TWO-TEMPERATURE PHOTOTHERMAL INTERACTIONS IN A SEMICONDUCTING MATERIAL WITH A 3D SPHERICAL CAVITY

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АННОТАЦИЯ

научной статьи по физике, автор научной работы — Ibrahim A. Abbas, Aatef D. Hobiny

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ПРЕДВАРИТЕЛЬНЫЙ ПРОСМОТР

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Two-temperature photothermal interactions in a semiconducting material with a 3D spherical cavity

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In this paper, a two-temperatures photothermoelastic interactions in an infinite semiconductor medium with a spherical cavity were studied using mathematical methods. The cavity internal surface is traction free and the carrier density is photogenerated by boundary heat flux with an exponentially decaying pulse. Laplace transform techniques are used to obtain the exact solution of the problem in the transformed domain by the eigenvalue approach and the inversion of Laplace transforms has been carried numerically. Numerical computations have been also performed for a silicon-like semiconductor material.

Keywords: semiconducting material, two temperature, Laplace transform, spherical cavity

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Двухтемпературное фототермическое взаимодействие в полупроводниковой среде со сферической полостью

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В работе с использованием математических методов изучено двухтемпературное фототермоупругое взаимодействие в бесконечной полупроводниковой среде со сферической полостью. Внутренняя поверхность полости свободна от нагрузки, а плотность носителей определяется фотогенерацией граничным тепловым потоком с экспоненциально затухающим импульсом. С помощью преобразований Лапласа получено точное решение задачи в преобразованном пространстве методом собственных значений,

ДВУХТЕМПЕРАТУРНОЕ ФОТОТЕРМИЧЕСКОЕ ВЗАИМОДЕЙСТВИЕ В ПОЛУПРОВОДНИКОВОЙ СРЕДЕ СО СФЕРИЧЕСКОЙ ПОЛОСТЬЮ

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ТЕКСТ НАУЧНОЙ РАБОТЫ

на тему «Two-temperature photothermal interactions in a semiconducting material with a 3D spherical cavity»

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Two-temperature photothermal interactions in a semiconducting material

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Ключевые слова: полупроводниковый материал, двухтемпературный, преобразование Лапласа, сферическая полость

1. Introduction

What happens when a laser beam with an energy E is focused on a semiconductor with band gap energy Eg? If E > Eg, then an electron will be jump from the valence band to an energy level (E - Eg) above the conduction band. Nonradiative transitions will occur because photoexcited free carries will relax to one of the empty levels nearby the bottom of the conduction band. These nonradiative transitions are followed by process called recombination which takes place through the formation of electron-hole pairs. Before the recombination, there is electron and hole plasma, which density is controlled by the diffusion behavior that similar to heat flow of the thermal source. Thus, on the

modulation of the incident laser intensity in addition to the thermal wave, a modulated plasma density can be observed whose spatial profile is that of a critical damping wave, i.e., a plasma wave.

The theory of thermoelasticity with two temperatures was presented by Williams and Gurtin [1], Chen et al. [2] and Gurtin and Chen [3], wherein a dependence on two temperatures (thermodynamic temperature T * and conductivity temperature ^) was used instead of the classical Clausius-Duhem inequality. The first is due to the inherent mechanical processes between the particles and the elastic material layers, and the second is due to the thermal processes. Only in the last decade the thermoelasticity theory

dependent on two temperatures was developed in many works. Carrera et al. [4] have investigated the influence of two-temperature model in the vibrational analysis for an axially moving microbeam. Deswal and Kalkal [5] used the state space formulation to study the influence of two temperatures and initial stress parameters in magneto-ther-moelasticity model. Abbas et al. [6] have studied the effects of thermal source under Green-Naghdi type II in the two-temperature model for transversely isotropic thermo-elastic medium.

The different influences of electronic deformation and thermoelasticity in semiconductor materials with neglecting the coupled system of thermal, plasma, and elastic equations have been analyzed by many authors [7]. In these studies, theoretical analysis was used to describe these two phenomena that give information about the properties of carrier recombination and transport in the semiconductor. Changes in the propagation of plasma and thermal waves due to the linear coupling between heat and mass transport (i.e., thermos diffusion) were included. Kuo et al. [8] studied the interface thermal resistance and thermal conductivity of Si film on Si substrate using photothermal displacement interferometry. Nestoros et al. [9] performed a quantitative analysis of photothermal reflection versus temperature. Rosencwaig et al. [10] detailed an analysis on the local thermoelastic deformations occurred at the specimen surface due to the excitation by a focused probe beam.

The aim of the present paper is to investigate the effect of two temperatures on photothermoelastic interaction in an unbounded semiconductor medium with the spherical cavity. Based on the eigenvalue techniques and Fourier-Laplace transformations, the governing relations are processed using the numerical and analytical methods. In the Laplace domain, the eigenvalue method gives analytical solutions without any supposed restrictions on the physical variables. Numerical computations are also performed for a silicon-like semiconductor material. The results indicate that the difference between the coupled theory of thermal, plasma, and elastic waves with one temperature (b = 0) and with two temperatures (b ^ 0) are very pronounced.

2. Physical model

We will theoretically analyse of the transport in semiconducting materials with simultaneous consideration of coupled thermal, plasma, and elastic waves. The basic variables are the density of carrier n(r, t) the distribution of thermodynamic temperature, the distribution of conductivity temperature ^°(r, t) and components of elastic displacement u(r, t). In the context of the two-temperature photothermal model, the basic equations can be expressed by [11]

^V2u(r, t) + (A + ^)V(V • u(r, t)) -

d2u(r, t)

DeV2N(r, t) =

dN(r, t) N(r, t) k

-YnVN -YTVT = p-

dt2

(1)

dt

—T(r, t), (2) t

KV2^(r, t) = pCe dT(Tlt) - ^ N(r, t) + dt t

+ YT0V

du (r, t) dt '

(3)

Heat conduction correlates with the dynamical heat through the expression [2, 12]

T(r, t) = $(r, t) -bVfyr, t). (4)

The constitutive relationships are written in the form:

(r, t) = 2]ieij (r, t) +

+ (lekk (r, t) -y„N (r, t) - yTT (r, t))Sj, (5)

eij (r, t) =1 —j (r, t) + Uji (r, t)),

(6)

where b > 0 is the parameter of two temperatures, A, ^ are the Lame's constants, p is the material density, T0 is the reference temperature, ^ = ^°-T0, is the temperature conductivity increment, T = T° - T0, T° is the increment of thermodynamic temperature, N = n - n0, n0 is the carrier concentration at equilibrium, ut are the displacement components, CTj are the stress components, e^ are the strain components, ce is the specific heat at constant strain, t is the photogenerated carrier lifetime, yn = (3A + 2lx)dn, dn is the electronic deformation coefficient, yT = (3A + 2^)aT, aT is the linear thermal expansion coefficient, t is the time, K is the thermal conductivity, r is the position vector, De is the carrier diffusion coefficient, k = dn0/dT ° is the thermal activation coupling parameter [11], and i, j, k = 1, 2, 3.

3. Formulation of the problem

Let us consider a homogeneous isotropic unbounded semiconductor material containing a spherical cavity. The spherical polar coordinates (r, 6, are taken for any representative point of the body at time t with the center of the spherical hole as the origin. Due to spherical symmetry, the carrier density, thermodynamic temperature, conductivity temperature, displacement and stress are assumed to be functions of r and time t only. Thus, only the radial displacement ur = u (r, t) nonvanishing, so that

du u .

err =~dr' e66 = ew = r' er6 = 0 ery = 0 e6V = 0, (7) and the dilatation ekk will be

du 2u

ekk =3- + — • or r

(8)

The constitutive relationships for a spherically symmetric system are expressed by

a„. = (X + 2n) f- + ^ — -YnN-YtT, (9)

or r

aee =aw = (X + 2^)- + + - I - YnN - yT. (10)

r \dr r

The relation between thermodynamic and conductive temperatures will be

fa 2,

T _i-b

dli+2 di 3r2 r dr

\

(11)

Finally, Eqs. (1)-(3) for the motions, plasma and heat conduction can be rewritten as

(A + 2^)

f + 2 a« - 2

dr2 r dr r2

dN - dT = d^u

Yn -, Yx -, =P 2 dr dr dt

fa 2

D

d 2 N 2 dN

\

dr2 r dr

V y

fa 2A i

dN N -+---T,

dt TT

(12)

(13)

K

d 2i + 2 di dr2 r dr

_PCe

dT - £g

dt T

N +

„ d f du 2u . + YxT0-1 —+ —l.

' dt [dr r 1

On the internal cavity surface r = a, the boundary conditions can be expressed by CTrr (a, t) = 0, dN(r, t)

De

-K

dr di(r, t)

= SaN(a, t),

(15)

(16)

dr

=

t V^ 16tP2

(17)

where Sa is the recombination velocities on the internal cavity surface, q0 is a constant, and t is a characteristic time of the pulse heat flux [13]. For convenience, the dimensionaless variables can be considered:

N° = —, r = , T° = T, (r°, u°) = nc(r, u),

(ao ao ao) = (Orr ■ ^99 ■)

(t°, t°, to) = nc2(t, T, tp),

(18)

qo

,b° = n2c2b,

ncT0K

n = pcjK and c2 = (A, + 2^)/P- (19)

In terms of this nondimensional form of the variables in (19), Eqs. (9)-(18) can be taken in the following form (after dropping the superscript ° for convenience):

fa 2,

T _i-b

d 2i + 2 di

dr2

dr

(20) (21)

du 2u , T ^ orr _—+ m—-m,N-m2T, dr r

f du u ^ u ^ .„.

°99_°W_ m + rj + 7 " m1N - m2T' (22)

d2u 2 du 2u dN dT d2u

dr2 r dr r d 2 N 2 dN

- - —^ - m,

dr

dr dt2

_, dN m m4

+--= m-+ ^ N -—4 T,

r dr dt T T

dr2 r dr 3 dt d2i + 2 di = dT - m5 dr2 r dr dt T CTrr (a, t) = 0, dN (r, t)

N + m6

d f du 2u

dt i dr r

dr di(r, t)

dr

= m7 N (a, t),

tV^

= -qo-

where

m, =

no Y n

m2 _■

1 _ *-, '"2

1 A + 2^ 2

kTo

«4 —-, m5

4 nonDe 5

16tpP

ToYT , X + 2^'

no ^g

(23)

(24)

(25)

(26)

(27)

(28)

m7 =

ncDe

, m _ -

PCeTo À

À + 2|x

, m6

PCe

4. Solution of the problem

Let us define the Laplace transform for a function ©(r, t)

by

L[0(r, t)] = 0(r, p) = J©(r, t)e~ptdt, p> 0 . (29)

0

Using the Laplace transform, Eqs. (20)-(28) reduce to

T _i-b

f d2i dr2 r dr

_ du 2u

Orr + m-

dr r

- m,N - m2T,

_ _ . du u \ u

o99 _aw = m| "dr+ — | + — -m,N-m2T

2T ,

du 2 du 2u

dN

- +--- —r- - m,-- m2

dr2 r dr r2 d2N 2 dN

dr2 r dr

d2i + 2 di dr2 r dr Orr (a, r) = o. dN(r, t)

dr 1

dT dr

= pu,

= m3| p + - | N -

m

= pT -—5N + pm6

du + 2u dr r

dr di(r, t)

dr

= m7 N (a, t),

_ -qotp = 8(ptp +1)3'

(30)

(31)

(32)

(33)

(34)

(35)

(36)

(37)

(38)

Differentiating Eqs. (30), (34) and (35) with respect to r and using Eq. (33) yields

d2u 2 du 2u _ _ dN di

dr2 r dr

- — _ riu + r2

dr dr '

(39)

dr 2

dN dr

+2A | dN

r drI dr dN d^

dN

dr

d

dr

2 (d^Y 2 d

- + r6

dr 2

dr

I + --I ^ dr I r dr \ dr

dN

= r7u + r8—— + r9

dф

dr dr where

r1 = p2 - m2br7, r2 = m1 - m2br8, r3 = m2 - щЬ^ 1 ^ , m,

(40)

(41)

i m4 I . 1 I . , m4

r4 = b~4rT r5 = m3 I P + - I+ r8b— T I T I T

m4

r6 = (br9 -1), r7 = T

r6P

r8 =

= Pr6ri - rs/T 1 + pb(1 + /to)' * 1 + pb(1+ r6r2)

1 + pb(1 + r6r2) P(1 + r6r2)

r9 =

Let us now proceed to solve the coupled differential equations (39), (40) and (41) by the eigenvalue approach [14]. From Eqs. (39)-(41), the matrix-vector can be given in the following form:

LQ = R Q, (42)

where

d2 2d 2

L = —++ dr

2 r dr r2

dN dr

d-ф dr

T r1 r2 r3

, R = r4 r5 r6

_r7 r8 r9 _

X =

(44)

The characteristic equation of matrix R take the form

тa3 -ra2(r5 + r9 + rj) + ra(r5r9 - r6r8 + г5— + -

- r4r2 - r7r3) + r6r8r1 - r5r9r1 - r6r7r2 + r4r9r2 +

+ r5r7r3 - r4r8r3 = 0. (43)

The three roots of Eq. (43) are the eigenvalues of matrix R which defines by the form та1, та2, та3. Thus, the corresponding eigenvectors X can be calculated as

(-r6r2 + (-та + r5)r3 ^ r6(^ + r1) - r4r3

-та2 + ^(та - r1) + та^ + r4r2 The solutions of Eq. (42) which is bounded as r ^ ^ can be written as

"(r, P) = E AiXir"V2Km(ntr), (45)

i=1

where ni = -у/та", K3j2 is the modified of Bessel function of order 3/2, A1, A2 and A3 are constants that can be calculated using the boundary conditions of the problem. Hence, the field variables have the solutions with respect to r andp in the following form:

u (r, p) = E au/1/2 KV2(n-r), i=1

_ 3 "V2

N (r, p) = -E ani — Ky2 (nr)

i=1

ni 12

Φ(г, p) = -E AT—KV2(n-r),

i=1 n

_ 3 (1 - bn2) r-V2

T(r, p) = -Еад(bni)r KV2(n-r),

i=1 n

3

^rr (r, p) = E a—"V2 x i=1

(m1Ni + (1 - bn2)m2T- - n^U, x

xKyi(nir) + 2(1 m)Ui K^r)

aee (r, p) = (Л p) = E Ar 1/1 x i=1

.„2\— T7 -----2T

(47)

(48)

(49)

(50)

(

m1Ni + (1 - Ьщ)m2T- - mni Ui

ni

x KV2(n-r) + (1 m)UiK3I2(nir)

(51)

5. Numerical results and discussion

Some numerical values for the physical constants were presented in order to discuss the theoretical results observed in the previous section. Assuming that an isotropic semiconductor is a silicon-like material with the following physical constants: p = 2330 kg/m3, ce = 695 J/(kg • K), lx=5.46 x x 1010 N/m2, tp = 2, Eg = 1.11 eV, Sa = 2 m/s, n0 = 1020 1/m3, T0 = 300 K, De = 2.5 • 10-3 m2/s.

Firstly, a numerical inversion method was adopted to obtain displacement, carrier density, thermodynamic temperature, conductive temperature and stress variations. The numerical outcomes have been presented using the Riemann sum. The function of the Laplace domain transformation to the time domain can be expressed as

_mt

V (z, t) = — X

x^Re EH)"V^z, m + ^ j + ±Re[V(z, m)] j, (52)

where i refers to the imaginary part, and Re refers to the real part. For faster convergence, the numerical experiments stated that m = 4.7/1 [15]. At time t = 0.5, the calculations have been obtained. Here all the parameters/variables are taken in nondimensional form. Figures 1-3 are drawn to give comparison of the results obtained for the radial displacement, the variations of thermodynamic temperature, the conductive temperature variations, the variations of carrier density, the radial and hoop stresses for two models of

0.60.40.2-

Fig. 1. The variation of thermodynamic (a) and conductive temperature (b) with distance for different values of b: 0.0 (1), 0.2 (2), 0.5 (3)

the coupled theorem of plasma and thermoelastic waves with and without two temperatures.

Figure 1, a displays the variations of thermodynamic temperature with respect to the radial distance r. It indicates that the thermodynamic temperature field have maximum value at the boundary r = 1 and then reduces with increasing the radial distance r to reach the values of zero for large r. This figure shows that there is significant variance between the models of two temperatures (b ^ 0) and one temperature (b = 0) for all physical quantities. The thermodynamic temperature decreases with decreasing b.

Figure 1, b shows the increment of conductive temperature with respect to r. It is clear that all curves start from positive ultimate values at the internal surface r = 1 of the cavity and decrease with the increase of the radial distance r and then all curves close to zero. It is observed that the values of conductive temperature increase with the decrease of the two-temperature parameter b before the intersection of three curves. The values of conductive temperature decrease as the two-temperature parameter b decrease.

Figure 2, a explains the variation of carrier density with respect to the radial distance r for different values of the two-temperature parameter b. The carrier density has ultimate values at the internal cavity surface r = 1 then it progressively increases with decreasing the radial distance r until it close to zero. The values of carrier density increase with the decrease of the two-temperature parameter b before the intersection of three curves. However, after the

intersection, the carrier density decreases as the two-temperature parameter b decreases.

Figure 2, b represents the variations of displacement with respect to the radial distance r for two models. When the internal surface of the spherical cavity is taken to be traction free and the carrier density decays with heat flux applied on the surface, the displacement shows negative values at the cavity boundary and it attains stationary maximum values after some distance. Finally, it decreases to zero values. These figures reveal that there is significant difference between the models of two temperature (b ^ 0) and one temperature (b = 0) where the magnitude of displacement decreases with increasing b.

Figure 3, a depicts the variations of radial stress along the radial distance r. The magnitudes of radial stress begin from zero values at the cavity surface, then increase with increasing the radial distance to get stationary ultimate values, and decrease quickly as r increases to reach to zero. The magnitudes of stress increase with the decreasing the two-temperature parameter b in the range $1.0 < r < 1.9$, then decreases.

Figure 3, b shows the variations of hoop stress with respect to the radial distance r. The absolute values of hoop stress start from the maximum values at the cavity boundary, then decrease quickly as r increases to reach to zero. In addition, the values of hoop stress increase with the decreasing the two-temperature parameter b before the intersection of three curves. However, after the intersection, the

Fig. 2. The variation of carrier density (a) and displacement (b) with distance for different values of b: 0.0 (1), 0.2 (2), 0.5 (3)

Fig. 3. The variation of radial (a) and hoop stress (b) with distance for different values of b: 0.0 (1), 0.2 (2), 0.5 (3)

values of hoop stress decrease as the two-temperature parameter b decreases.

6. Conclusions

The interactions in an infinite semiconductor material with a spherical cavity has been investigated by using mathematical methods. Laplace transform technique has been employed to obtain the exact solution of the problem in the transformed domain by the eigenvalue approach and the inversion of Laplace transforms has been obtained numerically. A comparison between the present solution and the available data from a silicon-like semiconductor material has been carried out to validate the proposed solution. The results are in a good agreement.

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