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ONE-DIMENSIONAL THERMAL SHOCK PROBLEM FOR A SEMI-INFINITE SEMICONDUCTING ROD WITH HYDROSTATIC INITIAL STRESS

JEDNODIMENZIONALNI PROBLEM TERMIČKOG ŠOKA KOD POLUBESKONAČNOG POLUPROVODNOG ŠTAPA SA HIDROSTATIČKIM INICIJALNIM NAPONOM

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Keywords
- semiconducting
- hydrostatic initial stress
- heat source
- carrier density

Abstract

The theory of generalised thermoelasticity is used to solve a boundary value problem of one-dimensional semi-infinite semiconducting rod with hydrostatic initial stress of length l. The left boundary of the rod is subjected to a sudden heat source. Normal mode analysis technique is applied to solve governing equations of the medium. The analytical expressions of displacement, carrier density, temperature distribution and stresses are obtained analytically. The numerical results are also presented graphically to show the effect of hydrostatic initial stress on the components.

Ključne reči
- poluprovodnik
- hidrostatički inicijalni napon
- toplotni izvor
- gustina nosećeg medijuma

Izvod

Primenjena je teorija generalisane termoelastičnosti za rešavanje problema graničnih uslova kod jednodimenzionalnog polubeskonačnog štapa dužine l, sa hidrostatičkim inicijalnim naponom. Leva granica štapa je iznenada opterećena toplotnim izvorom. Metoda analize u normalnom modu je primenjena za rešavanje izvedenih jednačina date sredine. Analitički su dobijeni izrazi za pomeranje, gustine nosećeg medijuma, raspodele temperature i napona. Dobijeni numerički rezultati su takođe predstavljeni grafički, kako bi se pokazao uticaj inicijalnog hidrostatičkog napona na komponente.

INTRODUCTION

Study-related to generalised thermoelasticity has dragged considerable attention during the last few decades due to its application in various practical aspects of life processes such as earthquake prediction, exploration of minerals, soil dynamics, etc. Many researchers investigated wave propagation in elastic medium, neglecting the interaction between thermal effects and coupled plasma effects. Firstly, the uncoupled classical theory of thermoelasticity which assumed infinite speed of heat propagation was replaced by Biot /1/ by considering the theory of coupled thermoelasticity. Later on, generalised theories of thermoelasticity were developed by Lord and Shulman /2/, Green and Lindsay /3/ which were further reviewed by Green and Naghdi /4/, Hetnarski and Ignaczak /5/, and Ignaczak and Ostoja-Starzewski /6/.

Variation in temperature has a considerable impact on mechanical and thermal properties of a material. Therefore the effect of temperature gradient which was overlooked in various studies related to the generalised theory of thermoelasticity has been taken into consideration by many researchers /7-11/. Properties of a material cannot be taken as having constant values under the effect of temperature variation thereby making it essential for consideration of temperature dependence of material properties. A model showing the dependence of thermal conductivity and modulus of elasticity on temperature was developed and the problem of an infinite material with spherical cavity was solved by Youssef /12/. Some other authors working in this field are listed /13-17/. Various theories of generalised thermoelasticity are being developed by researchers resulting in the addition of different outer fields to equations governing motion and heat. Vlase et al. /18/ established the motion equations of a one-dimensional finite element having a general three-dimensional motion using the Lagrange's equations. Bhatti et al. /19/ presented a theoretical study on the swimming of migratory gyrotactic microorganisms in a non-Newtonian blood-based nanofluid via an anisotropically narrowing artery.

The study of initially stressed bodies has always been an interesting problem for researchers. Initial stresses in a medium can develop due to many factors such as the slow process of crawling, variations in gravity, temperature difference, etc. Our earth can also be considered to be under initial stresses. So significance of these initial stresses on surface wave propagation cannot be overlooked. Formulation of isotropic thermoelasticity was designed by Montanaro /20/ under influence of hydrostatic initial stress. The above formulation was used for studying plane harmonic waves under generalised thermoelasticity by many authors /21-23/. Said /24/ employed three-phase-lag model and Green Naghdi theory without energy dissipation to study the deformation of a two-temperature generalised-magneto thermoelastic medium with an internal heat source under hydrostatic initial stress and rotation. Ailawalia and Budhiraja /25/ demonstrated the effect of internal heat source under influence of hydrostatic initial stress in temperature rate dependent thermoelastic medium. Sarkar and Lotfy /26/ studied the problem of thermoelastic interactions in a half-space medium under hydrostatic initial stress in the context of a fractional order heat conduction model with two-temperature theory. Aljadani and Zenkour /27/ investigated the deformation of a rotating thermoelastic half-space under simple and refined L-S and G-L theories.

In the current era, wave propagation problems in the semiconducting medium are gaining importance by serving the base for various fields such as plasma physics, oil extraction, mechanical engineering, etc. When light falls on a semiconducting material, a change in physical properties and temperature of the material is caused by light energy. Due to this temperature gradient elastic deformation, free carrier density appears. Gordon et al. /28/ discovered electronic deformations to photothermal spectroscopy. Photothermal methods are being applied for measuring physical quantities such as temperature, electric effects of semiconducting material /29-31/. Besides this, many researchers have explored semiconducting mediums /32-37/. In above studies relation between thermoelasticity and photothermal theory was not taken into account. In recent years, interaction between the thermal wave, elastic wave, and plasma wave motion during the photo-excitation process in dual-phase-lag thermoelastic model with moving internal heat source under effect of gravitational field was described by Lotfy /38/. Othman et al. /39/ studied the time parameter effect on the photothermal waves in an isotropic, homogeneous, semiconducting medium. A new model of two-temperature theory under the photothermal theory for the semiconducting elastic medium was demonstrated by Abo-Dahab and Lotfy /40/. Othman et al. /41/ discussed the gravitational effect in a homogeneous isotropic semiconducting medium subjected to an internal heat source based on Lord-Shulman theory. Othman et al. /42/ investigated the effect of two-temperature parameter and rotation in a semiconducting medium into the context of the two-temperature generalised thermoelasticity theory with one relaxation time. Memory-dependent derivatives in the context of the two-temperature theory were used in generalised thermoelasticity under photothermal theory by Lotfy and Sarkar /43/. Lotfy /44/ investigated the problem for a photothermal semiconducting medium for two temperatures with hydrostatic initial stress under the dual phase lag model. A functional gradient semiconductor material was employed for investigating the fractional heat order by Hobiny and Abbas /45/ under the Green and Naghdi Model. Under the exposure of strong magnetic field, the effect of Hall current of elastic semiconductor medium was studied by Lotfy et al. /46/. Ailawalia and Kumar /47/ studied deformation in a semiconducting medium subjected to ramp type heating. A novel mathematical model under hydrostatic initial stress was developed by Lotfy /48/ for explaining the effect of the magnetic field for polymer photothermal diffusion semiconductor medium. Recently Lotfy and his co-workers /49-51/ have studied different types of problems in semiconducting medium under photothermal theory.

In the present paper, the deformation in a photothermal semiconducting rod with hydrostatic initial stress of length l is discussed. The rod is subjected to sudden heating at one end. The displacement components, carrier density, temperature distribution and stress components are evaluated and presented graphically to show the effect of hydrostatic initial stress on these quantities for different theories of thermoelasticity.

BASIC EQUATIONS

We shall consider a thin semi-infinite photothermal semiconducting rod occupying the region $x \geq 0$. The governing equations and constitutive relations for a semiconducting medium under hydrostatic initial stress with isotropic and homogenous properties are given by Mandelis et al. /35/ and Todorovic /36/,

$$\left(\mu-\frac{p}{2}\right)\nabla^2\vec{u}(\vec{r},t)+\left(\lambda+\mu-\frac{p}{2}\right)\nabla(\nabla.\vec{u}(\vec{r},t))-\gamma\left(1+v_0\frac{\partial}{\partial t}\right)\times$$
$$\times\nabla T(\vec{r},t)-\delta_n\nabla N(\vec{r},t)=p\ddot{\vec{u}}\,, \qquad (1)$$

$$D_e\nabla^2 N(\vec{r},t)-\frac{1}{\tau}N(\vec{r},t)+\kappa T(\vec{r},t)-\frac{\partial N(\vec{r},t)}{\partial t}=0\,, \qquad (2)$$

$$k^*\nabla^2 T(\vec{r},t)-\frac{E_g}{\tau}N(\vec{r},t)+\gamma T_0\left(n_1+n_0\tau_0\frac{\partial}{\partial t}\right)\nabla.\frac{\partial\vec{u}(\vec{r},t)}{\partial t}-$$
$$-\rho C^*\left(n_1+n_0\tau_0\frac{\partial}{\partial t}\right)\frac{\partial T(\vec{r},t)}{\partial t}=0\,, \qquad (3)$$

$$\sigma_{ij}=-p(\delta_{ij}+w_{ij})+2\mu e_{ij}+(\lambda u_{k,k}-\delta_n N-\gamma T)\delta_{ij}\,, \qquad (4)$$
$$e_{ij}=\frac{1}{2}(u_{j,i}+u_{i,j}),\quad w_{ij}=\frac{1}{2}(u_{j,i}-u_{i,j})\,,$$

where: λ, μ are Lame's constants; σ_{ij} is stress tensor; ρ is density; N is carrier density; E_g is the energy gap of the semiconductor; C^* is specific heat at constant strain; δ_n is the difference of deformation potential of conduction and valence band; D_e is carrier diffusion coefficient; k is coefficient of thermal conductivity; α_t is the coefficient of linear thermal expansion; $\kappa = (\partial N_0/\partial t)(T/\tau)$; N_0 is equilibrium carrier concentration at temperature T; τ is the photogenerated carrier lifetime; T is thermodynamic temperature; $\gamma = (3\lambda + 2\mu)\alpha_t$; $\delta_n = (3\lambda + 2\mu)d_n$ in the semiconducting medium.

The problem is discussed in context of generalised thermoelasticity. Results for different theories are obtained as:
1) coupled theory (C-T): $v_0 = 0$, $\tau_0 = 0$, $n_0 = 0$, $n_1 = 1$
2) Lord-Shulman theory (L-S): $v_0 = 0$, $\tau_0 > 0$, $n_0 = 1$, $n_1 = 1$
3) Green-Lindsay theory (G-L): $v_0 > 0$, $\tau_0 > 0$, $n_0 = 0$, $n_1 = 1$

In L.H.S. of Eq.(1), third and fourth term represent the source term and influence of thermal wave, plasma wave and elastic wave, whereas the second term in L.H.S. of Eq.(3) represents effect of heat generation by carrier volume and surface de-excitation in the sample, and third term describes heat generated by stress waves.

FORMULATION OF THE PROBLEM

The waves are assumed to propagate along x axis to make it a one-dimensional problem, therefore the displacement vector in semiconducting medium are considered as $\vec{u} = (u,0,0)$, where $u = u(x,t)$ which further reduces the equations of motion Eqs.(1)-(3) and constitutive relations Eq.(4) in one dimension as follows,

$$(\lambda+2\mu-p)\frac{\partial^2 u}{\partial x^2}-\gamma\left(1+v_0\frac{\partial}{\partial t}\right)\frac{\partial T}{\partial x}-\delta_n\frac{\partial N}{\partial x}=\rho\frac{\partial^2 u}{\partial t^2}\,, \tag{5}$$

$$D_e\frac{\partial^2 N}{\partial x^2}-\frac{1}{\tau}N+\kappa T-\frac{\partial N}{\partial t}=0\,, \tag{6}$$

$$k^*\frac{\partial^2 T}{\partial x^2}-\frac{E_g}{\tau}N+\gamma T_0\left(n_1+n_0\tau_0\frac{\partial}{\partial t}\right)\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}\right)- -\rho C^*\left(n_1+n_0\tau_0\frac{\partial}{\partial t}\right)\frac{\partial T}{\partial t}=0\,. \tag{7}$$

The stress component σ_{xx} in one dimension reduces to,

$$\sigma_{xx}=-p+(\lambda+2\mu)\frac{\partial u}{\partial x}-(3\lambda+2\mu)(\alpha_t T+d_n N)\,. \tag{8}$$

Further, for the convenience of numerical computations, following dimensionless quantities are introduced,

$$x'=\frac{1}{c_1t^*}x,\ u'=\frac{1}{c_1t^*}u,\ t'=\frac{t}{t^*},\ p'=p,\ \sigma'_{ij}=\frac{\sigma_{ij}}{\mu},$$
$$v'_0=\frac{1}{t^*}v_0,\ \tau'_0=\frac{1}{t^*}\tau_0,\ T'=\frac{\gamma T}{\lambda+2\mu},\ N'=\frac{\delta_n}{\lambda+2\mu}N\,, \tag{9}$$

where: $c_1^2=\dfrac{\lambda+2\mu}{\rho}$, $t^*=\dfrac{k^*}{\rho C^* c_1^2}$.

Using Eq.(9) in Eqs.(5)-(8), we get the following non-dimensional equations and stress component in semiconducting medium with hydrostatic initial stress (after dropping primes) as,

$$(\lambda+2\mu-p)\frac{\partial^2 u}{\partial x^2}-\lambda\left(1+v_0\frac{\partial}{\partial t}\right)\frac{(\lambda+2\mu)}{\gamma}\frac{\partial T}{\partial x}-(\lambda+2\mu)\frac{\partial N}{\partial x}= =\frac{\rho c_1^2t^2}{t^{*2}}\frac{\partial^2 u}{\partial t^2}\,, \tag{10}$$

$$\frac{D_e}{c_1^2t^{*2}}\frac{\partial^2 N}{\partial x^2}-\frac{1}{\tau}N+\frac{\kappa\delta_n}{\gamma}T-\frac{1}{t^*}\frac{\partial N}{\partial t}=0\,, \tag{11}$$

$$\frac{\rho k^*}{t^{*2}\gamma}\frac{\partial^2 T}{\partial x^2}-\frac{E_g(\lambda+2\mu)}{\tau\delta_n}N+\frac{\gamma T_0}{t^*}\left(n_1+n_0\tau_0\frac{\partial}{\partial t}\right)\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}\right)- -\frac{\rho C^*}{\gamma t^*}\left(n_1+n_0\tau_0\frac{\partial}{\partial t}\right)\frac{\partial T}{\partial t}=0\,. \tag{12}$$

SOLUTION OF THE PROBLEM

The considered physical variables may be decomposed, and the solution may be assumed in the form:

$$\{u,N,T\}=[\bar{u},\bar{N},\bar{T}](x)\exp(\omega t)\,, \tag{13}$$

where: ω is complex frequency.

Using the solution given by Eq.(13) in Eqs.(10)-(12), we obtain the following equations:

$$(a_1D^2-a_2)\bar{u}-a_3D\bar{N}-a_4D\bar{T}=0\,, \tag{14}$$

$$(b_1D^2-b_2)\bar{N}+b_3\bar{T}=0\,, \tag{15}$$

$$d_1D\bar{u}-d_2\bar{N}+(d_3D^2-d_4)\bar{T}=0\,, \tag{16}$$

where:
$a_1=(\lambda+2\mu-p)$; $a_2=\rho c_1^2\omega^2$; $a_3=\lambda+2\mu$; $a_4=(\lambda+2\mu)\cdot(1+v_0\omega)$; $D=d/dx$; $b_1=D_e/c_1^2t^{*2}$; $b_2=(1/\tau)+(\omega/t^*)$; $b_3=\kappa\delta_n/\gamma$; $d_1=(\omega\gamma T_0/t^*)(n_1+n_0\omega\tau_0)$; $d_2=E_g(\lambda+2\mu)/\tau\delta_n$; $d_3=\rho k^*/\gamma t^{*2}$; $d_4=(\rho C^*\omega/\gamma t^*)(\lambda+2\mu)(n_1+n_0\omega\tau_0)$. (17)

Solving Eqs.(14)-(16), we obtain a sixth order differential equation given by,

$$[D^6+AD^4+BD^2+C](\bar{u},\bar{N},\bar{T})=0\,, \tag{18}$$

where:

$$A=\frac{a_4b_1d_1-a_1b_1d_4-a_2b_1d_3-a_1b_2d_3}{a_1b_1d_3}\,,$$
$$B=\frac{a_1b_3d_2-a_3b_3d_1+a_2b_1d_4-a_4b_2d_1+a_1b_2d_4+a_2b_2d_3}{a_1b_1d_3}\,,$$
$$C=-\frac{a_2(b_2d_4+b_3d_2)}{a_1b_1d_3}\,. \tag{19}$$

The solution of Eq.(18) may be expressed in the form:

$$\bar{T}=E_1e^{-k_1x}+E_2e^{k_1x}+E_3e^{-k_2x}+E_4e^{k_2x}+E_5e^{-k_3x}+E_6e^{k_3x}, \tag{20}$$
$$\bar{N}=E_1^*e^{-k_1x}+E_2^*e^{k_1x}+E_3^*e^{-k_2x}+E_4^*e^{k_2x}+E_5^*e^{-k_3x}+E_6^*e^{k_3x}, \tag{21}$$
$$\bar{u}=E_1^{**}e^{-k_1x}+E_2^{**}e^{k_1x}+E_3^{**}e^{-k_2x}+E_4^{**}e^{k_2x}+E_5^{**}e^{-k_3x}+E_6^{**}e^{k_3x}, \tag{22}$$

where: k_i (I = 1,2,3) are the roots of Eq.(18); and the coupling constants E_i^* and E_i^{**} are given by,

$$E_1^*=P_{11}E_1,\ E_2^*=P_{11}E_2,\ E_3^*=P_{12}E_3,\ E_4^*=P_{12}E_4,\ E_5^*=P_{13}E_5,$$
$$E_6^*=P_{13}E_6,\ E_1^{**}=P_{21}E_1,\ E_2^{**}=-P_{21}E_2,\ E_3^{**}=P_{22}E_3,$$
$$E_4^{**}=-P_{22}E_4,\ E_5^{**}=P_{23}E_5,\ E_6^{**}=-P_{23}E_6, \tag{23}$$

and
$$P_{1i}=\frac{b_3}{b_2-b_1k_i^2},\ P_{2i}=\frac{d_3k_i^2-d_4-d_2P_{1i}}{d_1k_i}. \tag{24}$$

BOUNDARY CONDITIONS

We consider a semiconducting rod under photothermal theory at a uniform temperature T_0 with its boundary $0\le x\le l$, free of stress and subjected to sudden heating so that the boundary conditions are,

(i) $u(0,t)=0$,
(ii) $u(l,t)=0$,
(iii) $N(0,t)=0$,
(iv) $N(l,t)=0$,
(v) $T(0,t)=P_0\exp(\omega t)$,
(vi) $T(l,t)=0$. (25)

Using Eq.(13), Eqs.(20)-(22) in boundary conditions Eq. (25), we get the following non-homogeneous system of six equations:

$$P_{21}E_1-P_{21}E_2+P_{22}E_3-P_{22}E_4+P_{23}E_5-P_{23}E_6=0\,, \tag{26}$$

$$P_{21}E_1e^{-k_1l}-P_{21}E_2e^{k_1l}+P_{22}E_3e^{-k_2l}-P_{22}E_4e^{k_2l}+ +P_{23}E_5e^{-k_3l}-P_{23}E_6e^{-k_4l}=0\,, \tag{27}$$

$$E_1+E_2+E_3+E_4+E_5+E_6=P_0\,, \tag{28}$$

$$E_1e^{-k_1l}+E_2e^{k_1l}+E_3e^{-k_2l}+E_4e^{k_2l}+E_5e^{-k_3l}+E_6e^{-k_3l}=0, \tag{29}$$

$$P_{11}E_1+P_{11}E_2+P_{12}E_3+P_{12}E_4+P_{13}+E_5+P_{13}E_6=0\,, \tag{30}$$

$$P_{11}E_1e^{-k_1l}+P_{11}E_2e^{k_1l}+P_{12}E_3e^{-k_2l}+P_{12}E_4e^{k_2l}+ +P_{13}E_5e^{-k_3l}+P_{13}E_6e^{k_3l}=0\,. \tag{31}$$

The non-homogeneous system above of six equations is solved by developing codes in MATLAB® and the values of constants E_n (n = 1, …6) are evaluated.

Using the expressions of $\bar{u}$, $\bar{N}$, and $\bar{T}$ given by Eqs.(20)-(22) in the Eq.(13), the displacement component, stress, carrier density, and temperature field in the semiconducting medium are obtained.

NUMERICAL RESULTS

To investigate the numerical approach of the results obtained, we consider the material properties of silicon (Si) material. The physical constants for silicon are given by

Song et al. /34/ as: $\lambda = 3.64\times10^{10}$ N/m^2, $\mu = 5.46\times10^{10}$ N/m^2, $\rho = 2330$ kg/m^3, $T_0 = 800$ K, $\tau = 5\times10^{-5}$ s, $D_e = 2.5\times10^{-3}$ m^2/s, $E_g = 1.11$ V, $\alpha_t = 4.14\times10^{-6}$ 1/K, $k_0 = 150$ W/mK, $d_n = 9\times10^{-31}$ m^3, $C^* = 695$ J/kgK, $s = 2$ m/s, $b = 0.6$, $P_0 = 1.0$.

The numerical results are obtained for displacement, force stress, carrier density, and temperature distribution for $l = 1.0$ against horizontal distance x. The graphical results are shown for L-S, G-L, and C-T theories of thermoelasticity in the presence and absence of hydrostatic initial stress ($p = 0$, and $p = 5.0$).

DISCUSSION

The values of normal displacement and carrier density lie in a very short range in the interval $0 \le x \le 7.0$. The values of normal stress and temperature field are also less in magnitude in the range $0 \le x \le 6.0$. The values of normal displacement are quite significant in nature for LS theory with hydrostatic initial stress and CT theory without hydrostatic initial stress in the range $7.0 \le x \le 10.0$. The values of carrier density and temperature field are very close to each other for LS theory (with hydrostatic initial stress) and CT theory (without hydrostatic initial stress) in the range $7.0 \le x \le 10.0$. These variations of normal displacement, normal stress, carrier density and temperature field are presented in Figs. 1-4, respectively.

CONCLUSION

The numerical and graphical results of the present problem conclude that:

(a) values of all the quantities are less in magnitude in the initial range irrespective of theory of thermoelasticity and presence of initial stress;

(b) variations of normal displacement and normal force stress are more significant for LS theory with hydrostatic initial stress in the range $7.0 \le x \le 10.0$;

(c) significant effect of the variation of quantities is observed in the range $7.0 \le x \le 10.0$.

(d) the present problem finds its applications in dynamical problems involving thermoelastic rod heated from one end.

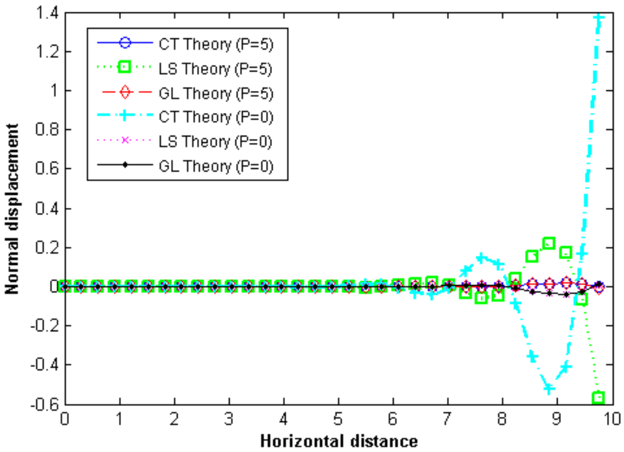

Figure 1. Variation of displacement u with horizontal distance x.

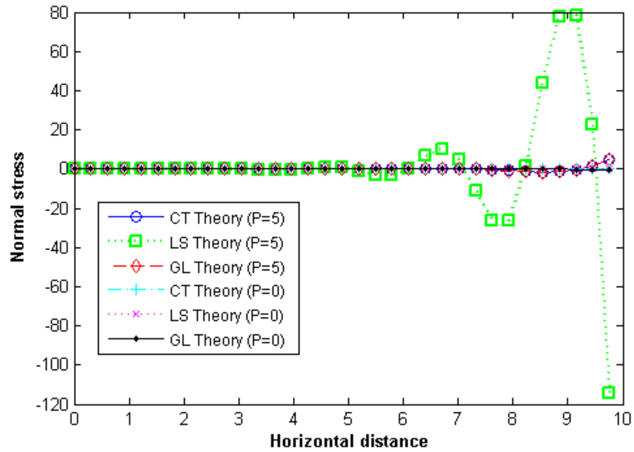

Figure 2. Variation of force stress σ_{xx} with horizontal distance x.

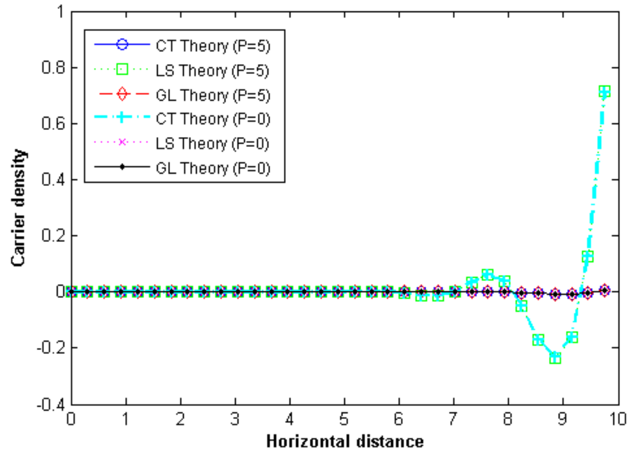

Figure 3. Variation of carrier density N with horizontal distance x.

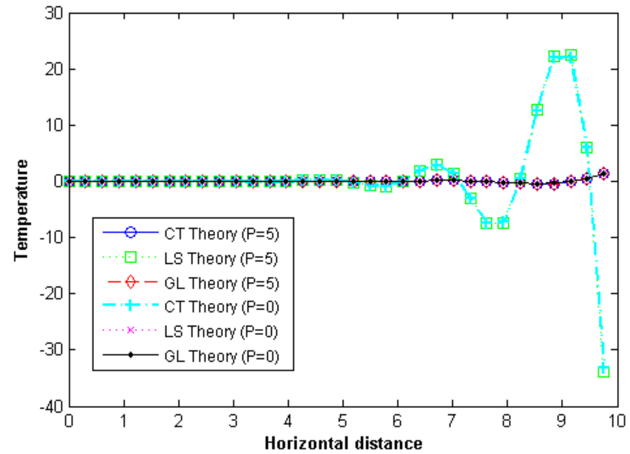

Figure 4. Variation of temperature field T with horizontal distance x.

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