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RAYLEIGH WAVE IN SEMICONDUCTOR MEDIUM UNDER PHOTOTHERMAL THEORY

FOTOTERMALNA TEORIJA REJLIJEVOG TALASA U POLUPROVODNIČKOJ SREDINI

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Abstract

The present investigation deals with study of propagation of Rayleigh wave in semiconducting medium under photothermal theory. The governing equations for two-dimensional semi-infinite semiconducting medium at thermally insulated stress free surface are solved for surface wave solutions. Velocity equation for Rayleigh wave is obtained showing the dispersive nature of the wave.

Izvod

U radu su predstavljena istraživanja o prostiranju Rejlijevog talasa u poluprovodničkoj sredini, sa primenom fototermalne teorije. Odgovarajuće jednačine za dvodimenzionalnu polubeskonačnu poluprovodničku sredinu kod toplotno izolovane površine, bez prisustva napona, su rešene za slučaj površinskih talasa. Dobijena je jednačina brzine Rejlijevog talasa, koja pokazuje disperzionu prirodu talasa.

INTRODUCTION

Thermoelasticity deals with a dynamical system whose interaction with surroundings includes not only mechanical work and external work but exchange of heat also. Biot /1/ formulated the coupled thermoelasticity theory to eliminate the paradox inherent in the classical uncoupled theory that elastic deformation has no effect on the temperature. The generalized theory of thermoelasticity is a modified version of classical uncoupled and coupled theory of thermoelasticity developed by Lord and Shulman /2/, and Green and Lindsay /3/. They treated heat propagation as wave phenomenon rather than diffusion phenomenon. Green and Naghdi /4/ postulated a new concept of thermoelasticity which is called thermoelasticity without energy dissipation in which the classical Fourier law is replaced by a heat flux rate temperature gradient relation. The above theories are reviewed by Hetnarski and Ignaczak /5/, and Ignaczak and Ostoja-Starzewski /6/.

Study of wave propagation has various applications in fields of seismology, geophysical exploration engineering, astrophysical problems, aerospace, nuclear industry, oil and mineral exploration, etc. In earthquake engineering study of surface waves, it is important due to the stratification in the earth's crust. Rayleigh waves, Love waves and Stoneley waves are particular cases of general surface waves which play an important role in earthquake spectrum analysis. Rayleigh waves are extensively used in material characterization and to analyse structural and mechanical properties of objects due to their property of travelling along the surface of solids. Surface defects of thick solids can be discovered using Rayleigh waves. In 1885, Lord Rayleigh /7/ carried out study on propagation of surface waves along the free surface of an isotropic elastic solid. Thermal effects on the velocity of Rayleigh waves were studied by Lockett /8/. A study on propagation of thermoelastic Rayleigh waves in a half space subjected to large uniform extension at constant temperature in three mutually perpendicular directions was carried out by Flavin /9/. Effect of heat conduction in a semi-infinite elastic solid on propagation of Rayleigh waves was investigated by Chadwick and Windle /10/, for two particular cases. In the first case the surface of the solid is maintained at constant temperature and in the second case the surface of the solid is thermally insulated. A study on Rayleigh waves for anisotropic homogenous thermoelastic half space was carried out by Chirita, /11/. Response of the thermal source in transversely isotropic thermoelastic materials with two temperatures and without energy dissipation was thoroughly investigated by Abbas et al. /12/.

The photothermal method was first discovered by Gordan et al. /13/ on finding an intracavity sample and laser based apparatus producing photothermal blooming. Kreuzer /14/ demonstrated the use of photoacoustic spectroscopy for sensitive analysis. Various researchers /15-17/ had used the photothermal methods for measuring various parameters such as sound velocity, surface thickness, temperature, thermal diffusivities, specific heat, and bulk flow velocities. Todorović et al. /18/ investigated production of periodic elastic deformation by photoexcited free carriers for semiconducting materials. A system of elastic and coupled plasma and a thermoelastic wave was analysed by Todorović /19/. Song et al. /20/ investigated the reflection of plane waves under photothermal theory in a semi-conducting medium. Thermoelectronic wave coupling was studied by Mandelis et al. /21/ in laser photothermal theory of semi conductors.

Todorović /22/ and Todorović et al. /23/ investigated properties of waves and electronic strain contributions in semiconductors. The effect of initial stress and a temperature dependent parameter in dual phase lag model on a semiconductor material was analysed by Othman et al. /24/. Lotfy /25/ studied photothermal waves in a semiconducting medium for two temperatures and hydrostatic initial stress under dual phase lag model. Lotfy and Sarkar /26/ studied memory-dependent derivatives in generalized thermoelasticity with two-temperature for a photothermal semiconducting medium. Recently Ailawalia and Kumar /27/ investigated the effect of ramp type heating under photothermal theory in semiconducting medium, and Lotfy et al. /28/ investigated the influence of Hall current microtemperature in magneto-elastic semiconductor material.

The aim of this paper is to investigate the behaviour of Rayleigh wave in semiconducting medium under photothermal theory. Thermally insulated stress free boundaries are considered and equations governing the two-dimensional semiconducting medium are solved for obtaining surface wave solutions. Biquadratic equation governing the velocity of Rayleigh wave is found showing the fact that Rayleigh wave is dispersive in nature.

BASIC EQUATIONS

In a semiconducting medium with isotropic and homogenous properties, equations for coupled plasma, thermal and elastic transport are given by Song et al. /20/

$$\mu\nabla^2\vec{u}(\vec{r},t)+(\lambda+\mu)\nabla(\nabla.\vec{u}(\vec{r},t))-\gamma\nabla T(\vec{r},t)-\delta_d\nabla N(\vec{r},t)= =\rho\frac{\partial^2\vec{u}(\vec{r},t)}{\partial t^2}, \quad (1)$$

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

$$t_c\nabla^2 T(\vec{r},t)-\frac{S_e}{\tau}N(\vec{r},t)+\gamma T_0\nabla.\frac{\partial\vec{u}(\vec{r},t)}{\partial t}-\rho C_e\frac{\partial T(\vec{r},t)}{\partial t}=0 \quad (3)$$

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

A rectangular cartesian coordinate system OXYZ with z-axis vertically downward is taken. We take displacement vector $\vec{u}=(u,0,w)$, where $u=u(x,z,t)$, $w=w(x,z,t)$

$$(\lambda+2\mu)\frac{\partial^2 u}{\partial x^2}+(\lambda+\mu)\frac{\partial^2 w}{\partial x\partial z}+\mu\frac{\partial^2 u}{\partial z^2}-\gamma\frac{\partial T}{\partial x}-\delta_d\frac{\partial N}{\partial x}=\rho\frac{\partial^2 u}{\partial t^2} \quad (4)$$

$$\mu\frac{\partial^2 w}{\partial x^2}+(\lambda+\mu)\frac{\partial^2 u}{\partial x\partial z}+(\lambda+2\mu)\frac{\partial^2 w}{\partial z^2}-\gamma\frac{\partial T}{\partial z}-\delta_d\frac{\partial N}{\partial z}=\rho\frac{\partial^2 w}{\partial t^2} \quad (5)$$

$$A_e\nabla^2 N-\frac{1}{\tau}N+\kappa T-\frac{\partial N}{\partial t}=0 \quad (6)$$

$$t_c\nabla^2 T-\frac{S_e}{\tau}N+\gamma T_0\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}\right)-\rho C_e\frac{\partial T}{\partial t}=0 \quad (7)$$

Further constitutive stress relations can be written as below (Song et al. /20/),

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

$$\sigma_{zz}=(\lambda+2\mu)\frac{\partial w}{\partial z}+\lambda\frac{\partial u}{\partial x}-(3\lambda+2\mu)(\alpha_t T+d_n N), \quad (9)$$

$$\sigma_{zx}=\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right), \quad (10)$$

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

FORMULATION OF PROBLEM

We introduce the following dimensionless quantities in the above equations for making numerical calculations convenient,

$$x'=\frac{1}{c_T t*}x,\quad z'=\frac{1}{c_T t*}z,\quad u'=\frac{1}{c_T t*}u,\quad w'=\frac{1}{c_T t*}w,$$

$$t'=\frac{t}{t*},\quad \sigma'_{ij}=\frac{\sigma_{ij}}{\mu},\quad T'=\frac{\gamma T}{(\lambda+2\mu)},\quad N'=\frac{\delta_d N}{(\lambda+2\mu)},$$

$$c_T^2=\frac{(\lambda+2\mu)}{\rho},\quad t*=\frac{t_c}{\rho C_e c_T^2}. \quad (11)$$

After using above dimensionless variables in Eqs.(4) to (10) and dropping primes, we obtain the following non-dimensional equations,

$$\frac{\partial^2 u}{\partial x^2}+a_{11}\frac{\partial^2 w}{\partial x\partial z}+a_{12}\frac{\partial^2 u}{\partial z^2}-\frac{\partial T}{\partial x}-\frac{\partial N}{\partial x}=\frac{\partial^2 u}{\partial t^2}, \quad (12)$$

$$a_{12}\frac{\partial^2 w}{\partial x^2}+a_{11}\frac{\partial^2 u}{\partial x\partial z}+\frac{\partial^2 w}{\partial z^2}-\frac{\partial T}{\partial z}-\frac{\partial N}{\partial z}=\frac{\partial^2 w}{\partial t^2}, \quad (13)$$

$$\nabla^2 N-b_{11}N+b_{12}T-b_{13}\frac{\partial N}{\partial t}=0, \quad (14)$$

$$\nabla^2 T-c_{11}N+c_{12}\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}\right)-c_{13}\frac{\partial T}{\partial t}=0, \quad (15)$$

$$\sigma_{xx}=c_{14}\frac{\partial u}{\partial x}+c_{15}\frac{\partial w}{\partial z}-(c_{14}T+c_{14}N), \quad (16)$$

$$\sigma_{zz}=c_{14}\frac{\partial w}{\partial z}+c_{15}\frac{\partial u}{\partial x}-(c_{14}T+c_{14}N), \quad (17)$$

$$\sigma_{zx}=\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}, \quad (18)$$

where: $a_{11}=\dfrac{(\lambda+\mu)}{(\lambda+2\mu)}$; $a_{12}=\dfrac{\mu}{(\lambda+2\mu)}$; $b_{11}=\dfrac{c_T^2 t*^2}{\tau A_e}$; $b_{12}=\dfrac{\kappa\delta_d c_T^2 t*^2}{\gamma A_e}$; $b_{13}=\dfrac{c_T^2 t*}{A_e}$; $c_{11}=\dfrac{S_e(\lambda+2\mu)t*^2\gamma}{\tau\delta_d t_c\rho}$; $c_{12}=\dfrac{\gamma^2 T_0 t*}{t_c\rho}$;

$$c_{13}=\frac{C_e(\lambda+2\mu)t*}{t_c};\quad c_{14}=\frac{1}{a_{12}};\quad c_{15}=\frac{\lambda}{\mu}. \quad (19)$$

We consider the following surface wave solution for waves propagating in half space in x-direction,

$$\{u,w,T,N\}=\{A,B,C,D\}\exp\{-\chi z+i(sx-pt)\}\ , \quad (20)$$

where: p is angular velocity; s is wave number; and χ is constant which is to be determined.

Using Eq.(20) in Eqs.(12) to (15) we get the following

$$\left(p^2-s^2+a_{12}\chi^2\right)A-a_{11}is\chi B-isC-isD=0\ , \quad (21)$$

$$-a_{11}is\chi A+\left(\chi^2-a_{12}s^2+p^2\right)B+\chi C+\chi D=0\ , \quad (22)$$

$$b_{12}C+\left(\chi^2-s^2-b_{11}+ipb_{13}\right)D=0\ , \quad (23)$$

$$c_{12}psA+c_{12}i\chi pB+\left(\chi^2-s^2+c_{13}ip\right)C-c_{11}D=0\ . \quad (24)$$

Equations (21) to (24) constitute a homogenous system of four equations in four unknowns, namely A, B, C, D, and determinant of coefficients of these four unknowns must vanish for the existence of a non-trivial solution that will further lead to the following equation of the eighth degree,

$$\chi^8+X_1\chi^6+X_2\chi^4+X_3\chi^2+X_4=0\ . \quad (25)$$

Values of X_1, X_2, X_3, X_4 are given in the Appendix. Equation (25) is biquadratic in χ^2 whose roots are given by χ_1^2, χ_2^2, χ_3^2, χ_4^2, which further leads to the following particular solutions in half space, $z > 0$,

$$u=A_1\exp\{-\chi_1 z+i(sx-pt)\}+A_2\exp\{-\chi_2 z+i(sx-pt)\}+A_3\exp\{-\chi_3 z+i(sx-pt)\}+A_4\exp\{-\chi_4 z+i(sx-pt)\}\ , \quad (26)$$

$$w=B_1\exp\{-\chi_1 z+i(sx-pt)\}+B_2\exp\{-\chi_2 z+i(sx-pt)\}+B_3\exp\{-\chi_3 z+i(sx-pt)\}+B_4\exp\{-\chi_4 z+i(sx-pt)\}\ , \quad (27)$$

$$T=C_1\exp\{-\chi_1 z+i(sx-pt)\}+C_2\exp\{-\chi_2 z+i(sx-pt)\}+C_3\exp\{-\chi_3 z+i(sx-pt)\}+C_4\exp\{-\chi_4 z+i(sx-pt)\}\ , \quad (28)$$

$$N=D_1\exp\{-\chi_1 z+i(sx-pt)\}+D_2\exp\{-\chi_2 z+i(sx-pt)\}+D_3\exp\{-\chi_3 z+i(sx-pt)\}+D_4\exp\{-\chi_4 z+i(sx-pt)\}\ , \quad (29)$$

where: B_j, C_j, D_j can be expressed in terms of A_j,

$$B_j=E_jA_j\ ,\quad C_j=F_jA_j\ ,\quad D_j=G_jA_j\ . \quad (30)$$

Values of E_j, F_j, G_j are given in the Appendix.

BOUNDARY CONDITIONS

The following boundary conditions at the thermally insulated stress free surface $z = 0$ are applied,

$$\sigma_{zz}=0,\quad \sigma_{zx}=0,\quad \frac{\partial T}{\partial z}=0,\quad \frac{\partial N}{\partial x}-\frac{\kappa}{A_e}N=0\ . \quad (31)$$

As z approaches infinity, the stresses, displacement, temperature, and carrier density satisfy the radiation condition. Using above boundary conditions in Eqs.(26) to (29), we get the following expressions

$$-c_{14}\sum_{j=1}^{4}\chi_jB_j+c_{15}is\sum_{j=1}^{4}A_j-c_{14}\sum_{j=1}^{4}C_j-c_{14}\sum_{j=1}^{4}D_j=0\ , \quad (32)$$

$$-\sum_{j=1}^{4}\chi_jA_j+is\sum_{j=1}^{4}B_j=0\ , \quad (33)$$

$$-\sum_{j=1}^{4}\chi_jC_j=0\ , \quad (34)$$

$$is\sum_{j=1}^{4}D_j-\frac{\kappa}{A_e}\sum_{j=1}^{4}D_j=0\ . \quad (35)$$

Eliminating B_j, C_j, D_j using Eq.(30) we get the following relations in terms of A_1, A_2, A_3, and A_4 as

$$\sum_{j=1}^{4}L_jA_j=0,\quad \sum_{j=1}^{4}M_jA_j=0,\quad \sum_{j=1}^{4}N_jA_j=0,\quad \sum_{j=1}^{4}O_jA_j=0 \quad (36)$$

where values of L_j, M_j, N_j, O_j are given in the Appendix.

Now the above system is a homogenous system of four equations in four unknowns, and for non-trivial solution of this system, the determinant of coefficients must vanish which upon calculations will yield the following equation,

$$(L_1M_2-L_2M_1)(N_3O_4-N_4O_3)+(L_3M_1-L_1M_3)(N_2O_4-N_4O_2)+(L_2M_3-L_3M_2)(N_1O_4-N_4O_1)+$$
$$+(L_1M_4-L_4M_1)(N_2O_3-N_3O_2)+(L_4M_2-L_2M_4)(N_1O_3-N_3O_1)+(L_3M_4-L_4M_3)(N_1O_2-N_2O_1)=0\ . \quad (37)$$

The above equation governs the velocity of the Rayleigh wave in semiconducting medium under photothermal theory. Involvement of frequency in this equation shows the dispersive nature of the Rayleigh wave.

APPENDIX

$$X_1=\frac{e'+d'a_{12}}{a_{12}}\ ,\quad X_2=\frac{f'+d'e'-a'}{a_{12}}\ ,\quad X_3=\frac{g'+d'f'-b'}{a_{12}}\ ,$$

$$X_4=\frac{d'g'-c'}{a_{12}}\ ,\quad E_j=i\frac{a_{12}\chi_j^3+\left(p^2-s^2+a_{11}s^2\right)\chi_j}{\chi_j^2(s-a_{11}s)+\left(sp^2-a_{12}s^3\right)}\ ,$$

$$F_j=-\frac{h'+l'}{m'n'}\ ,\quad G_j=\frac{(h'+l')q'}{m'n'}\ ,\quad a'=-a_{12}b_{12}(c_{11}+ic_{12}p)\ ,$$

$$b'=b_{12}c_{11}a_{12}\left(a_{12}s^2-p^2\right)-b_{12}\left(p^2-s^2\right)(c_{11}+ic_{12}p)-$$
$$-b_{12}\left(s^2a_{11}^2c_{11}+a_{11}is^2pc_{12}+ia_{11}c_{12}s^2p-is^2c_{12}p\right)$$

$$c'=b_{12}c_{11}\left(p^2-s^2\right)\left(a_{12}s^2-p^2\right)+ib_{12}c_{12}ps^2\left(p^2-a_{12}s^2\right)\ ,$$

$$d'=ipb_{13}-s^2-b_{11}\ ,$$

$$e'=a_{12}\left(c_{13}ip-s^2-a_{12}s^2+p^2-ic_{12}p\right)+\left(p^2-s^2\right)+a_{11}^2s^2\ ,$$

$$f'=a_{12}\left(p^2-a_{12}s^2\right)\left(c_{13}ip-s^2\right)+\left(c_{13}ip-s^2-a_{12}s^2+p^2-ic_{12}p\right)\times$$
$$\times\left(p^2-s^2\right)+a_{11}is\left(a_{11}is^3+a_{11}sc_{13}p-c_{12}ps\right)+ic_{12}ps^2(1-a_{11})\ ,$$

$$g'=\left(p^2-s^2\right)\left(p^2-a_{12}s^2\right)\left(c_{13}ip-s^2\right)+ic_{12}ps^2\left(p^2-a_{12}s^2\right),$$

$$h'=\chi_j(a_{11}isc_{11}+c_{12}ps)\left[\chi_j^2(s-a_{11}s)+\left(sp^2-a_{12}s^3\right)\right],$$

$$l'=i\left\{\chi_j^2(c_{11}+c_{12}ip)+c_{11}\left(p^2-a_{12}s^2\right)\right\}\times$$
$$\times\left\{a_{12}\chi_j^3+\left(p^2-s^2+a_{11}s^2\right)\chi_j\right\}\ ,$$

$$m'=\chi_j^3+\chi_j\left(c_{11}-s^2+c_{13}ip\right),\quad n'=\chi_j^2(s-a_{11}s)+\left(sp^2-a_{12}s^3\right),$$

$$q' = \frac{b_{12}}{\chi_j^2 - s^2 - b_{11} + ipb_{13}},\ L_j = -c_{14}\chi_j E_j + c_{15} is - c_{14} F_j - c_{14} G_j,$$

$$M_j = -\chi_j + isE_j,\ N_j = -\chi_j F_j,\ O_j = \left(is - \frac{\kappa}{A_e}\right) G_j.$$

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