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ORIGINAL PAPER

Analytical Solutions of Plasma and Thermoelastic Waves Photogenerated by a Focused Laser Beam in a Semiconductor Material

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Abstract

In the present work, the coupled plasma theory (thermally and elasticity waves) was used to study the wave propagation of semiconducting sample through photothermal process. The coupled of the plasma, thermally, and elastic waves that photo-generated through intensity modulated laser beam and tightly focused has been considered to study an elastic homogeneous semiconducting medium with isotropic thermo-elastic properties. Laplace transformations were used to investigate analytically solutions in the transformed domain based on the approach of eigenvalue. Numerically calculations were carried out for silicon semiconductor sample. The results were graphical observed to show the influence the coupled wave of plasma, thermal, and elastic.

Keywords Photothermal theory · Plasma waves · Eigenvalue approach · Laser beam · Laplace transformation

1 Introduction

At start, considering qualitatively what is the effect of the falling beam of laser on a semiconductor has energy of the band gap (E_g)? An electron may be transferred from the valency band to a state of energy ($E - E_g$, whereas E is the energy of incident photon) higher than the edge of the conduction band only if $E > E_g$. The photoexcited free carriers will relaxes to one of the empty levels nearby the conductance band bottom during the nonradiative transitions. After that, a process of recombination will occur during the formation of the pairs of electron-hole. There is plasma of electron-hole prior to the recombination process. The plasma density was governed by the diffusion behavior that like thermally source heating inflow. Thus, if the incident laser ferocity as well as the thermal wave was altered one may be expecting to show a altered density of plasma which specify outline is that of a threshold demoralized wave, i.e., a wave of plasma. In semiconductors an electronic distortion (ED) which is periodic elastic distortion in the material produced by the photoexcited carriers that can cause locally strain in the material which may produce plasma waves. These waves behave as well as the thermal wave generated by local periodic elastic deformation.

Recently, the photoacoustic (PA) and photothermal (PT) methods were taken as diagnostic tools with high sensitivity to the electronic transport and thermal processes in microelectronic structures. Semiconducting material may be has crystalline or non-crystalline nature with largely resistance which decreases with the increase of temperature otherwise that was investigated of the metal. The electricity conduction of semiconducting material may be enhanced through doping which decreases its resistance and assist to design of semiconducting junctions between various doping crystal regions. The charge carriers manner at

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these junctions is the main of diode, solar cell, transistor, semiconducting detector as well as all recently electronic devices. Besides, perspicuous Si (intrinsic semiconductor) is used in large area of semiconductor manufacturing viz. the wafers of Si were created using mono-crystalline Si. Unlike metals the conduction in pure Si through electrons-holes and electrons that may be released from atoms within the crystal by heat, and thus decrease silicon's electrical resistivity with higher temperatures.

Previously, Todorovic et al. [1–3] introduced a theoretical and experimental study of the micro-mechanical structure of the plasma, thermally and elastic fields in only one porporation (1D). In this study, theoretical analyses to investigate the two phenomena which gives information about the properties of carrier recombination and transport in semiconductor. The changes in the propagation of plasma and thermally waves because of the linear coupling between heat and mass transport (i.e., thermos diffusion) were included. The influences of various thermoelastic and electronically distortion in semiconducting material without considering the coupled system of plasma, thermally, and elastic relations have been detailed in the literature [4–6]. Also, Rosencwaig et al. [7] suggested an analyses on the local thermos-elastic distortion occurred at the surface of the sample because of the excitation through a focused probe beam. Based on the results shown in ref. [7] Opsal and Rosencwaig [8] published their study of semiconducting material. On the other hand, the generalized thermos-elastic vibrations of the optical agitated semiconductor microcantilevers were detailed here [9, 10]. They illustrated the plane waves reflectance in a semiconducting medium beneath photo-thermal and generalization of the thermos-elastic theories [11, 12].

In the present work, we attempt to study the analytical solutions of plasma and thermoelastic waves photogenerated by a focused laser beam in a semiconductor material. Depending on Laplace transform and eigenvalues approach, the non-dimensional equations are handled by employing an analytical–numerical method. The physical interpretations are given seriatim corresponding to the distributions of the considered physical parameters observed in the present study.

2 Formulation of the Problem

Generally, theoretically analyses of the transport process in a semiconductor with considering of simultaneously coupling of the waves of plasma, thermally and elastic. The main parameters are the carrier density $n(\boldsymbol{r}, t)$, distribution of temperature $T^*(\boldsymbol{r}, t)$ and elastic displacement components $u_i(\boldsymbol{r}, t)$. In the case of falling an ultrafast laser $Q(\boldsymbol{r}, t)$ onto isotropic elastic homogeneous semiconductor. The controlling relations in the context of the photothermal theory are [12, 13] respectively the motion, plasma and heat conduction relations:

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \mu u_{i,jj} + (\lambda + \mu)\, u_{j,ij} - \gamma_n N_{,i} - \gamma_t T_{,i}. \tag{1}$$

$$\frac{\partial N}{\partial t} = D_e N_{,jj} - \frac{N}{\tau} + kT + Q(\boldsymbol{r}, t). \tag{2}$$

$$\rho c_e \frac{\partial T}{\partial t} = K T_{,jj} + \frac{E_g}{\tau} N - \gamma_t T_o \frac{\partial u_{j,j}}{\partial t} + \delta_E Q(\boldsymbol{r}, t). \tag{3}$$

The constituent relationships are written as

$$\sigma_{ij} = \mu\left(u_{i,j} + u_{j,i}\right) + \left(\lambda u_{k,k} - \gamma_n N - \gamma_t T\right)\delta_{ij}, \tag{4}$$

where $i, j, k = 1, 2, 3$, $N = n - n_o$, n_o is the equilibrium carrier concentration, $T = T^* - T_o$, T_o is the reference temperature, λ, μ are the Lame's constants, ρ is the density of medium, u_i and σ_{ij} are the displacement stress components respectively, $\gamma_n = (3\lambda + 2\mu)\, d_n$, d_n is the electronic distortion parameter, $\gamma_t = (3\lambda + 2\mu)\, \alpha_t$, α_t is the parameter of linear thermal expansion, K is the thermally conductance, c_e is the specific heat at steady strain, D_e is the coefficient of carrier diffusion, τ is the lifetime of photogenerated carriers $\delta_E = E - E_g$, E is the excitation energy, E_g is the semiconductor energy gap, $Q(\boldsymbol{r}, t) = \alpha \Phi(\boldsymbol{r})\, f(t)$, α is the coefficient of the optical absorption, $\Phi(\boldsymbol{r})$ is the influence of the falling laser, $f(t)$ is the function of temporal modulation for ferocity of laser beam, $\boldsymbol{r}$ is the position vector, t is the time and $k = \frac{\partial n_o}{\partial T} \frac{1}{\tau}$ [13]. Let us consider the case that of semiconductor half-space $z \geq 0$ and the state of the medium based only on z and the time parameter t. Therefore, Eqs. 1–4 can be rewritten as:

$$\rho \frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu) \frac{\partial^2 u}{\partial z^2} - \gamma_n \frac{\partial N}{\partial z} - \gamma_t \frac{\partial T}{\partial z}, \tag{5}$$

$$\frac{\partial N}{\partial t} = D_e \frac{\partial^2 N}{\partial z^2} - \frac{N}{\tau} + kT + Q, \tag{6}$$

$$\rho c_e \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2} + \frac{E_g}{\tau} N - \gamma_t T_o \frac{\partial^2 u}{\partial t \partial z} + \delta_E Q. \tag{7}$$

$$\sigma_{zz} = (\lambda + 2\mu) \frac{\partial u}{\partial z} - \gamma_n N - \gamma_t T, \tag{8}$$

3 Initial and Boundary Conditions

Initially the boundary conditions must be taken in consideration before solving the problem. The problem initially conditions are supposed to be homogeneous and are supplemented by considering the boundary $z = 0$ is neighporing to space. It is dragign free so that the boundary condition take the form of:

$$\sigma_{zz} = 0, \tag{9}$$

Through the processes (transport and recombination) of the photogenerated carrier and surface recombination source which due to the carriers recombination at the surface $z = 0$. So the carriers density and heat flux boundary conditions can be written as

$$D_e \frac{\partial N}{\partial z} = s_o N \quad \text{on} \quad z = 0, \tag{10}$$

$$-K \frac{\partial T}{\partial z} = E_g s_o N \quad \text{on} \quad z = 0, \tag{11}$$

where s_o is the surface recombination velocity. It is suitable to rewrite the above relations in the dimensionless formula. Therefore, the dimensionless parameters were shown as:

$$\left(z', u'\right) = \varsigma c\,(z, u)\,, T' = \frac{T}{T_o}, N' = \frac{N}{n_o}, \sigma'_{zz} = \frac{\sigma_{zz}}{\lambda + 2\mu},$$
$$\left(t', \tau'\right) = \varsigma c^2\,(t, \tau)\,, Q' = \frac{Q}{n_o \varsigma^2 c^2 D_e}, \tag{12}$$

where $c^2 = \frac{\lambda+2\mu}{\rho}$, $\varsigma = \frac{\rho c_e}{K}$.

Canceling the primes and rewrite Eqs. 5–11, we observe:

$$\frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial z^2} - a_1 \frac{\partial N}{\partial z} - a_2 \frac{\partial T}{\partial z}, \tag{13}$$

$$a_3 \frac{\partial N}{\partial t} = \frac{\partial^2 N}{\partial z^2} - a_4 N + \beta T + Q, \tag{14}$$

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + a_5 N - a_6 \frac{\partial^2 u}{\partial t \partial z} + a_7 Q. \tag{15}$$

$$\sigma_{zz} = \frac{\partial u}{\partial z} - a_1 N - a_2 T, \tag{16}$$

$$\sigma_{zz} = 0, \frac{\partial N}{\partial z} - s_1 N = 0, \frac{\partial T}{\partial z} + s_2 N = 0 \quad \text{on} \quad z = 0, \tag{17}$$

where $a_1 = \frac{n_o \gamma_n}{\lambda+2\mu}$, $a_2 = \frac{T_o \gamma_t}{\lambda+2\mu}$, $a_3 = \frac{1}{\varsigma D_e}$, $a_4 = \frac{1}{\tau \varsigma D_e}$, $\beta = \frac{k T_o}{n_o \varsigma^2 c^2 D_e}$, $a_5 = \frac{n_o E_g}{\rho c_e T_o \tau}$, $a_6 = \frac{\gamma_t}{\rho c_e}$, $a_7 = \frac{\delta_E n_o D_e}{K T_o}$, $s_1 = \frac{1}{\varsigma c D_e}$ and $s_2 = \frac{E_g n_o}{\varsigma c K T_o}$.

4 Solution in the Laplace Transformation Tract

For $G\,(z, t)$ function Laplace transform was written as

$$\overline{G}\,(z, s) = L\,[G\,(z, t)] = \int_0^\infty G\,(z, t)\, e^{-st} dt, s > 0 \tag{18}$$

where s is the Laplace transfer parameter. So, the above relations will be rewritten as:

$$s^2 \overline{u} = \frac{d^2 \overline{u}}{dz^2} - a_1 \frac{d\overline{N}}{dz} - a_2 \frac{d\overline{T}}{dz}, \tag{19}$$

$$a_3 s \overline{N} = \frac{d^2 \overline{N}}{dz^2} - a_4 \overline{N} + \beta \overline{T} + \overline{Q}, \tag{20}$$

$$s \overline{T} = \frac{d^2 \overline{T}}{dz^2} + a_5 \overline{N} - a_6 s \frac{d\overline{u}}{dz} + a_7 \overline{Q}. \tag{21}$$

$$\overline{\sigma}_{zz} = \frac{d\overline{u}}{dz} - a_1 \overline{N} - a_2 \overline{T}, \tag{22}$$

$$\overline{\sigma}_{zz} = 0, \frac{d\overline{N}}{dz} - s_1 \overline{N} = 0, \frac{d\overline{T}}{dz} + s_2 \overline{N} = 0 \quad \text{on} \quad z = 0. \tag{23}$$

Assuming that the temporory profile of the laser pulse is non-Gaussian that can be written as:

$$f\,(t) = \frac{I_o t}{t_p^2} e^{-\frac{t}{t_p}}. \tag{24}$$

According to Song et al. [14], the laser source $Q(z, t)$ can be expressed as

$$Q\,(z, t) = \frac{I_o \alpha\,(1 - R)}{2E} \frac{t}{t_p^2} e^{-\alpha z - \frac{t}{t_p}}, \tag{25}$$

where I_o is the energy absorbed, R is the reflectance of the material surface, t_p is the pulse rise time. Hence

$$\overline{Q}\,(z, s) = \frac{I_o \alpha\,(1 - R)}{2E\left(s t_p + 1\right)^2} e^{-\alpha z}. \tag{26}$$

Let us now proceed to solving the nonhomogeneous coupled differentially relations (19), (20) and (21) using the approach of eigenvalue [15–19]. Equations 19–21 can be written in a vectoral matrix differential equations in the form of:

$$\frac{dV}{dz} = AV - f e^{-\alpha z}, \tag{27}$$

where $V = \left[\overline{u}\ \overline{N}\ \overline{T}\ \frac{d\overline{u}}{dz}\ \frac{d\overline{N}}{dz}\ \frac{d\overline{T}}{dz}\right]^T$, $f = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ a_8 \\ a_9 \end{bmatrix}$ and

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ a_{41} & 0 & 0 & 0 & a_{45} & a_{46} \\ 0 & a_{52} & a_{53} & 0 & 0 & 0 \\ 0 & a_{62} & a_{63} & a_{64} & 0 & 0 \end{bmatrix}, \text{ with } a_9 = \frac{I_o \alpha (1-R)}{2E(s t_p+1)^2},$$

$a_9 = a_7 a_8$, $a_{41} = s^2$, $a_{45} = a_1$, $a_{46} = a_2$, $a_{52} = s a_3 + a_4$, $a_{53} = -\beta$, $a_{62} = -a_6$, $a_{63} = s$, $a_{64} = a_6$

Then, the matrix A distinctive relationship has the following form

$$\xi^6 - M_1 \xi^4 + M_2 \xi^2 + M_3 = 0, \tag{28}$$

where

$$M_1 = a_{41} + a_{52} + a_{63} + a_{46}a_{64},$$
$$M_2 = a_{41}a_{52} - a_{53}a_{62} + a_{41}a_{63} + a_{52}a_{63} + a_{46}a_{52}a_{64} - a_{45}a_{53}a_{64},$$
$$M_3 = a_{41}a_{53}a_{62} - a_{41}a_{52}a_{63}.$$

The roots of the Eq. 27 that are also the eigenvalues of matrix C are of the form $\pm\xi_1, \pm\xi_2, \pm\xi_3$. The eigenvector $\vec{Y} = [Y_1, Y_2, Y_3, Y_4, Y_5, Y_6]$ corresponding to eigenvalue ξ can be estimated as:

$$\begin{aligned} Y_1 &= \xi a_{46}(-\xi^2 + a_{52}) - \xi a_{45}a_{53}, \\ Y_2 &= -(\xi^2 - a_{41})a_{53}, \\ Y_3 &= -(\xi^2 - a_{41})(\xi^2 - a_{52}), \\ Y_4 &= \xi Y_1, Y_5 = \xi Y_2, Y_6 = \xi Y_3. \end{aligned} \tag{29}$$

Using Eq. 29 the eigenvector $\vec{Y}$ corresponding to eigenvalue ξ_j, $j = 1, 2, 3, 4, 5, 6$ easy estimated. For further reference, we can use the following notations:

$$\begin{aligned} Y_1 &= \left[\vec{Y}\right]_{\xi=-\xi_1}, Y_2 = \left[\vec{Y}\right]_{\xi=-\xi_2}, Y_3 = \left[\vec{Y}\right]_{\xi=-\xi_3}, \\ Y_4 &= \left[\vec{Y}\right]_{\xi=\xi_1}, Y_5 = \left[\vec{Y}\right]_{\xi=\xi_2}, Y_6 = \left[\vec{Y}\right]_{\xi=\xi_3}, \end{aligned} \tag{30}$$

The solution of Eq. 27 has the following from:

$$V(z, s) = \sum_{i=1}^{3} B_i Y_i e^{-\xi_i z} + f^* e^{-\alpha z}, \tag{31}$$

where the exponential terms growing state in the space variable z have been canceled due to of the solution harmony condition at infinity, B_1, B_2 and B_3 are constants to be investigated from the problem boundary condition, $f^* = [f_1, f_2, f_3, f_4, f_5, f_6]^T$,

$$\begin{aligned} f_1 &= \frac{1}{g}\Big(\alpha(a_{10}(a_{46}(\alpha^2 - a_{52}) + a_{45}a_{53}) \\ &\quad + a_9(a_{46}a_{62} + a_{45}(\alpha^2 - a_{63})))\Big), \\ f_2 &= \frac{1}{g}\Big(\alpha(a_{10}(a_{46}(\alpha^2 - a_{52}) + a_{45}a_{53}) \\ &\quad + a_9(a_{46}a_{62} + a_{45}(\alpha^2 - a_{63})))\Big), \\ f_3 &= \frac{1}{g}\Big(\alpha(a_{10}(a_{46}(\alpha^2 - a_{52}) + a_{45}a_{53}) \\ &\quad + a_9(a_{46}a_{62} + a_{45}(\alpha^2 - a_{63})))\Big), \\ f_4 &= -\alpha f_1, f_5 = -\alpha f_2, f_6 = -\alpha f_3, \\ g &= (\alpha^2 - a_{41})(\alpha^4 - a_{53}a_{62} - \alpha^2 a_{63} + a_{52}(-\alpha^2 + a_{63})) \\ &\quad - \alpha^2(a_{46}(\alpha^2 - a_{52}) + a_{45}a_{53})a_{64}. \end{aligned}$$

From Eqs. 31 and 27, the generic solutions of the field variables may be expressed for z and s as:

$$\bar{u}(z, s) = \sum_{i=1}^{3} B_i U_i e^{-\xi_i z} + f_1 e^{-\alpha z}, \tag{32}$$

$$\overline{N}(z, s) = \sum_{i=1}^{3} B_i N_i e^{-\xi_i z} + f_2 e^{-\alpha z}, \tag{33}$$

$$\overline{T}(z, s) = \sum_{i=1}^{3} B_i T_i e^{-\xi_i z} + f_3 e^{-\alpha z}, \tag{34}$$

$$\begin{aligned} \bar{\sigma}_{zz}(z, s) &= -\sum_{i=1}^{3} B_i (\xi_i U_i + a_1 N_i + a_2 T_i) e^{-\xi_i z} \\ &\quad - (\alpha f_1 + a_2 f_2 + a_2 f_3) e^{-\alpha z}, \end{aligned} \tag{35}$$

For finally solution of displacement, density of carriers, temperatures and stress distribution a numerically reversal analysis was adopted depending on the Riemann-sum approximation method is used to investigate the numerical results. According to this analysis, a function in the Laplace domain may be transformt to the time domain as:

$$V(z, t) = \frac{e^{mt}}{t}\left(\frac{1}{2} Re\left[\overline{V}(z, m)\right] + Re\sum_{n=0}^{N}(-1)^n\, \overline{V}\left(z, m + \frac{in\pi}{t}\right)\right), \tag{36}$$

whereas Re is the actual part and i is the imaginative number unit. For quicker assemblage, numerically methods decieded that $m = \frac{4.7}{t}$ that satisfing the above equation [20].

5 Numerically Results and Discussion

To investigate the theoretically results illustrated in the previously part, a few of numerically values for the physical constants were presented. With the assume that, the semiconducting material is made of isotropic and the silicon sample has been chosen. The physical constants are listed below [10]:

$$\begin{aligned} \rho &= 2330\,(kg)\left(m^{-3}\right), \lambda = 3.64 \times 10^{10}\,(N)\left(m^{-2}\right), \\ &\quad \mu = 5.46 \times 10^{10}\,(N)\left(m^{-2}\right), \\ \alpha_t &= 3 \times 10^{-6}\left(k^{-1}\right), c_e = 695\,(J)\left(kg^{-1}\right)\left(k^{-1}\right), \\ &\quad T_o = 300\,(k), d_n = -9 \times 10^{-31}\left(m^3\right), \\ E &= 2.33\,(eV), E_g = 1.11\,(eV), s_o = 2\,(m)\left(s^{-1}\right), \\ &\quad D_e = 2.5 \times 10^{-3}\left(m^2\right)\left(s^{-1}\right), R = 0.3, \\ \alpha &= 5 \times 10^5\left(m^{-1}\right), I_o = 13.4\,(J)\left(m^{-2}\right), t_p = 10\,(s), \\ &\quad n_o = 10^{20}\left(m^{-3}\right), \tau = 10^{-2}\,(s). \end{aligned}$$

Based on the data set, Figs. 1, 2, 3, 4, 5, 6, 7 and 8 represent the numerically computed physical quantities at different values of the distance z. Numerical calculations are carried out for the temperature, the carrier density, the displacement and the stresses distribution over the z-direction in the situation of the coupling photothermal theory.

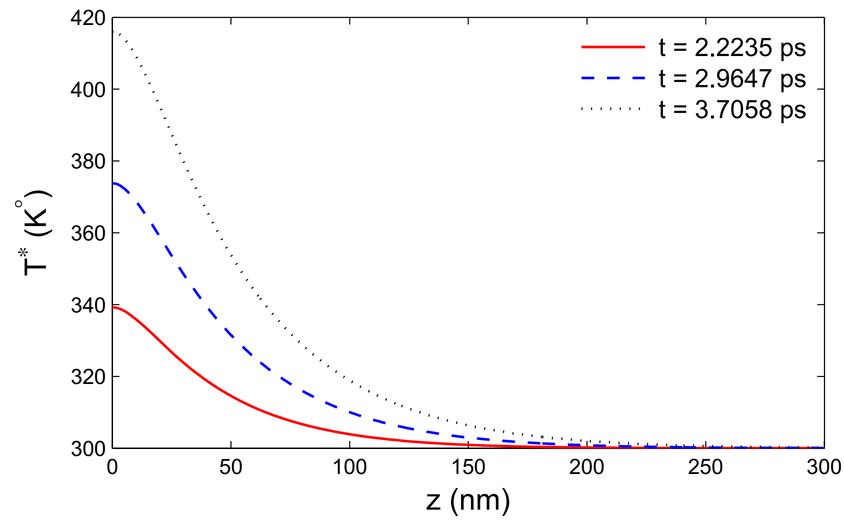

Fig. 1 The temperature changes versus distance at different values of time

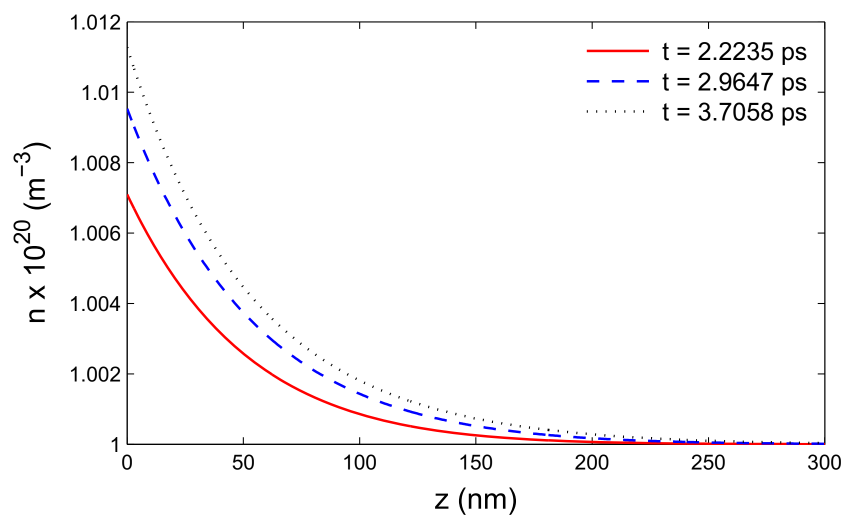

Fig. 2 The changes of carrier densities versus distance at different values of time

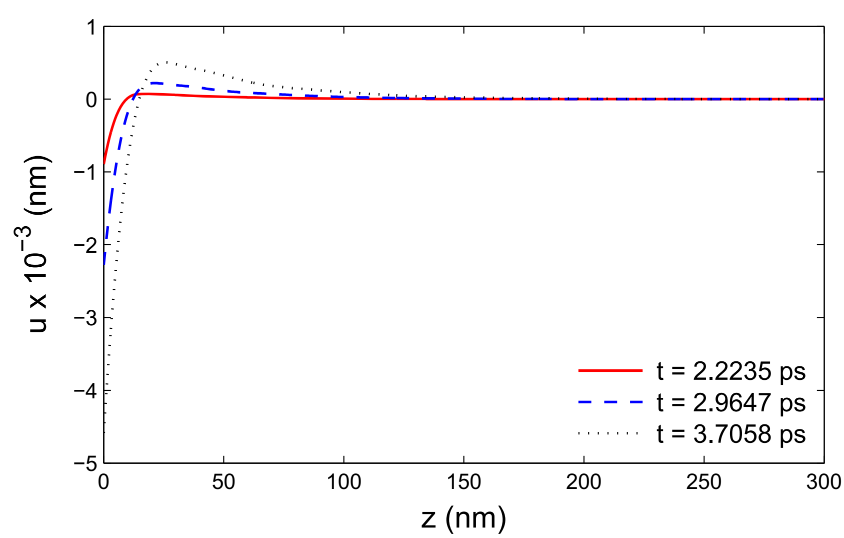

Fig. 3 The displacement changes versus distance at different values of time

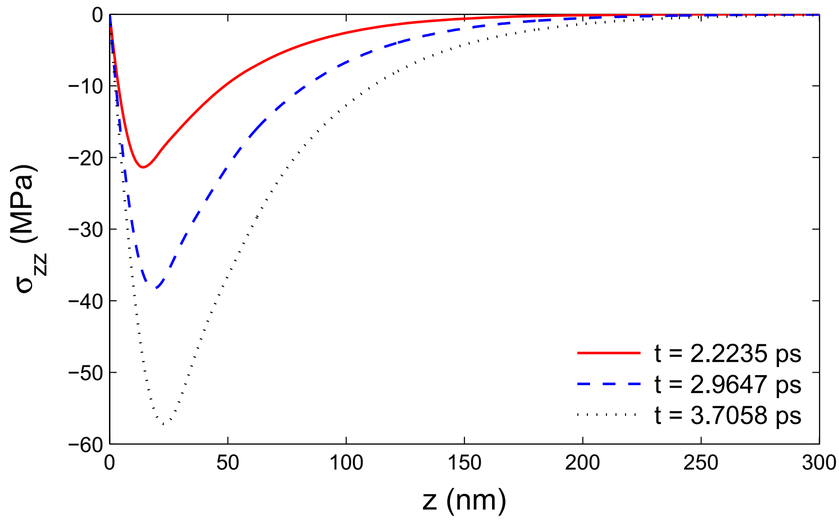

Fig. 4 The stress changes versus distance at different values of time

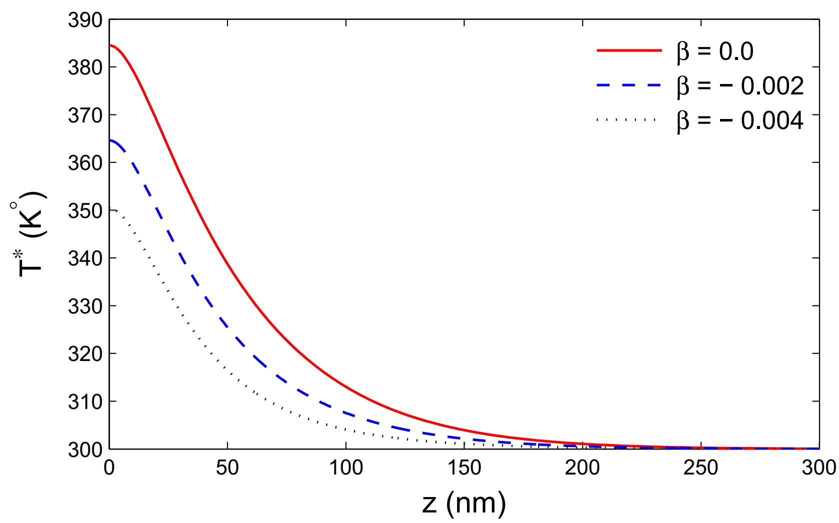

Fig. 5 The variation of temperature vs distance with and without coupled parameter β

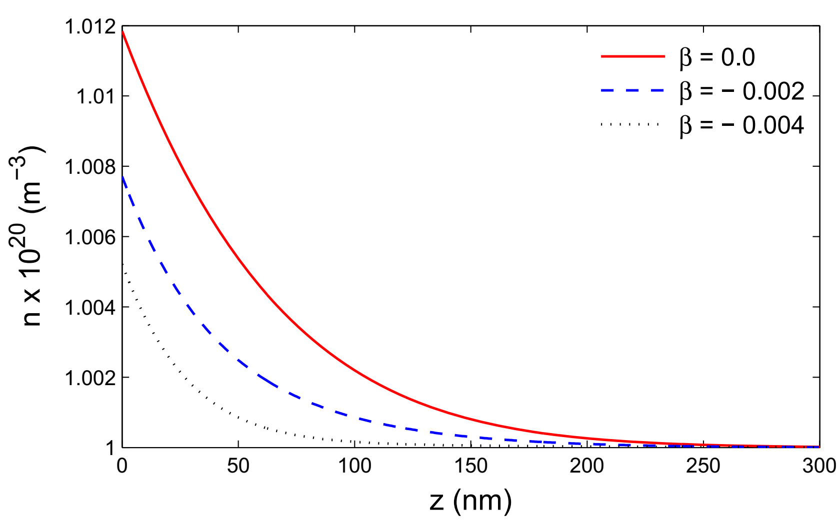

Fig. 6 The variation of carrier density vs distance with and without coupled parameter β

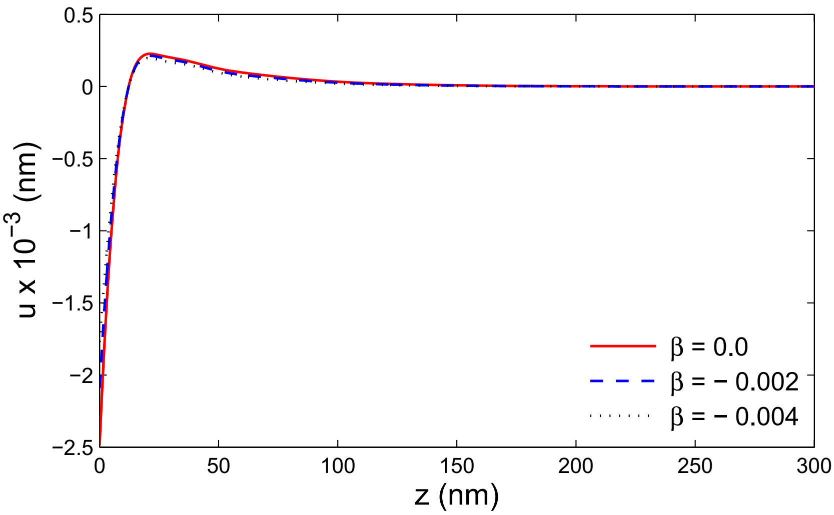

Fig. 7 The variation of displacement vs distance with and without coupled parameter β

Figures 1, 2, 3 and 4 represents the three curves predicted by different values of time considering the coupled parameter ($\beta = -0.001$). From Fig. 1, it was noted that the temperature starts with its maximum value at $z = 0$ and decreases gradually with increases the distance z until attaining zero beyond a wave front for the photo-thermal theory, which satisfies our theoretical boundary conditions. Figure 2 represents the variation of carrier density as a function of to the distance$z$. It is observed that the n value is a highest value on $z = 0$ and decreases with the increasing the distance z to close to zero on $z = 250$ nanometear. The displacement changes versus z are shown in Fig. 3. It was observed that the displacement attains some maximum negative values then it increases gradually up to it attains a peak value at a particular location proximately close to the surface and then continuously decreases to zero. Figure 4 investigates the changes of stress versus distance z at various times. It is noticed that the stress, permanently begin by zero value and terminated at the zero value to mind the boundary conditions.

The Figs. 5, 6, 7 and 8, the graph shows the temperature changes, carrier density, displacement and stress versus the distance z in the obscurity and turnout of the non-dimensional coupled parameter β when the time ($t = 2.9647$ ps) remain constant. The solid lines in these figures, shows the solution in the uncoupled photo-thermal theory, while the dashed and dotted lines represent the solution in the coupled photo-thermal theory. In compression between the solutions, one can have concluded that, the coupled photo-thermal theory is necessarily phenomena and has large influence on the field quantities distribution.

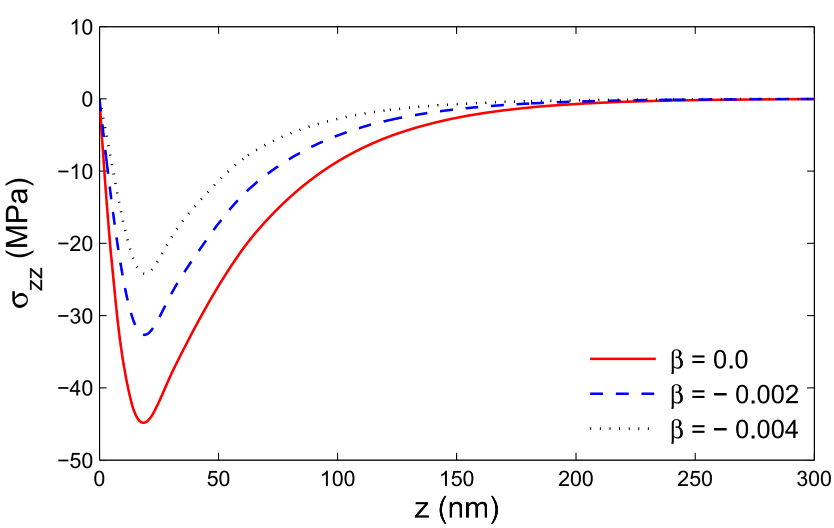

Fig. 8 The variation of stress vs distance with and without coupled parameter β

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