# Photo-thermal interactions in a semi-conductor material with cylindrical cavities and variable thermal conductivity

Ibrahim Abbas, Aatef Hobiny and Marin Marin

**ABSTRACT**

This study investigates the photo-thermo-elastic interaction in an infinite semi-conductor material with cylindrical cavities. The effect of variable thermal conductivity through the photo-thermo-elastic transport process is studied using the coupled models of thermo-elasticity and plasma waves. The internal surface of the cylindrical cavity is loaded by a thermal shock varying heat. The eigenvalue method, under Laplace transforms scheme, is used to get the analytical solution of the studied field distribution as parts of this phenomenon. A detailed analysis of the impacts of the variable thermal conductivity on the physical fields is debated. The numerical outcomes of the studied fields are displayed graphically. According to them, the variable thermal conductivity offers finite speed of the mechanical wave and the thermal wave propagations.

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Eigenvalue approaches; cylindrical cavity; variable thermal conductivity; Laplace transforms; semiconductor medium

## 1. Introduction

The theory of bodies explained the properties of the internal structures of mediums when the second law of thermodynamics was used. In this theory the internal structures of medium depend on the micro-elements that possess micro-temperatures and the gradient of temperature. The balance laws of continuum mediums are used for the first moment (heating flux) of the heating energy equation with microstructures when subjoined to the basic equations. The heating energy conduction in thermo-elastic media is studied during the internal structures. To recognize the inner structural property of elastic mediums, essentially in semiconductor mediums, the electrical property of these mediums should be deliberated taking into account their thermo-mechanical properties. Pure silicon is a semi-conductor that is used enormously in the manufacture of semi-conductors, for example, mono-crystal lines Si are used to make silicon wafers. Todorovic [1,2] studied the thermo-elastic and plasma wave in a semi-conductor medium.

The thermo-elastic (TE) machining of the generation of elastic wave is explained by the propagations of elastic hesitations toward the surfaces of the material subjected to the heating waves in that material.
conductor mediums were only investigated as elastic mediums without taking into consideration the effect of light beam on them. But semiconductor mediums are considered nanomaterial in modern technology that has more use in photovoltaic solar cell industries. Semiconductor mediums have many applications in modern technology; therefore, they are more important in scientific studies. Most of these studies are concerned with the study of renewable energy. Semiconductors are a model for using renewable energy when exposed to sunlight. Most previous studies did not take into consideration the dependence of thermal conductivity on temperature and the inner structure of these mediums when exposed to an external strong magnetic field and excited by beams of laser. The variable thermal conductivity is very difficult in comprehending the analysis of thermal loads of certain materials, essentially semi-conductor devices, as it depends on the temperature. Hobiny and Abbas [3] analysed the photo-thermal interaction in a two-dimensional semiconductor plane under G-N models. Lotfy et al. [4] used the fractional-order magneto-photothermal model to investigate the thermoelasticity model of optically excited semiconductor mediums without energy dissipation. Shah and Tongxing [37] investigated the thermal and laminar boundary layer flows over prolate and oblate spheroids. Singh et al. [38] studied the impacts of mechanical and thermal loadings on edge cracks of finite length in an unbounded orthotropic strip. Marin et al. [39] presented the solution of generalization of the Saint-Venant’s principle for an elastic medium with dipolar structures.

The aim of this work is to investigate the effect of the variability of thermal conductivity in semi-conductor media with cylindrical cavity using the eigenvalue methods. By using the eigenvalue methods and Laplace transform based on analytical-numerical techniques, the basic equations are handled. For all physical quantities, the numerical outcomes are obtained and theoretically discussed and represented graphically.

2. Mathematical model

The governing equations, under photothermoelastic model for isotropic semi-conducting materials, in the absence of body force heat source can be expressed by

\[
\begin{align*}
\mu u_{ij} + (\lambda + \mu) u_{jj} - \gamma N_j - \gamma T_j - \rho \frac{\partial^2 u_i}{\partial t^2} &= 0.0. \\
D_k u_{ij} - \frac{N}{\tau} + \frac{k}{\tau} u_{ij} - \frac{\partial N}{\partial t} &= 0.0, \\
(\mathbf{K}_T)_{ij} + \frac{E}{\tau} N_{ij} - \rho c_e \frac{\partial T}{\partial t} - \gamma T_j \frac{\partial u_{ij}}{\partial t} &= 0.0. \\
\sigma_{ij} = (\lambda u_{kk} - \gamma N - \gamma T) \delta_{ij} + \mu (u_{ij} + u_{ji}),
\end{align*}
\]

Considering that the thermal conductive has a linear form as in [43]

\[
K(T) = K_o (1 + K_1 T),
\]

The following mapping [43] is used

\[
\phi = \frac{1}{K_o} \int_0^T K(T) dT,
\]

where the new function \(\phi\) expresses the thermal condudction. Substituting from (5) in (6) and integrating the resulting equation, the following can be obtained [43]

\[
\phi = T + \frac{1}{2} K_1 T^2.
\]

From Equations (6) and (7), we can obtain the following relations

\[
\begin{align*}
K_o \phi_i &= K(T) T_i, \\
K_o \phi_{ii} &= (K(T) T_j)_i, \\
K_o \frac{\partial \phi}{\partial t} &= K(T) \frac{\partial T}{\partial t}.
\end{align*}
\]
Thus, the above Equations (1), (2), (3) and (4) can be rewritten in the following form:

\[ \mu u_{ij} + (\lambda + \mu)u_{ij} - \gamma_N N_j - \gamma_T \phi_j = \rho \frac{\partial^2 u_i}{\partial t^2}, \]  
\[ D_e N_{ij} - \frac{N}{\tau} + \frac{k}{\tau} \phi = \frac{\partial N_i}{\partial t}, \]  
\[ K_0 \phi_{ij} + \frac{E_s N}{\tau} = \rho c_e \frac{\partial \phi}{\partial t} + \gamma_T \frac{\partial u_{ij}}{\partial t}. \]  
\[ \sigma_{ij} = \mu (u_{ij} + u_{ji}) + \left( \lambda u_{kk} - \gamma_N N - \frac{\gamma_f}{K_1} \left( -1 + \sqrt{1 + 2K_1 \phi} \right) \right) \delta_{ij}, \]  
\[ \left( \lambda + 2\mu \right) \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} \right) - \gamma_N \frac{\partial u}{\partial r} - \gamma_T \phi = \frac{\partial^2 u}{\partial t^2}, \]  
\[ \frac{\partial^2 N}{\partial r^2} + \frac{1}{r} \frac{\partial N}{\partial r} = \frac{\partial N}{\partial t}, \]  
\[ K_0 \left( \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} \right) + \frac{E_s N}{\tau} = \rho c_e \frac{\partial \phi}{\partial t} + \gamma_T \frac{\partial u}{\partial t} - \frac{\gamma_f}{K_1} \left( -1 + \sqrt{1 + 2K_1 \phi} \right), \]  
\[ \sigma_{\theta r} = \frac{\lambda u}{r} + (\lambda + 2\mu) \frac{\partial u}{\partial r} - \gamma_N N + \left( \lambda + 2\mu \right) \frac{u}{r} - \gamma_N N + \frac{\gamma_f}{K_1} \left( -1 + \sqrt{1 + 2K_1 \phi} \right), \]  
\[ \sigma_{\theta \theta} = \frac{\lambda u}{r} + (\lambda + 2\mu) \frac{u}{r} + \gamma_N N + \frac{\gamma_f}{K_1} \left( -1 + \sqrt{1 + 2K_1 \phi} \right). \]

3. Application

The homogeneous initial conditions are supposed, while the boundary conditions are expressed as follows:

\[ u(b, t) = 0, \]  
\[ T(b, t) = T_1 H(t). \]

From Equations (7) and (21), the thermal shock boundary condition can be given by

\[ \phi(b, t) = T_1 H(t) + \frac{1}{2} K_1 (T_1 H(t))^2. \]  

The carrier density boundary condition in the internal surface of the hole is written as

\[ D_e \left. \frac{\partial N(r, t)}{\partial r} \right|_{r=b} = s_b N(b, t). \]  

Now, for suitability, the non-dimensional parameters are defined as

\[ N^* = \frac{N}{n_0}, \phi^* = \frac{\phi}{T_0}, K_1^* = T_o K_1, (\sigma_{n}, \sigma_{\theta \theta}) = \frac{(\sigma_n, \sigma_{\theta \theta})}{\lambda + 2\mu}, \]  
\[ (r^*, \tau^*) = \frac{r_c (r, u)}{\eta c (t, \tau)}, \]  
\[ c^2 = (\lambda + 2\mu)/\rho \]  
\[ \eta = ((\rho c_e)/K). \]

In these forms of the physical quantities in Equation (24), the governing equations can be presented as (for suitability, the stars have been ignored)

\[ \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} - f_1 \frac{\partial N}{\partial t} - f_2 \frac{\partial \phi}{\partial t} = \frac{\partial^2 u}{\partial t^2}, \]  
\[ \frac{\partial^2 N}{\partial r^2} + \frac{1}{r} \frac{\partial N}{\partial r} = f_3 \frac{\partial N}{\partial t} + f_4 N - f_5 \phi, \]  
\[ \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} = f_6 \frac{\partial \phi}{\partial t} + f_6 \frac{\partial u}{\partial t} + \frac{u}{r}, \]  
\[ \sigma_{n} = \frac{\partial u}{\partial r} + f_7 - f_1 N - f_2 \left( -1 + \sqrt{1 + 2K_1 \phi} \right), \]  
\[ \sigma_{\theta \theta} = f_7 \frac{\partial u}{\partial r} + \frac{u}{r} - f_1 N - f_2 \left( -1 + \sqrt{1 + 2K_1 \phi} \right), \]  
\[ u(b, t) = 0, \frac{\partial N(r, t)}{\partial r} \bigg|_{r=b} = f_8 N(b, t), \]  
\[ \phi(b, t) = T_1 H(t) + \frac{1}{2} K_1 (T_1 H(t))^2, \]

where

\[ f_1 = \frac{n_0 \gamma_n}{\lambda + 2\mu}, f_2 = \frac{T_0 \gamma_T}{K_1 (\lambda + 2\mu)}, f_3 = \frac{1}{\eta D_e}, \]  
\[ f_4 = \frac{k T_0}{n_0 \eta D_e}, f_5 = \frac{n_0 \gamma_n}{\rho c_e T_0}, \]  
\[ f_6 = \frac{\gamma_T}{\rho c_e}, f_8 = \frac{S_a}{\eta c D_e}. \]

For \( f(r, t) \) function Laplace transform is defined by

\[ \tilde{f}(r, p) = \mathcal{L}[f(r, t)] = \int_0^\infty f(r, t) e^{-pt} dt, p > 0, \]

where \( p \) is the Laplace transform parameter; therefore, the governing equations are written in the following
form
\[
\begin{align*}
d^2 \ddot{u} + \frac{1}{r} \frac{d u}{dr} - \ddot{u} - f_1 \frac{d N}{dr} - f_2 \frac{d \phi}{dr} &= \rho^2 \ddot{u}, & (32) \\
d^2 \ddot{N} + \frac{1}{r} \frac{d N}{dr} - \ddot{N} - f_3 \frac{d N}{r} &= \rho^2 \ddot{N}, & (33) \\
d^2 \ddot{\phi} + \frac{1}{r} \frac{d \phi}{dr} - \ddot{\phi} - p \phi &= \rho^2 \ddot{\phi}, & (34) \\
\end{align*}
\]
where \( r \) refers to the radius.

By using Equation (32), differentiating Equations (33) and (34) with respect to \( r \), one can obtain
\[
\begin{align*}
d^2 \ddot{u} + \frac{1}{r} \frac{d u}{dr} - \ddot{u} &= a_1 \ddot{u} + a_2 \frac{d N}{dr} + a_3 \frac{d \phi}{dr}, & (38) \\
d^2 \ddot{N} + \frac{1}{r} \frac{d N}{dr} - \ddot{N} &= b_1 \ddot{N} + b_2 \frac{d N}{dr} + b_3 \frac{d \phi}{dr}, & (39) \\
\end{align*}
\]
where \( a_1 = p^2, a_2 = f_1, a_3 = f_2, b_1 = 0, b_2 = f_3 (p + (1/\tau), b_3 = (-f_4/\tau), c_1 = pf_6 a_1, c_2 = pf_6 a_2 - (f_5/\tau), c_3 = p(1 + f_6 a_3). \)

The matrix eigenvalues of \( M \) are the three roots \( \omega_1, \omega_2, \omega_3 \). Thus, the eigenvector \( Y \) is calculated by
\[
Y = \begin{pmatrix}
(\omega_1 + b_2 a_3 - b_3 a_2) \\
(\omega_2 - \omega_1) + b_2 a_3 + b_1 a_2 - \omega^2
\end{pmatrix}.
\]

The analytical solution of Equation (41), which are bounded as \( r \rightarrow \infty \), is expressed as
\[
V(r, p) = \sum_{i=1}^{3} R_i Y_i K_n(n r),
\]
where \( n_i = \sqrt{\omega_i}, R_1, R_2 \) and \( R_3 \) are constants calculated by the present problem boundary conditions and \( K_n \) is the order \( n \)-modified Bessel's function; therefore, the solutions of the studying field depending on \( r \) and \( p \) are presented in the following forms:
\[
\begin{align*}
\ddot{u}(r, t) &= a_1 \ddot{u} + a_2 \frac{d N}{dr} + a_3 \frac{d \phi}{dr}, & (42) \\
\ddot{N}(r, t) &= b_1 \ddot{N} + b_2 \frac{d N}{dr} + b_3 \frac{d \phi}{dr}, & (43) \\
\ddot{\phi}(r, t) &= c_1 \ddot{\phi} + c_2 \frac{d N}{dr} + c_3 \frac{d \phi}{dr}, & (44)
\end{align*}
\]
where \( a_1 = p^2, a_2 = f_1, a_3 = f_2, b_1 = 0, b_2 = f_3 (p + (1/\tau), b_3 = (-f_4/\tau), c_1 = pf_6 a_1, c_2 = pf_6 a_2 - (f_5/\tau), c_3 = p(1 + f_6 a_3). \)

Now, to obtain the exact solutions of Equations (38), (39) and (40) by the eigenvalue scheme proposed at refs [4, 6, 14, 46]. From Equations (38)–(40), the matrix–vectors are written as follows.
\[
LV = MV,
\]
where
\[
L = \frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} - \frac{1}{r^2}, \quad V = \begin{bmatrix} \ddot{u} & \ddot{N} & \ddot{\phi} \end{bmatrix}^T
\]
and
\[
M = \begin{bmatrix} a_1 & a_2 & a_3 \\
1 & b_1 & b_2 \\
\omega_3 & \omega_3 & \omega_3
\end{bmatrix}.
\]

The characteristics relation of matrix \( M \) is expressed as
\[
\begin{align*}
\omega^3 - \omega^2 (b_2 + c_3 + a_1) + \omega (b_2 c_3 - b_3 c_2) \\
+ b_2 a_1 + c_3 a_1 - b_1 a_2 - c_1 a_3) + b_2 c_2 a_1 - b_2 c_3 a_1 \\
- b_3 c_1 a_2 + b_1 c_2 a_2 + b_2 c_1 a_3 - b_1 c_2 a_3 &= 0.
\end{align*}
\]

4. Numerical results

For illustrating the theoretical results and numerical discussions we take a model for the calculation purpose like the silicon(Si) material with the physical parameters
by [48]

\[ E_g = 1.11 (eV), \rho = 2330 (kg/m^3), \]
\[ c_e = 695 (J/kg^{-1})(k^{-1}), \alpha_t = 3 \times 10^{-6} (k^{-1}), \]
\[ d_n = -9 \times 10^{-31} (m^3), \lambda = 3.640 \times 10^{10} (N/m^2), \]
\[ \mu = 5.46 \times 10^{10} (N/m^2), T_o = 300 (k), \]
\[ s_o = 2 (m/s^{-1}), n_o = 10^{20} (m^{-3}), \tau = 5 \times 10^{-5} (s), \]
\[ D_e = 2.5 \times 10^{-3} (m^2/s^{-1}), T_1 = 1. \]

The calculations are carried out for the time \( t = 0.3 \).

Based on the above list of constants, the calculated physical quantities (numeral), along the radial distance \( r \) with the coupled theory of thermoelasticity and plasma waves, are represented in Figures 1–5. The variation of radial displacement, the variation of carrier density, the variation of temperature, the radial stress and hoop stress distributions versus the radial distance \( r \) under the photo-thermoelastic model are numerically computed. Figure 1 exhibits the variation of temperature along \( r \). It is cleared that the temperature has maximum values \( (T_1 = 1) \) which accept the boundary condition of the problem when \( r = 1 \) consequently it progressively reduces with the rising of distance until it reaches to zero. Figure 2 shows the variations of carrier density versus \( r \). It is noticed that it begins with its ultimate values at the boundary \( r = 1 \) after that the carrier

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**Figure 1.** The variation of temperature versus the radial distance with several values of \( K_1 \).  

**Figure 2.** The variation of carrier density versus the radial distance with several values of \( K_1 \).
density gradually reduces with the rise of redial distance $r$ until it reaches to zero. Figure 3 shows the variation of radial displacement with respect to the radial distance $r$. It is noticed that the radial displacement begins from zeros which satisfy the problem boundary condition when $r = 1$ attains, then it reduces progressively up to peak values, then decreases to close to zero. Figure 4 shows the variations of redial stress with respect to $r$. It is noticed that the radial stress attains maximum negative values, then it increases progressively to close to zero. The variations of hoop stress versus $r$ are exhibited in Figure 5. It is observed that it attains maximum negative values, then constantly rises to zero.

Finally, in the comparison between the numerical results, it can be accomplished that the consideration of coupled photothermoelastic model with variable thermal conductivity is an important phenomenon and has a great effect on the physical quantity distribution.

5. Conclusions
Based on this coupled photo-thermal theory with variable thermal conductivity, the components of stress distributions, the variation of radial displacement, the variations of temperature and the variation of carrier density in semi-conducting mediums are presented. In comparing between the numerical results, it can be concluded that the consideration of coupled photothermoelastic theory with variable thermal conductivity is a significant phenomenon and has a great effect on field quantity distribution.
Figure 5. The variations of hoop stress versus the radial distance with several values of $K_1$.

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