SOLUTION OF LORD-SHULMANS AND DUAL-PHASE-LAG THEORIES PROBLEM ON A PHOTOTHERMAL ROTATIONAL SEMICONDUCTOR MEDIUM WITH VOIDS AND INITIAL STRESS

by

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This paper discusses a photo-thermal rotational semiconductor medium with initial stress, and voids by considering two thermoelastic theories: Lord-Shulman and Dual-Phase-Lag models. The equations of motion, temperature, voids, and photothermal have been investigated under two generalized thermoelastic theory. The technique of normal mode has been applied to solve the differential equations system with appropriate boundary conditions. Quantities of physical interest such as displacement, stress components, concentration, temperature, and carrier density are calculated and displayed graphically to demonstrate the effect of the external parameters. The obtained results, by using the two theories, show that the dual-phase-lag theory gives an origin results comparing with obtained results by Lord-Shulman theory. By neglecting the initial stress and voids, and considering the only dual-phase-lag theory, then the results obtained in this paper are deduced to the results of Abbas et al. [1].

Key words: *photothermal waves, Lord-Shulman, dual-phase-lag, voids, initial stress, normal mode analysis technique, semiconductor*

Introduction

In recent years, there has been a growing interest in voids and photo-thermal, with applications in many areas including acoustics, physics, optics, engineering, and technology. Many researchers are interested to explore the effect of the voids in the presence of thermoelasticity [2, 3, *e. g*]. Biot [4, *e. g*.] explores the solution of the paradox of the infinite speeds due to the signals thermal on the motion of the waves. Lord and Shulman [5] introduce a new model to generalized thermoelasticity theory by considering one relaxation time that can modify a new law of heat conduction which contains the heat flux vector and its time derivative. The equation of heat for this theory ensures finite speeds of propagation for heat and elastic waves with signal thermal. Hetnarski and Ignaczak [6] explore the effect of the relaxation times in generalized thermoelasticity and effect these times to find the velocity of the wave. Bachher *et al.* [7] introduce a generalization for a thermoelastic infinite medium in the presence of instantaneous heat sources with voids by considering fractional derivative heat transfer. In elastic materials, Cowin and Nunziato [8] extend the voids linear theory problem. Dhaliwal and Singh [9] investigate dynamic coupled thermoelasticity to the stress-strain constitutive relations and equation of motion. Eringen and Suhubi [10] discuss the fundamental equations of the basic field, constitutive equations *simple micro-elastic* which are affected by *micro* deformations and

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rotations not encountered for finite elasticity and boundary conditions. Othman *et al*. [11] discuss photothermal wave propagation in a semiconducting medium with one relaxation time. Song *et al*. [12] investigate the reflection of the photo thermal waves in a semiconducting medium in the context of a generalised thermoelastic theory. Todorović *et al*. [13] explore the transmission of the technique of photoacoustic frequency, electronic deformation mechanism effect in semiconductors. Lotfy and Gabr [14] extend the study of semiconducting infinite response under photothermal excitation due to laser pulses and two temperature theories. Todorović [15] analyses the system of elastic wave equations, partially coupled plasma and thermal field. Abbas *et al*. [1] illustrate the dual-phase lag model of a photothermal interaction in a semiconductor material.

Formulation of problem

For the purposes of discussion consider a semiconductor, homogeneous, isotropic medium in the present of initial stress and rotation. Here, we assume that the systems could have voids and photo-thermal. We consider the case of 2-D, with the aim of determining the effects of external parameters on physical phenomena. The basic governing equations are listed [16]:

– equation of motion

$$\sigma_{ji,j} = \rho[\ddot{u}_i + (\Omega\times\Omega\times u)_i + \left(2\times\Omega\times\dot{u})_i\right]$$

that tends to:

$$\left(\mu-\frac{p}{2}\right)\nabla^2 u_i + \left(\lambda+\mu+\frac{p}{2}\right)\nabla_e - \gamma\nabla T - \delta N + b_v\phi_{vi} = \rho[\ddot{u}_i + (\Omega\times\Omega\times u)_i + \left(2\times\Omega\times\dot{u})_i\right] \tag{1}$$

– heat conduction equation:

$$K\left(1+\tau_\Theta\frac{\partial}{\partial t}\right)\nabla^2 T + \frac{E_g}{\tau}N - \gamma T_0\left(1+\tau_0\frac{\partial}{\partial t}\right)\dot{e} = \rho c_e\left(1+\tau_0\frac{\partial}{\partial t}\right)\dot{T} + mT_0\left(1+\tau_0\frac{\partial}{\partial t}\right)\dot{\phi}_v \tag{2}$$

– governing equations in the presence of volume fraction, thermoelastic waves, and plasma are given:

$$D_E\nabla^2 N - \frac{N}{\tau} + k\tau = \frac{\partial N}{\partial t} \tag{3}$$

– volume fraction field equation

$$\alpha\phi_{v,ji} - b_v u_{ij} - \zeta\phi_v - \omega_v \dot{phi}_v + mT = \rho\chi\ddot{\phi}_v \tag{4}$$

– constitutive relations are given

$$\sigma_{ij} = 2\mu\varepsilon_{ij} + \left[\lambda e - \gamma T - \delta_n N + b_v\Phi_v - P\right]\delta_{ij} - P\omega_{ij} \tag{5}$$

where

$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right),\ \omega_{ij} = \frac{1}{2}\left(u_{j,i} - u_{i,j}\right),\ e = u_{i,j},\ i,j = 1,2,3$$

Here, let $u(x, y, t)$ be the displacement (elastic waves), and $T(x, y, t)$ be the temperature (thermal waves). Let $N(x, y, t)$ be the carrier density (plasma waves) and $\Phi(x, y, t)$ be the volume fraction. For the 2-D problem, the photo-thermal voids transport process can be found by considering the thermal activation of coupling parameter K, then the displacement takes the form:

$$u = \left(u_1, u_2, 0\right),\quad \text{where}\quad u_1 = u\left(x,y,t\right),\quad u_2 = v\left(x,y,t\right) \tag{6}$$

For simplicity in simulation, we prefer to deal with a non-dimensional system, in which the governing equations and all physical quantities such as the displacement, temperature, and density are non-dimensionalised by chosen representative values. It is convenient to non-dimensionalise all the aforementioned equations by using the following non-dimensional variables:

$$\left(x',y',u',v'\right)=\frac{1}{C_T t^*}\left(x,y,u,v\right),\ \left(t',\tau_0',\tau_d'\right)=\frac{1}{t^*}\left(t,\tau_0,\tau_d\right),\ T'=\frac{\gamma}{\left(\lambda+2\mu\right)}T,\ P'=\frac{1}{\mu}P$$
$$N'=\frac{\delta_N}{\lambda+2\mu}N,\quad \phi_v'=\frac{\chi}{\lambda+2\mu}\phi_v,\ \sigma_{ij}'=\frac{1}{\mu}\sigma_{ij},\ C_T^2=\frac{\lambda+2\mu}{\rho},\ t^*=\frac{K}{\rho c_e C_T^2},\quad \Omega=t^*\Omega \tag{7}$$

The displacement must be written as addition of scalar and vector potential functions $\Phi(x, y, t)$ and $\Psi(x, y, t)$ related by the following form *Lame's potential method*:

$$u=\Phi_x+\Psi_y,\quad v=\Phi_y-\Psi_x \tag{8}$$

Substituting eqs. (6)-(8) into eqs. (1)-(5) we obtain new equations:

– the equation of motion becomes

$$\left[\nabla^2-\frac{\partial^2}{\partial t^2}+\Omega^2\right]\Phi-2\Omega\frac{\partial}{\partial t}\Psi-T-N+\hat{b}\phi_v=0$$
$$\left[\Gamma_1\nabla^2-\frac{\partial^2}{\partial t^2}+\Omega^2\right]\Psi+2\Omega\frac{\partial}{\partial t}\Phi=0 \tag{9}$$

– heat conduction equation becomes

$$\left[\left(1+\tau_\Theta\frac{\partial}{\partial t}\right)\nabla^2-\left(1+\tau_o\frac{\partial}{\partial t}\right)\frac{\partial}{\partial t}\right]T-\varepsilon_1\left(1+\tau_o\frac{\partial}{\partial t}\right)\nabla^2\Phi+\varepsilon_2 N-\varepsilon_4\left(1+\tau_o\frac{\partial}{\partial t}\right)\phi_v=0 \tag{10}$$

– governing equations in the presence of volume fraction, thermoelastic waves, and plasma becomes

$$\left[\nabla^2-\frac{Kt^*}{\rho c_e\tau D_E}-\frac{K}{\rho c_e D_E}\frac{\partial}{\partial t}\right]N+\varepsilon_3 T=0 \tag{11}$$

– volume fraction field equation becomes

$$\left[\nabla^2-S_2-S_3\frac{\partial}{\partial t}-S_5\frac{\partial^2}{\partial t^2}\right]\phi_v-S_1\nabla^2\Phi+S_4T=0 \tag{12}$$

– constitutive relations become:

$$\sigma_{xx}=\beta^2u_{,x}+\left(\beta^2-2\right)v_{,y}-\beta^2T-\beta^2N+\beta^2\hat{b}\phi_v-P \tag{13}$$

$$\sigma_{yy}=\left(\beta^2-2\right)u_x+\beta^2v_y-\beta^2T-\beta^2N+\beta^2\hat{b}\phi_v-P \tag{14}$$

$$\sigma_{zz}=\left(\beta^2-2\right)\nabla^2\Phi-\beta^2T-\beta^2N+\beta^2\hat{b}\phi_v-P \tag{15}$$

$$\sigma_{xy}=u_y+v_x-\frac{P}{2}\left(v_x-u_y\right),\quad \sigma_{xz}=\sigma_{yz}=0 \tag{16}$$

where

$$\varepsilon_1 = \frac{\gamma^2 T_0 t^*}{K\rho},\ \varepsilon_2 = \frac{\alpha_t E g t^*}{\rho c_e \tau d_n},\ \varepsilon_3 = \frac{K k d_n t^*}{\rho c_e \alpha_t D_E},\ \varepsilon_4 = \frac{m T_0 \gamma}{\rho c_e \chi}$$

$$\beta^2 = \frac{\lambda + 2\mu}{\mu},\ \hat{b} = \frac{b_v}{\chi},\ S_1 = \frac{b_v t^{*2} \chi^2}{\alpha\rho},\ S_2 = \frac{\zeta C_T^2 t^{*2}}{\alpha}$$

$$S_3 = \frac{\omega_v C_T^2 t^*}{\alpha},\ S_4 = \frac{m C_T^2 t^{*2} \chi}{\alpha\gamma},\ S_5 = \frac{\rho C_{T\chi}^2}{\alpha},\ \varGamma_1 = \frac{2-P}{2\beta^2}$$

Normal mode analysis

This section applies the normal mode analysis technique so that the physical quantities take the form:

$$\left[\varPhi, \Psi, T, N, \phi_v, \sigma_{ij}\right](x,y,t) = \left[\varPhi^*, \Psi^*, T^*, N^*, \phi_v^*, \sigma_{ij}^*\right](x)\exp(\omega t + iby) \tag{17}$$

By using this eq. (17), eqs. (9)-(12) can be written:

$$\begin{gathered}(D^2 - a_1)\varPhi^* - a_5\Psi^* - T^* - N^* + \hat{b}\phi_v^* = 0\\ (\varGamma_1 D^2 - m^2)\Psi^* + a_5\varPhi^* = 0\\ -a_2(D^2 - b^2)\varPhi^* + (\Lambda_1 D^2 - a_3)T^* + \varepsilon_2 N^* - a_6\phi_v^* = 0\\ (D^2 - a_4)N^* + \varepsilon_3 T^* = 0\\ (D^2 - a_{55})\phi_v^* - S_1(D^2 - b^2)\varPhi^* + S_4 T^* = 0\end{gathered} \tag{18}$$

where

$$a_1 = b + \omega^2 - \Omega^2,\ a_2 = \varepsilon_1\omega(1 + \tau_0\omega),\ a_3 = \varLambda_1 b^2 + \omega(1 + \tau_0\omega),\ a_4 = b^2 + \alpha$$

$$a_5 = 2\Omega\omega, a_{55} = b^2 + S_2 + S_3\omega + S_5\omega^2,\ a_6 = \varepsilon_4\omega(1 + \tau_0\omega),\ \varLambda_1 = (1 + \tau_\Theta\omega)$$

$$\alpha = \frac{K t^*}{\rho c_e \tau D_E} + \frac{K\omega}{\rho c_e D_E},\ m^2 = \varGamma_1 b^2 + \omega^2 - \Omega^2$$

To solve the system of eq. (18), we must eliminate $\varPhi^*(x)$, $T^*(x)$, $N^*(x)$, and $\phi_v^*(x)$ between them, to obtain the tenth-order ODE in the form:

$$D^{10} - A_s D^8 + B_s D^6 - C_s D^4 + E_s D^2 - L_s = 0 \tag{19}$$

where A_s, B_s, C_s, E_s, and L_s are given in *Appendix*. By factoring out this eq. (19), we obtain the problem:

$$\left(D^2 - k_1^2\right)\left(D^2 - k_2^2\right)\left(D^2 - k_3^2\right)\left(D^2 - k_4^2\right)\left(D^2 - k_5^2\right)\left\{\varPhi^*, T^*, N^*, \phi_v^*\right\} = 0 \tag{20}$$

where $k_j^2 = 1, 2, 3, 4, 5$ are the characteristic equation roots of this eq. (20). By considering the bounded as x goes to infinity, we obtain the solution of eq. (20) in the form:

$$\varPhi^* = \sum_{n=1}^{4} M_n \mathrm{e}^{-k_n x},\ \Psi^* = \sum_{n=1}^{5} H_{1n} M_n \mathrm{e}^{-k_n x},\ T^* = \sum_{n=1}^{5} H_{2n} M_n \mathrm{e}^{-k_n x}$$

$$N^* = \sum_{n=1}^{5} H_{3n} M_n \mathrm{e}^{-k_n x},\ \phi_v^* = \sum_{n=1}^{5} H_{4n} M_n \mathrm{e}^{-k_n x}$$

The components of displacement take the form:

$$u^* = \sum_{n=1}^{5} \Upsilon_{1n} M_n \mathrm{e}^{-k_n x}, \quad v^* = \sum_{n=1}^{5} \Upsilon_{2n} M_n \mathrm{e}^{-k_n x}$$

Using previous equations we obtain:

$$\sigma_{xx} = \sum_{n=1}^{5} H_{5n} M_n \mathrm{e}^{\omega t + iby - k_n x} - P, \ \sigma_{yy} = \sum_{n=1}^{5} H_{6n} M_n \mathrm{e}^{\omega t + iby - k_n x} - P, \ \sigma_{xy} = \sum_{n=1}^{5} H_{7n} M_n \mathrm{e}^{\omega t + iby - k_n x}$$

where

$$H_{1n} = \frac{-a_5}{\Gamma_1 k_n^2 - m^2}, \quad H_{2n} = \frac{\left[a_6 \mho_4 - a_2 \hat{b} \mho_1\right] \mho_5 - a_5 a_6 \mho_5 H_{1n}}{\varepsilon_3 \left(\varepsilon_2 \hat{b} - a_6\right) - \left[\mho_6 \hat{b} - a_6\right] \Lambda_5}$$

$$H_{3n} = \frac{\varepsilon_3 H_{2n}}{a_4 - k_n^2}, \quad H_{4n} = \frac{S_4 H_{2n} - S_1 \mho_1}{a_{55} - k_n^2}$$

$$H_{5n} = \beta^2 \left(k_n^2 - b^2 - H_{2n} - H_{3n} - \hat{b} H_{4n}\right) + 2b^2 - 2ibk_n H_{1n}$$

$$H_{6n} = \beta^2 \left(k_n^2 - b^2 - H_{2n} - H_{3n} + \hat{b} H_{4n}\right) - 2\left(k_n^2 - ibk_n H_{1n}\right)$$

$$H_{7n} = ib\Upsilon_{1n} - k_n \Upsilon_{2n} + \frac{P}{2}\left(k_n \Upsilon_{2n} + ib\Upsilon_{1n}\right)$$

$$\mho_1 = \left(k_n^2 - b^2\right), \quad \mho_2 = \left(k_n^2 - a_5\right), \quad \mho_3 = \left(k_n^2 - a_3\right), \quad \mho_4 = \left(k_n^2 - a_1\right)$$

$$\mho_5 = \left(k_n^2 - a_4\right), \ \mho_6 = \left(\Lambda_1 k_n^2 - a_3\right), \ \Upsilon_{1n} = -k_n + ibH_{1n}, \ \Upsilon_{2n} = ib + k_n H_{1n}$$

Boundary conditions

This section considers the appropriate boundary conditions at the boundary $x = 0$ to determine the coefficients M_n for ($n = 1, 2, 3$). The appropriate boundary conditions are considered as following:

– The normal stress condition is: $\sigma_{xx} = -P - p_1^* \mathrm{e}^{\omega t + iby}$, where p_1^* is an arbitrary constants.
– The tangential stresses vanishing: $\sigma_{xx} = 0$.
– The thermal boundary condition is: $\partial\phi_v/\partial x = 0$.
– The condition of change of the volume fraction field is: $\partial\phi_v/\partial x = 0$.
– The condition of change of carrier density field is: $D_E \partial N/\partial x = sN$, where s is an arbitrary constant.

By substituting the considered quantities in the previous boundary conditions, we obtain a system of five equations. By applying the inverse of matrix method, we obtain the values of the constants M_n for ($n = 1, 2, 3$).

$$\begin{pmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \end{pmatrix} = \begin{pmatrix} H_{51} & H_{52} & H_{56} & H_{54} & H_{55} \\ H_{71} & H_{72} & H_{73} & H_{74} & H_{75} \\ k_1 H_{21} & k_2 H_{22} & k_3 H_{23} & k_4 H_{24} & k_5 H_{25} \\ k_1 H_{41} & k_2 H_{42} & k_3 H_{43} & k_4 H_{44} & k_5 H_{45} \\ (k_1 + v) H_{31} & (k_2 + v) H_{32} & (k_3 + v) H_{33} & (k_4 + v) H_{34} & (k_5 + v) H_{35} \end{pmatrix}^{-1} \begin{pmatrix} -p_1^* \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Numerical results and discussion

This section presents numerical calculations for the physical quantities to demonstrate the effect of the external parameters on the phenomenon, as shown in figs. 1-7. The numerical calculation were carried out for silicon. Table 1 lists the physical constants in our calculation, and tab. 2 lists the voids parameters.

Table 1. The values of the physical constants used in our calculations [17]

Physical constance	Value	Physical constance	Value
λ	3.64	μ	$5.46 \cdot 10^{10}$ kg/ms
ρ	$2.33 \cdot 10^{3}$ kg/m^{3}	K	150 W/mk
b	1.8	s	2 m/s
P_1^*	1	d_n	$-9 \cdot 10^{-31}$ m^{3}
D_e	$2.5 \cdot 10^{-3}$ m^{2}/s	E_g	1.12 eV
y	0.5	i	$\sqrt{-1}$
t	0.002	α_t	$3 \cdot 10^{-6}$ 1/k
T_0	300 K	ξ	1.2
ω	$\omega_0 + i\xi$	c_e	695
τ	$5 \cdot 10^{-5}$	τ_0	$5 \cdot 10^{-5}$
Ω	0.3	x	[0, 2.5]

Table 2. The values of the voids parameters used in our calculations

Voids parameters	Value	Voids parameters	Value
b_v	$1.13849 \cdot 10^{10}$	ζ	$1.475 \cdot 10^{10}$
ω_r	$0.078 \cdot 10^{-3}$	For LS: τ_0	0.3
χ	$1.756 \cdot 10^{-15}$	For LS: τ_Θ	0
α	$3.688 \cdot 10^{-5}$	For DPL: τ_0	0.9
m	2	For DPL: τ_Θ	0.7

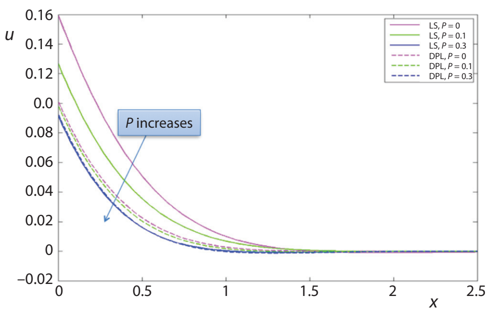

Figure 1. Plot the longitudinal displacement *u* against the axial *x* under initial stress for LS and DPL model

Figure 1 displays the variation of axial co-ordinate on the horizontal displacement u concern to x under the effects of initial stress and two thermoelastic theories (LS and DPL). By considering two models, the values of the displacement u become bigger than the corresponding values for DPL model. It is noticed that the the horizontal displacement u decreases with an increase in the initial stress, which indicates to the opposite behaviour for u with the positive behavior of the initial stress.

By increasing values of the axial co-ordinate x, the horizontal displacement u decreases to zero with time as x approaches infinity. Figure 2 displays the vertical displacement v with respect to axial co-ordinate x under the influence of the initial stress for LS and DPL models. It is clear that the values of the normal displacement v approach zero as x tends to infinity. Increasing values of initial stress results an increment in normal displacement v for the LS model in contrast with that values obtained by DPL model.

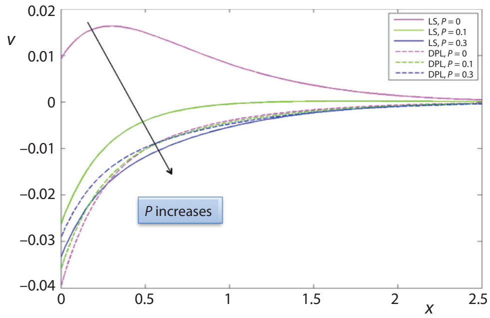

Figure 2. Plot the normal displacement v against the axial x under initial stress for LS and DPL models

The concentration ϕ_v with respect to axial x under initial stress for LS and DPL models has been displayed in fig. 3. By increasing the the values of the initial stress, the values of ϕ_v are also increasing with the LS model. Moreover, the value of the concentration ϕ_v, in both models, tends to zero as the value of x increases.

The variation of stress σ_{xx} with respect to axial x under the influence of the initial stress for LS and DPL models is presented in fig. 4. It is important to emphasise that $\sigma_{xx} = -P - p_1^* e^{\omega t + iby}$ at $x = 0$ satisfies the boundary conditions and also has different values with the variation of P and p_1. Also, it is clear that σ_{xx} tends to zero as x approaches to infinity. A comparison of results obtained from LS and DPL models shows that the values of stress σ_{xx} increases with DPL model. Also, the normal stress σ_{xx} tends to zero with large values of x.

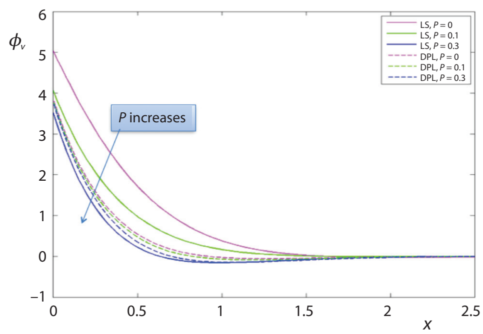

Figure 3. Plot the concentration ϕ_v against the axial x under initial stress for LS and DPL models

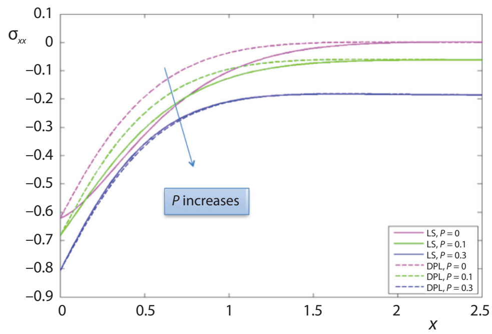

Figure 4. Plot the normal stress σ_{xx} against the axial x under initial stress for LS and DPL models

Figure 5 displays the variations of the shear stress σ_{xy} with respect to axial x in the presence of the initial stress for LS and DPL models. It is shown that the share stress σ_{xy} starts from zero at $x = 0$ and satisfies the boundary condition at the origin $\sigma_{xy} = 0$. The values of the shear stress increase until $x = 0.5$ and then start to decrease to a value reasonably close to zero as x approaches infinity. Also, it is obvious that the rise in initial stress results in small value of the shear stress, concerns the LS and DPL models. The shear stress has a large values with LS model in contrast with that values obtained by DPL model.

Figure 6 describes the influence of initial stress on the temperature, T, with respect to axial x, for LS and DPL models. It is clear that the temperature, T, satisfies the boundary conditions at $x = 0$. Also, it is obvious that the temperature, T, tends to decrease down to zero as x approaches infinity, when initial stress $P = 0$ in LS model, but increases for remain values for initial stress *P* for LS, while for DPL model, the temperature, *T*, tends to zero as *x* approaches infinity. Moreover, the temperature, *T*, decreases with an increase value in the initial stress *P*. But it is important to emphasise that reverse behaviour has been observed in fig. 7 for the carrier density *N* variation with concern to axial *x* under the initial stress for LS and DPL models. This demonstrates the influence of temperature, *T*, on carrier density *N* and vice versa.

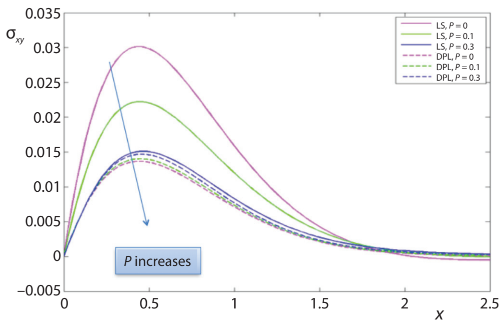

Figure 5. Plot the variations of shear stress σ_{xy} against the axial *x* under initial stress for LS and DPL models

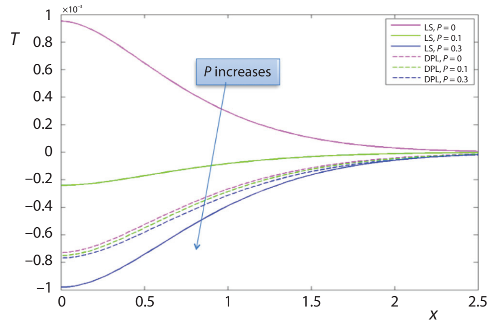

Figure 6. Plot the temperature *T* against the axial *x* under initial stress for LS and DPL models

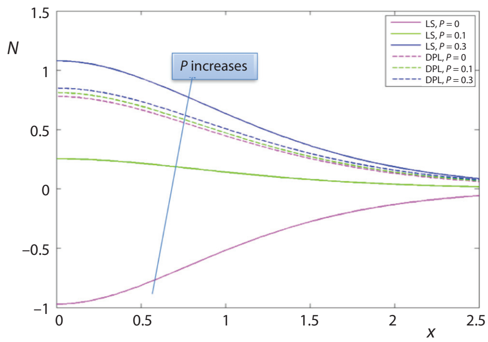

Figure 7. Plot the carrier density *N* against the axial *x* under initial stress for LS and DPL models

This section shows that all physical quantities approach zero as *x* approaches infinity. This result demonstrates that reasonable agreement exists with the exponential function behaviour of the solution of the quantities, and the reduction of the physical quantities approach the origin point. Moreover, when we neglect the initial stress and voids and considering only dpl theory, the results obtained in the current paper deduce to the results of Abbas *et al*. [1].

Conclusions

This paper explores a semiconductor, homogeneous, isotropic medium in the present of initial stress and rotation in 2-D. By using normal mode analysis technique, the systems of differential equations with appropriate boundary conditions are addressed. The influence of of the external parameters on some quantities of interest such as displacement, stress components, concentration, temperature, and carrier density are deliberated and bestowed through graphs, figs. 1-7. The effect of the relaxation time, temperature, volume friction has potential effect on the wave propagation which used in different applications, especially, in geomechanics, technology, engineering, and biology. The findings of this work are summarized.

- As *x* approaches infinity, all physical quantities of practical interest tend to zero.
- The variation of *y*-axis makes periodically change in the physical distributions.
- The relaxation times due to LS and DPL models, void, photo-thermal, initial stress and time parameter *t* have a strong effect on the phenomenon.
- The DPL model has a strong influence on the physical quantities comparing with the agreement values of LS model.

Appendix

$$A_s = \Gamma_1\Lambda_1\hat{b}S_1 - \Gamma_1 a_2 - \Gamma_1 a_3 - a_1\Gamma_1\Lambda_1 - a_4\Gamma_1\Lambda_1 - a_{55}\Gamma_1\Lambda_1 - m^2\Lambda_1$$

$$\begin{aligned}B_s = {} & a_2m^2 + a_3m^2 + \Lambda_1 a_5^2 - \Gamma_1\varepsilon_2\varepsilon_3 - \varepsilon_3\Gamma_1 a_2 + a_1m^2\Lambda_1 + a_4m^2\Lambda_1 + a_{55}m^2\Lambda_1 + \\ & + a_1a_3\Gamma_1 + a_2a_4\Gamma_1 + a_3a_4\Gamma_1 + a_2a_{55}\Gamma_1 + a_3a_{55}\Gamma_1 - a_6S_1\Gamma_1 + a_6S_4\Gamma_1 + \\ & + a_2b^2\Gamma_1 + a_1a_4\Gamma_1\Lambda_1 + a_1a_{55}\Gamma_1\Lambda_1 + a_4a_{55}\Gamma_1\Lambda_1 - \Lambda_1m^2\hat{b}S_1 - a_3\hat{b}S_1\Gamma_1 - \\ & - a_2\hat{b}S_4\Gamma_1 - a_4\hat{b}S_1\Gamma_1\Lambda_1 - a_4b^2S_1\Gamma_1\Lambda_1\end{aligned}$$

$$\begin{aligned}C_s = {} & \varepsilon_2\varepsilon_3m^2 - a_2a_5^2 - \varepsilon_3a_2m^2 - a_1a_3m^2 - a_2a_4m^2 - a_3a_4m^2 - a_2a_{55}m^2 - \\ & - a_3a_{55}m^2 + a_6S_1m^2 - a_6S_4m^2 - a_4a_5^2\Lambda_1 - a_{55}a_5^2\Lambda_1 - a_2b^2m^2 + \\ & + a_3\hat{b}S_1m^2 + a_2\hat{b}S_4m^2 - a_2b^2\varepsilon_3\Gamma_1 - a_2a_4b^2\Gamma_1 - a_2a_{55}b^2\Gamma_1 - \\ & - \varepsilon_2\varepsilon_3a_{55}\Gamma_1 - \varepsilon_3a_2a_{55}\Gamma_1 - a_1a_4m^2\Lambda_1 - a_1a_{55}m^2\Lambda_1 - a_4a_{55}m^2\Lambda_1 + \\ & + \varepsilon_3a_6\Gamma_1S_1 - a_1a_3a_4\Gamma_1 - a_1a_3a_{55}\Gamma_1 - a_1a_3a_{55}\Gamma_1 - a_2a_4a_{55}\Gamma_1 - \\ & - a_3a_4a_{55}\Gamma_1 - a_1a_6S_4\Gamma_1 + a_4a_6S_1\Gamma_1 - a_4a_6S_4\Gamma_1 - \varepsilon_2\varepsilon_3\hat{b}S_1\Gamma_1 - \Gamma_1\Lambda_1a_1a_4a_{55} + \\ & + a_4\hat{b}S_1m^2\Lambda_1 + a_6b^2\Gamma_1S_1 + \varepsilon_2\varepsilon_3a_1\Gamma_1 + a_3a_4\hat{b}S_1\Gamma_1 + a_2a_4\hat{b}S_4\Gamma_1 + \Lambda_1b^2\hat{b}S_1m^2 + \\ & + a_3b^2\hat{b}S_1m^2 + a_2b^2\hat{b}S_4m^2 + a_4b^2\hat{b}S_1\Gamma_1\Lambda_1\end{aligned}$$

$$\begin{aligned}E_s = {} & m^2\Big[b^2\left(a_2a_{55} + a_2\varepsilon_3 + a_2a_4\right) - \varepsilon_2\varepsilon_3a_1 + \\ & + a_{55}\left(a_2\varepsilon_3 - \varepsilon_2\varepsilon_3 + a_1a_3 + a_1a_4\Lambda_1 + a_2a_4 + a_3a_4\right) + a_1a_3a_4\Big] + \\ & + m^2S_1\Big[\hat{b}\left(\varepsilon_2\varepsilon_3 - a_4b^2\Lambda_1 - a_3a_4 - a_3b^2\right) - a_4a_6 - a_6\varepsilon_3 - a_6b^2\Big] + \\ & + m^2S_4\Big[a_6\left(a_1 + a_4 - a_1a_3\right) - a_2a_4\hat{b} - a_2b^2\hat{b}\Big] + \Gamma_1b^2\Big(a_2a_4a_6a_{55} - a_4a_6S_1 - \\ & - a_3a_4\hat{b}S_1 - a_2a_4\hat{b}S_4 + a_2a_{55}\varepsilon_3 - a_6S_1\varepsilon_3 + \varepsilon_2\varepsilon_3\hat{b}S_1\Big) + \\ & + a_1\Gamma_1\left(-\varepsilon_2\varepsilon_3a_{55} + a_3a_4a_{55} + a_4a_6S_4\right) + a_5^2\left(a_3a_4 - \varepsilon_2\varepsilon_3 + a_3a_{55} + a_6S_4 + a_4a_{55}\Lambda_1\right)\end{aligned}$$

$$\begin{aligned}L_s = {} & a_5^2\varepsilon_2\varepsilon_3a_{55} - a_3a_4a_5^2a_{55} - a_4a_6a_5^2S_4 + a_1a_{55}m^2\varepsilon_2\varepsilon_3 - a_1a_3a_4a_{55}m^2 - b^2\hat{b}S_1m^2\varepsilon_2\varepsilon_3 - \\ & - a_2a_{55}b^2m^2\varepsilon_3 + a_6b^2S_1m^2\varepsilon_3 - a_2a_4a_{55}b^2m^2 + a_4a_6S_1b^2m^2 + a_3a_4b^2\hat{b}S_1 + a_2a_4b^2\hat{b}S_1m^2\end{aligned}$$

$$F_r = \Gamma_1\Lambda_1,\ A = \frac{-A_s}{F_r},\ B = \frac{B_s}{F_r},\ C = \frac{-C_s}{F_r},\ E = \frac{E_s}{F_r},\ L = \frac{-L_s}{F_r}$$

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