C = 0,\\
&P = -e + q_3 C - q_4 T.
\end{aligned} \tag{26}$$

Using the linear form of variable thermal conductivity equation (6) and the mapping equation (7), one arrives at the following result [26]:

$$\begin{aligned}
\Theta &= \frac{1}{K_0}\int_0^T K_0(1+qT)dT = T + \frac{q}{2}T^2 = \frac{q}{2}\left(T + \frac{1}{q}\right)^2 - \frac{1}{2q},\\
T &= \frac{1}{q}\left[\sqrt{1+2q\Theta} - 1\right],\\
qT + 1 &= \sqrt{1+2q\Theta}.
\end{aligned} \tag{27}$$

The dimensionless equations for stress forces may be simplified as follows:

$$\begin{aligned}
&\left(1 - \xi^2\nabla^2\right)\sigma_{\mathrm{rr}} = e + (\beta-1)\frac{u}{r} - \left(\frac{-1 + \sqrt{1+2q\Theta}}{q}\right) - N - C,\\
&\left(1 - \xi^2\nabla^2\right)\sigma_{\psi\psi} = \beta e + (1-\beta)\frac{u}{r} - \left(\frac{-1 + \sqrt{1+2q\Theta}}{q}\right) - N - C,\\
&\left(1 - \xi^2\nabla^2\right)\sigma_{\mathrm{zz}} = \beta e - \left(\frac{-1 + \sqrt{1+2q\Theta}}{q}\right) - C - N,
\end{aligned} \tag{28}$$

where $q_1 = K_0 t^*/D_E\rho\tau C_e$, $q_2 = K_0/D_E\rho C_e$, $\varepsilon_1 = \beta_1^2 T_0 t^{*2}/K_0\rho$, $\varepsilon_2 = \alpha_T E_g t^*/d_n\rho\tau K_0 C_e$, $\varepsilon_3 = d_n\kappa t^*/\alpha_T\rho C_e D_E$, $\varepsilon_4 = \varepsilon_3 c\ \ C_T^2/\beta_1 K_0\beta_2$, $C_T^2 = 2\mu+\lambda/\rho$, $\delta_n = (2\mu+3\lambda)d_n$, $t^* = K_0/\rho C_e C_T^2$, $\beta = \lambda/2\mu+\lambda$, $q_3 = b\rho C_T^2/\beta_2^2$, $q_4 = c\rho C_T^2/\beta_1\beta_2$, and $q_5 = (2\mu+\lambda)t^{*2}C_T^2/D\beta_2^2$.

To solve this problem in Laplace transform domain, the initial conditions should be taken mathematically as follows:

$$\begin{aligned}
&\sigma_{rr}(r,t)\big|_{t=0} = \frac{\partial\sigma_{rr}(r,t)}{\partial t}\bigg|_{t=0} = 0\ P(r,t)\big|_{t=0} = \frac{\partial P(r,t)}{\partial t}\bigg|_{t=0} = 0, \Theta(r,t)\big|_{t=0} = \frac{\partial\Theta(r,t)}{\partial t}\bigg|_{t=0} = 0,\\
&C(r,t)\big|_{t=0} = \frac{\partial C(r,t)}{\partial t}\bigg|_{t=0} = 0, e(r,t)\big|_{t=0} = \frac{\partial e(r,t)}{\partial t}\bigg|_{t=0} = 0, N(r,t)\big|_{t=0} = \frac{\partial N(r,t)}{\partial t}\bigg|_{t=0} = 0.
\end{aligned} \tag{29}$$

3. The Solution in the Laplace Domain

It is possible to express the Laplace transform with parameter s as follows:

$$L(\Psi(r,t)) = \overline{\Psi}(r,s) = \int_0^\infty \Psi(r,t)e^{-st}\,dt. \quad (30)$$

Using the initial conditions equation (29) and performing the Laplace transform including both sides of all mathematical models after a small amount of modification, we get

$$\left(\nabla^2-\alpha_1\right)\overline{N}+\varepsilon_3\overline{\Theta}=0, \quad (31)$$

$$\left(\nabla^2-s\right)\overline{\Theta}+\varepsilon_2\overline{N}-\varepsilon_1 s\overline{e}-\varepsilon_4 q_6\overline{C}=0, \quad (32)$$

$$\left(\nabla^2-\Omega\right)\overline{e}-\varpi\nabla^2\left(\overline{\Theta}+\overline{N}+\overline{C}\right)=0, \quad (33)$$

$$\left(\nabla^2-q_6\right)\overline{C}-q_7\nabla^2\overline{e}-q_8\nabla^2\overline{\Theta}=0. \quad (34)$$

The stress components relations equations (28)–(30) can be represented as follows:

$$\begin{aligned}\left(1-\xi^2\nabla^2\right)\overline{\sigma}_{rr}&=\overline{e}+(\beta-1)\frac{\overline{u}}{r}-\left(\frac{-1+\sqrt{1+2q\overline{\Theta}}}{q}\right)-\overline{N}-\overline{C},\\ \left(1-\xi^2\nabla^2\right)\overline{\sigma}_{\psi\psi}&=\beta\overline{e}+(1-\beta)\frac{\overline{u}}{r}-\left(\frac{-1+\sqrt{1+2q\overline{\Theta}}}{q}\right)-\overline{N}-\overline{C},\\ \left(1-\xi^2\nabla^2\right)\overline{\sigma}_{zz}&=\beta\overline{e}-\left(\frac{-1+\sqrt{1+2q\overline{\Theta}}}{q}\right)-\overline{C}-\overline{N},\end{aligned} \quad (35)$$

where $\alpha_1=q_1+sq_2$, $q_6=q_5\left(s+\tau_d s^2\right)/q_3$, $q_7=1/q_3$, $q_8=q_4/q_3$, $\Omega=s^2\varpi$, and $\varpi=1/1+s^2\xi^2$.

Eliminating the set of equations (30)–(33) yields the following expressions for the physical fields $\overline{e}(r,s)$, $\overline{N}(r,s)$, $\overline{C}(r,s)$, and $\overline{\Theta}(r,s)$ as follows:

$$\left(\nabla^8-E_1\nabla^6+E_2\nabla^4-E_3\nabla^2+E_4\right)\left\{\overline{e},\overline{\Theta},\overline{N},\overline{C}\right\}(r,s)=0. \quad (36)$$

However, the main coefficients of equation (36) are [28] as follows:

$$\begin{aligned}E_1&=\left\{\Omega+q_6+s\left(1-q_7+\varepsilon_1\left(1+q_8\right)\right)+\varepsilon_4 q_8\left(q_7+q_8\right)+\varpi\alpha_1\left(1-q_7\right)\right\}\left(1-q_7\right)^{-1},\\ E_2&=\left\{\Omega\left(q_6+\varepsilon_4 q_8^2\right)+s\left(\Omega+q_7\left(1+\varepsilon_1\right)\right)+\varpi\alpha_1 g_1+g_2\right\}\left(1-q_7\right)^{-1},\\ E_3&=\left\{\varepsilon_1 s q_6\left(1+\varepsilon_3\right)-\varepsilon_2\varepsilon_3\left(\Omega+q_6\right)+\varpi g_3\right\}\left(1-q_7\right)^{-1}\\ E_4&=\left\{\Omega q_6\left(\alpha_1 s-\varpi\varepsilon_2\varepsilon_3\right)\right\}\left(1-q_7\right)^{-1},\end{aligned} \quad (37)$$

where $g_1=\{s^2+q_6+s(1-q_7)+\varepsilon_1 s(1+q_8)+\varepsilon_4 q_8(q_7+q_8)\}$, $g_2=\{\varepsilon_2\varepsilon_3(q_7-1)+\varepsilon_3 s(\varepsilon_1+\varepsilon_4 q_7)\}$, $g_3=s^2(sq_6+\varepsilon_4 q_8^2)+\alpha_1(s^2q_6+q_8(s^2+q_6))$

In factorized form, equation (36) takes the following form:

$$\left(\nabla^2-k_1^2\right)\left(\nabla^2-k_2^2\right)\left(\nabla^2-k_3^2\right)\left(\nabla^2-k_4^2\right)\left\{\overline{e},\overline{\Theta},\overline{N},\overline{C}\right\}(r,s)=0, \quad (38)$$

where k_n^2 $(n=1,2,3,4)$ represent the roots of the following characteristic equation:

$$k^8-E_1k^6+E_2k^4-E_3k^2+E_4=0. \quad (39)$$

For linearity, the solution to equation (36) when $r\longrightarrow 0$ may be expressed as follows:

$$\left.\begin{aligned}\overline{\Theta}(r,s)&=\sum_{i=1}^{4}\lambda_i(s)I_0\left(k_i r\right)\\ \overline{e}(r,s)&=\sum_{i=1}^{4}\lambda_i'(s)I_0\left(k_i r\right)\\ \overline{N}(r,s)&=\sum_{i=1}^{4}\lambda_i''(s)I_0\left(k_i r\right)\\ \overline{C}(r,s)&=\sum_{i=1}^{4}\lambda_i'''(s)I_0\left(k_i r\right)\end{aligned}\right\},\ (i=1,2,3,4), \quad (40)$$

where I_0 is the zero-order, first-kind modified Bessel function. The unknown parameters are $\lambda_i,\lambda_i',\lambda_i''$ and λ_i''' $(i=1,2,3,4)$, which are derived from the prepared circular plate and parameter s. From equations (30)–(33) and using equation (40), the relationship between these unknown parameters may be determined as follows:

$$\lambda_i'(s) = \frac{k_i^6 - g_8 k_i^4 + g_9 k_i^2 - g_5 q_7}{\left(k_i^2 - \alpha_1\right)\left(g_6 k_i^2 - g_7\right)}\lambda_i(s),$$

$$\lambda_i''(s) = -\frac{\varepsilon_3}{\left(k_i^2 - \alpha_1\right)}\lambda_i(s),$$

$$\lambda_i'''(s) = \frac{(g_6 - 1)k_i^8 - g_{10}k_i^6 + g_{11}k_i^4 - g_{12}k_i^2 + \Omega g_5 q_7}{k_i^2\left(k_i^2 - \alpha_1\right)^2\left(g_6 k_i^2 - g_7\right)}\lambda_i(s), \tag{41}$$

where, $g_4 = \alpha_1 + q_6$, $g_5 = \alpha_1 q_6 - \varepsilon_2\varepsilon_3$, $g_6 = \varepsilon_1 q_6 + q_4 q_6 q_8$, $g_7 = \varepsilon_1 q_6 q_7$, $g_8 = g_4 + q_7 + \varepsilon_4 q_6 q_9$, $g_9 = g_5 + g_4 q_7 \varpi + \varepsilon_4 q_6 q_9 \alpha_1$, $g_{10} = g_7 + (2\alpha_1 + \varepsilon_3)g_6 + \varpi g_8 + \Omega$, $g_{11} = (2\alpha_1 g_7 + \alpha_1^2 g_6) + \varepsilon_3 \varpi(\alpha_1 g_6 + g_7) + g_9 + \Omega g_8$ $g_{12} = (\alpha_1^2 + \varepsilon_3\alpha_1)g_7 + g_5 q_7 + \Omega g_9$.

Complete analytical solutions for the other main variables are as follows:

$$\bar{e}(r,s) = \sum_{i=1}^{4}\frac{k_i^6 - g_8 k_i^4 + g_9 k_i^2 - g_5 q_7}{\left(k_i^2 - \alpha_1\right)\left(g_6 k_i^2 - g_7\right)}\lambda_i(s) I_0(k_i r),$$

$$\overline{N}(r,s) = -\sum_{i=1}^{4}\frac{\varepsilon_3}{\left(k_i^2 - \alpha_1\right)}\lambda_i(s) I_0(k_i r), \tag{42}$$

$$\overline{C}(r,s) = \sum_{i=1}^{4}\frac{(g_6 - 1)k_i^8 - g_{10}k_i^6 + g_{11}k_i^4 - g_{12}k_i^2 + \Omega g_5 q_7}{k_i^2\left(k_i^2 - \alpha_1\right)^2\left(g_6 k_i^2 - g_7\right)}\lambda_i(s) I_0(k_i r).$$

Using Laplace transform, the displacement component may be derived from equations (21) and (42) as follows:

$$\bar{u}(r,s) = \sum_{i=1}^{4}\frac{k_i^6 - g_8 k_i^4 + g_9 k_i^2 - g_5 q_7}{\left(k_i^2 - \alpha_1\right)\left(g_6 k_i^2 - g_7\right)}\lambda_i(s) I_1(k_i r). \tag{43}$$

From equations (27) and (29), which may be written as follows, one can see the components of the radial stress and the chemical potential:

$$\bar{\sigma}_{rr}(r,s) = \sum_{i=1}^{4}\left\{\frac{\left[\left(\alpha_2 k_i^8 - \alpha_3 k_i^6 + \alpha_4 k_i^4 - \alpha_5 k_i^2 + \alpha_6\right)\lambda_i(s) I_0(k_i r)\right]}{k_i^2\left(1 - \xi^2 k_i^2\right)\left(k_i^2 - \alpha_1\right)^2\left(g_6 k_i^2 - g_7\right)} - \left(\frac{-1 + \sqrt{1 + 2q\lambda_i(s) I_0(k_i r)}}{q\left(1 - \xi^2 k_i^2\right)}\right) + \frac{(\beta - 1)\left\{k_i^6 - g_8 k_i^4 + g_9 k_i^2 - g_5 q_7\right\}}{r\left(1 - \xi^2 k_i^2\right)\left(g_6 k_i^2 - g_7\right)\left(k_i^2 - \alpha_1\right)}\lambda_i(s) I_1(k_i r)\right]\Bigg\}\Bigg\},$$

$$\overline{P}(r,s) = \sum_{i=1}^{4}\left\{\frac{\left(\alpha_7 k_i^8 - \alpha_8 k_i^6 + \alpha_9 k_i^4 - \alpha_{10} k_i^2 + \alpha_{11}\right)}{k_i^2\left(k_i^2 - \alpha_1\right)^2\left(g_6 k_i^2 - g_7\right)}\lambda_i(s) I_0(k_i r) - q_4\left(\frac{-1 + \sqrt{1 + 2q\lambda_i(s) I_0(k_i r)}}{q}\right)\right\}, \tag{44}$$

where, $\alpha_2 = 2 - g_6$, $\alpha_3 = g_9 + \varpi g_{10}$, $\alpha_4 = g_9 + \varepsilon_3 g_6 + g_{11}$, $\alpha_5 = g_5 g_7 + \varepsilon_3 g_7 + \varpi g_{12}$, $\alpha_6 = \Omega g_6 q_7$, $\alpha_7 = q_3(g_6 - 2)$, $\alpha_8 = q_3 g_{10} + g_8$, $\alpha_9 = g_{11} q_3 + \varpi g_9$, $\alpha_{10} = g_{12} q_3 + g_5 q_7$, $\alpha_{11} = \Omega g_5 q_3 q_7$.

Based on equation (28), the temperature in the Laplace transform domain may be expressed as follows:

$$\overline{T} = \frac{1}{q}\left[\sqrt{1 + 2q\overline{\Theta}} - 1\right]. \tag{45}$$

4. Boundary Conditions

To establish the unknown parameters λ_i, mechanical forces and thermal loads will be applied to the nonlocal semiconductor medium's free surface (where a is the radius of the circular plate), which is initially at rest. The nonmechanical loads are thus assumed to be traction-free at the cylinder's surface. Using Laplace transform on both sides and assuming thermal shock as the thermal load, we obtain [39, 40]:

(i) Nonmechanical loads are traction-free loads, which can be written as follows:

$$\overline{\sigma}_{rr}(a,s) = 0. \tag{46}$$

Hence,

$$\sum_{i=1}^{4}\left\{\frac{\left[\left(\alpha_2 k_i^8 - \alpha_3 k_i^6 + \alpha_4 k_i^4 - \alpha_5 k_i^2 + \alpha_6\right)\lambda_i(s) I_0(k_i a)\right]}{k_i^2\left(1-\xi^2 k_i^2\right)\left(k_i^2-\alpha_1\right)^2\left(g_6 k_i^2 - g_7\right)} - \left(\frac{-1+\sqrt{1+2q\lambda_i(s)I_0(k_i a)}}{q\left(1-\xi^2 k_i^2\right)}\right) + \frac{(\beta-1)\left\{k_i^6 - g_8 k_i^4 + g_9 k_i^2 - g_5 q_7\right\}}{r\left(1-\xi^2 k_i^2\right)\left(g_6 k_i^2 - g_7\right)\left(k_i^2-\alpha_1\right)}\lambda_i(s) I_1(k_i a)\Bigg]\Bigg\} = 0\right\} \tag{47}$$

(ii) The thermal state is considered a thermal shock when:

$$\overline{\Theta}(a,s) = T_0 \overline{L}(s). \tag{48}$$

Therefore,

$$\sum_{i=1}^{4} \lambda_i(s) I_0(k_i a) = \frac{T_0}{s}. \tag{49}$$

When the chemical potential is provided as a known function of time and the carriers' intensities can be obtained using a recombination process, the surface boundary conditions are determined.

(iii) This is how the chemical potential is written as follows:

$$\overline{P}(a,s) = P_0 \overline{\chi}(s), \tag{50}$$

which yields:

$$\sum_{i=1}^{4}\left\{\frac{\left(\alpha_7 k_i^8 - \alpha_8 k_i^6 + \alpha_9 k_i^4 - \alpha_{10} k_i^2 + \alpha_{11}\right)}{k_i^2\left(k_i^2-\alpha_1\right)^2\left(g_6 k_i^2 - g_7\right)}\lambda_i(s) I_0(k_i a) - q_4\left(\frac{-1+\sqrt{1+2q\lambda_i(s)I_0(k_i a)}}{q}\right)\right\} = \frac{P_0}{s}. \tag{51}$$

(iv) The recombination-restricted possibility of carrier-free charge density at the cylinder surface is expressed as follows:

$$\overline{N}(a,s) = \frac{\lambda\!\!\!^{-}}{D_e}\overline{\zeta}(s), \tag{52}$$

which leads to

$$\sum_{i=1}^{4}\frac{\lambda_i(s) I_0(k_i a)}{\left(k_i^2-\alpha_1\right)} = \frac{\lambda\!\!\!^{-}}{s\varepsilon_3 D_e}, \tag{53}$$

where ƛ is a constant. On the other hand, the quantities $L(t)$, $\zeta(s)$, and $\chi(t)$ represent the Heaviside unit step function [34, 35].

5. The Numerical Inversion of the Laplace Transforms

Using the inversion of the Laplace transform, a full solution in the time domain was found. Using the numerical inversion approach [39], the inverse of any function $\vartheta(t)$ in the Laplace domain may be expressed as follows:

$$\vartheta(r,t) = L^{-1}\left\{\overline{\vartheta}(r,s)\right\} = \frac{1}{2\pi i}\int_{n-i\infty}^{n+i\infty} \exp(st)\overline{\vartheta}(r,s)ds, \tag{54}$$

where $s = n + im$ $(n, m \in R)$, in this case, equation (55) can be represented as follows:

$$\vartheta(r,t) = \frac{\exp(nt)}{2\pi}\int_{-\infty}^{\infty} \exp(\mathrm{imt})\overline{\vartheta}(r, n+\mathrm{im})\mathrm{dm}. \tag{55}$$

Fourier series can be utilized to expand the function $e^{-\mathrm{nt}}\vartheta(r,t)$ during the closed interval $[0, 2t']$, yields

$$\vartheta(r,t) = \frac{e^{\mathrm{nt}}}{t}\left[-\frac{1}{2}\mathrm{Re}\,\overline{\vartheta}(r,n) + \mathrm{Re}\sum_{k=1}^{N}(-1)^n\overline{\vartheta}\left(r, n+\frac{\mathrm{ik}\pi}{t}\right)\right], \tag{56}$$

where $i = \sqrt{-1}$ and Re is the real part. N is a large finite integer that can be chosen for free.

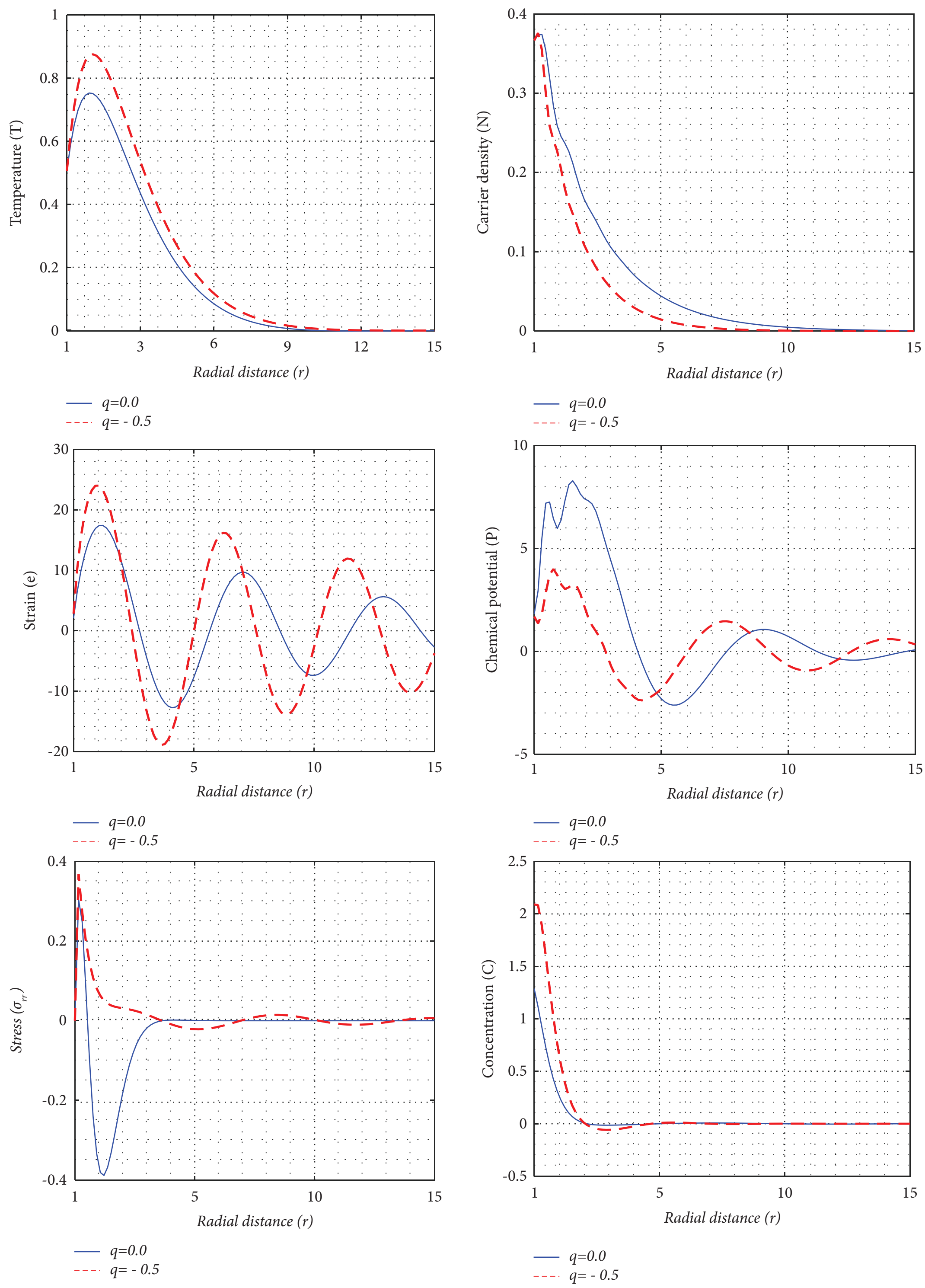

FIGURE 1: The variations of the main physical fields against the redial distance at different values variable thermal conductivity according to nonlocal semiconductor medium.

6. Numerical Results and Discussions

To show the impact of linearly varying thermal conductivity (which is dependent on the heat), simulations and theoretical discussions are conducted using silicon (n-type) as an elastic nonlocal semiconductor medium. Using the physical characteristics of isotropic nonlocal silicon medium, the variable thermal conductivity and diffusion relaxation time were investigated as a function of temperature [41–44]: $\lambda = 3.64\text{x}\,10^{10}\ \text{N/m}^2$, $\mu = 5.46 \times 10^{10}\ \text{N/m}^2$, $\rho = 2330\ \text{kg/m}^3$, $T_0 = 800\ \text{K}$, $a = 1$, $\tau_d = 5\text{x}\,10^{-5}\ \text{s}$, $d_n = -9\,\text{x}\,10^{-31}\ \text{m}^3$, $D_E = 2.5 \times 10^{-3}\ \text{m}^2/\text{s}$, $E_g = 1.11\ \text{eV}$, $\bar{\lambda} = 2\ \text{m/s}$,

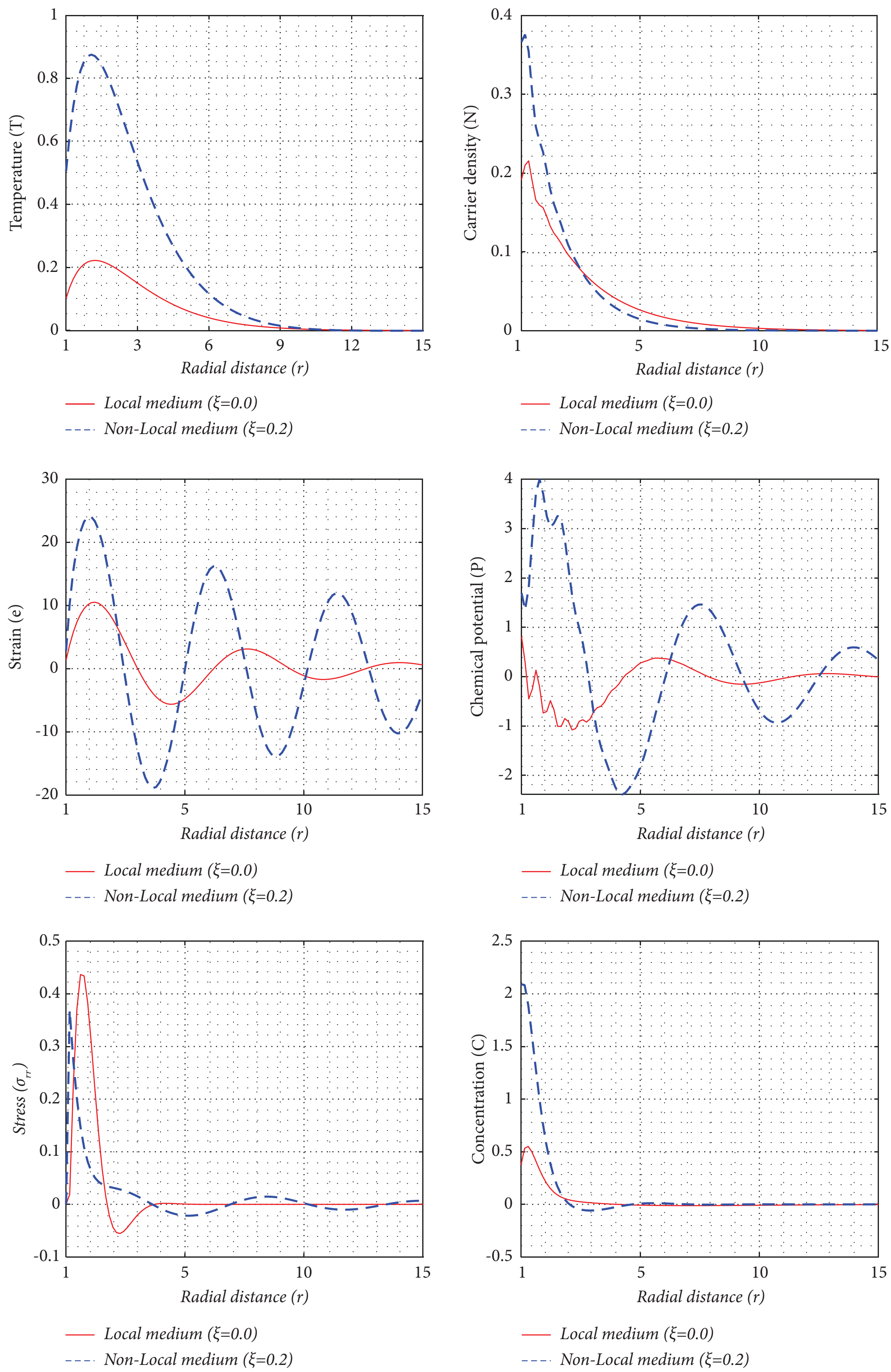

FIGURE 2: The variations of the main physical fields against the redial distance r at different values nonlocal parameters with variable thermal conductivity.

$\alpha_t = 4.14x\,10^{-6}\,K^{-1}$, $\alpha_c = 1.98x\,10^{-4}\,m^3/kg$, $c = 1.2x\,10^4$ m/Ks^2, $t = 7 \times 10^{-4}\,s$ $b = 0.9$, $C_e = 695\,J/(kg\,K)$, $D_c = 0.85 \times 10^{-8} kg\,s/m^3$.

The real part of the fundamental physical fields is taken into consideration when the wave propagation distributions are represented graphically.

Figure 1 (consisting of six subfigures) illustrates the change of physical quantities in this phenomenon versus radial distance for two cases of thermal conductivity that vary with distinct values. The first case represented by soiled lines refers to the issue of (heat) temperature independence $q = 0.0$. The second instance is depicted by dashed lines and represents the condition of temperature dependency $q = -0.5$. In response to the boundary conditions, the distributions of carrier density (plasma), strain (elastic), chemical potential, concentration (mass diffusion), and temperature (thermal) began with a positive value at the surface. But the distribution of redial stress begins at zero, indicating that traction is free at this surface $r = a = 1$. The first subfigure depicts the variation in temperature versus radius r for various nonlocal parameter values (two cases). It is evident from this subfigure that the temperature increases as the radius increases in the first range due to the thermal effect of light beams to reach the maximum value, and the exponential decreases until it agrees with the zero line. This subfigure indicates that the variable thermal conductivity influences the temperature change. The second subfigure shows the propagation of plasma waves with increasing radial distance for two different values of the variable thermal conductivity. It is clear that the carrier density distribution starts with a positive value increases slightly to reach the maximum value, and then decreases exponentially until it reaches equilibrium by diffusion within the nonlocal semiconductor material, following the zero line. From the first and second subfigures, it is clear that the theoretical numerical results obtained in this work are consistent with the experimental results [45]. The third and fourth subfigures were produced to study the nonlocal strain and chemical potential variation against the radius r for varying thermal conductivity. As shown in the fourth subfigure, the nonlocal chemical potential begins at a positive value at the boundary plane for all boundary-satisfying situations. However, the distribution of radial nonlocal stress (fifth subfigure) begins at zero, indicating that traction is free near the surface, and then begins to rise to its maximum value before decreasing quickly and convergently to zero as the distance increases to reach the equilibrium state. The concentration distribution begins with a positive value at the beginning and then drops gradually with exponential behavior to reach the zero-state line. A slight variation in linearly variable thermal conductivity has a significant effect on the wave propagation behavior, as shown by these subfigures.

Figure 2 depicts the variation of the principal variables (distributions of the carrier density (plasma waves), the concentration (diffusion), the strain (elastic waves), the temperature (thermal waves), and the radial stress (mechanical waves)) as a function of radial distance r for varying nonlocal parameter values. We observe that the distributions of the main physical quantities seem to exhibit the same pattern for various nonlocal parameters. With increasing values, the movements of elastic-thermal-plasma-mechanical waves are dampened to achieve chemical equilibrium. These subfigures illustrate that the nonlocal parameter has a significant effect on each of the investigated distributions.

7. Conclusion

The effects of changing thermal conductivity and nonlocal parameters on the photothermal excitation process and the chemical activity of elastic semiconductor materials have been investigated. The model was constructed in one dimension using the Laplace transform according to cylindrical coordinates. Graphs show the influence of variable thermal conductivity and nonlocal parameters. The numerical findings indicate that the change in thermal conductivity has a significant impact on the thermal-elastic-mechanical-plasma behavior of nonlocal semiconductor medium during photo-electronic deformations. A small change in the nonlocal parameter has a great influence and leads to differences in thermal-elastic-mechanical-plasma wave propagation in the elastic medium. Thus, the nonlocal parameter's ability to conduct and transfer thermal energy may serve as an additional identifier. Various uses of the variable thermal conductivity of nonlocal semiconductor elastic media in current physics via photo-elastic-thermal-diffusion excitation processes are applied in many industries. In particular, mass and heat transfer mechanisms are important in photovoltaic cells, display technologies, optoelectronic applications, and photoconductor devices.

Nomenclature

λ, μ:	Lame's parameters
N_0:	Equilibrium carrier concentration
δ_n:	The difference in deformation potential
$\theta = T - T_0$:	Thermodynamical temperature
T:	Absolute temperature
T_0:	Reference temperature and $\lvert (T - T_0)/T_0 \rvert < 1$
$\beta_1 = (3\lambda + 2\mu)\alpha_T$:	The volume thermal expansion
σ_{ij}:	Components of the stress tensor
ρ:	The density of the medium
α_T:	The coefficient of linear thermal expansion
e:	Cubical dilatation
τ_d:	The diffusion relaxation time
C_e:	Specific heat at a constant strain of the solid plate
$\rho C_e/K_0 = 1/k$:	The thermal viscosity
D_E:	The carrier diffusion coefficient
τ:	The photogenerated carrier lifetime
E_g:	The energy gap of the semiconductor
$\kappa = \partial N_0/\partial T T/\tau$:	The thermal activation coupling parameter
c:	Measure the effect of thermoelastic diffusion

D_c: The diffusion coefficient
d_n: The coefficient of electronic deformation.

Data Availability

The data used in this study are available upon reasonable request to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Kh. Lotfy conceptualized the data, contributed to methodology and Software, and curated the data. S. El-Sapa contributed to the writing the original draft. M. Ahmed performed supervision, visualization, investigation, software, and validation. A. El-Bary performed writing, reviewing, and editing.

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