Theoretical & Applied Mechanics Letters 8 (2018) 160-163

Contents lists available at ScienceDirect

Theoretical & Applied Mechanics Letters

journal homepage: www.elsevier.com/locate/taml

Wave reflection in semiconductor nanostructures

Feixiang Tang, Yaqin Song*

State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- Coupled nonlocal elasticity and coupled generazied thermoelastic theories were used to study wave reflection problem in nanostructure.
- Wave properties showed significant difference between classical theory and nonlocal theory.
- Reflection coefficient ratios showed significant under Lord–Shulman (LS), Green–Lindsay (GL), and classical dynamic (CD) theory.

ARTICLE INFO

Article history:
Received 8 January 2018
Received in revised form 24 January 2018
Accepted 5 February 2018
Available online 5 February 2018
*This article belongs to the Solid Mechanics.

Keywords:
Nonlocal theory
Generalized thermoelastic theory
Wave velocity
Reflection coefficient rate

ABSTRACT

Based on nonlocal thermoelastic theory, this article studies the reflection of waves in nanometer semi-conductor media. Firstly, the governing equations are established based on coupled nonlocal elasticity theory, plasma diffusion equation, and moving equation. Then, using the harmonic method, the solution of the dissipation equation and the analytic expression of the reflection coefficient rate are obtained. Finally, the influences of nonlocal parameters on wave velocities are showed graphically. It is found that after the introduction of nonlocal effect, the phase and group velocities all show the attenuation, and as the frequency increases, the nonlocal parameter is bigger, and the decay rate is faster. The reflection coefficient rate varies greatly with different theories, with different reflection coefficient rates depending on the incident angle.

Micro- and nano-structures have been used widely in many fields like biological, medical, environmental, etc. With the reduction of size, the study showed that the state of the object is not only related to the state of the current point, but also related to other matter points and historical time. Nonlocal theory can be used to describe this characterization. There are many nonlocal theories, such as stress gradient theory [1], strain gradient theory [2], and so on. Compared with classical elasticity theory, the results from nonlocal elasticity theory showed better agreement with molecular dynamics simulation [3] and phonon dispersion test observations.

Classical Fourier heat conduction law [4, 5] can explain the relationship between the heat flux density and the temperature gradient. However its defection is that the temperature control equation is a parabolic partial differential equation, indicating that the thermal signal spreads at an infinite rate, which is inconsistent with the hysical reality in low temperatures or very short heat conditions. In order to correct this defection, generalized thermoelastic theories were born. Lord–Shulman (LS) theory [6] and Green–Lindsay (GL) theory [7] have been widely used. The LS model and GL model introduces one or two thermal relaxation times, which allows the thermal signal to propagate at a finite velocity, and the two theories are in different structures. One cannot exist as a special case of the other's, but both can be degenerated to the traditional classical dynamic (CD) theory, which represents the classical thermoelastic theory based on Fourier's law). CD theory is sufficient for a large number of practical engineering problems, but the LS and GL theories can be more accurately solved when the thermal effects are extremely short or at very low temperatures, such as laser pulse heating.

With the decrease of dimension for nanostructure, the wave properties will have significant difference compare to macro-

* Corresponding author.
E-mail address: yqsong@xjtu.edu.cn (Y.Q. Song).

http://dx.doi.org/10.1016/j.taml.2018.03.003

structure. The wave frequencies will reach to TeraHertz. This kind of wave will carry enormous energy. So it is of great significance to study the propagation and reflection behavior of nanostructures. Based on the stress gradient nonlocal elasticity theory, the wave characterization and reflection problem of wave in semiconductor nanostructures is studied in this article.

In the process of analyzing the propagation of waves in the semiconductor medium, it is necessary to consider the coupled heat wave, elastic wave and plasma diffusion. Using the stress gradient nonlocal theory, the physical quantity e_0a is introduced, in which e_0 is the material constant characterizes the nonlocal effect, a is the material characteristic length. The semiconducting medium is assumed as a homogeneous isotropic material, the control Eqs. (11)-(13) are:

$$\frac{\partial N(\boldsymbol{r},t)}{\partial t} = D_E \nabla^2 N(\boldsymbol{r},t) - \frac{N(\boldsymbol{r},t)}{\tau}, \tag{1}$$

$$k\nabla^2 T(\boldsymbol{r},t) = \rho C_E \left(n_1 + \tau_0 \frac{\partial}{\partial t}\right) \frac{\partial T(\boldsymbol{r},t)}{\partial t} + \gamma T_0 \left(n_1 + n_0 \tau_0 \frac{\partial}{\partial t}\right) \nabla \dot{u}(\boldsymbol{r},t) + \frac{E_g N(\boldsymbol{r},t)}{\tau}, \tag{2}$$

$$\left[1-(e_0a)^2\nabla^2\right] \frac{\rho \partial^2 \boldsymbol{u}(\boldsymbol{r},t)}{\partial t^2} = \mu \nabla^2 \boldsymbol{u}(\boldsymbol{r},t) - \left[1-(e_0a)^2\nabla^2\right] \left[\beta_T \left(1 + v_0 \frac{\partial}{\partial t}\right) \nabla T + \delta_n \nabla N\right] + (\lambda+\mu)\nabla\left[\nabla \boldsymbol{u}(\boldsymbol{r},t)\right]. \tag{3}$$

The carrier density $N(\boldsymbol{r},t)$, temperature distribution $T(\boldsymbol{r},t)$, and elastic displacement $\boldsymbol{u}(\boldsymbol{r},t)$ are the main variable quantities. $\boldsymbol{r}$ is the position-vector, t is the time. D_E, τ, ρ, C_E, k are carrier diffusion coefficient, photogenerated carrier lifetime, density, coefficient of specific heat at constant strain, and thermal conductivity, respectively. λ, μ are the Lamé elastic constants, τ_0, v_0 are thermal relaxation times, n_0 are non-dimensional, E_g is the energy gap of the semiconductor parameters. $\beta_T = (3\lambda+2\mu)\,\alpha_T$ is the volume thermal expansion. α_T is the coefficient of linear thermal expansion. $\delta_n = (3\lambda+2\mu)\,d_n$ and d_n is the coefficient of electronic deformation.

When the parameter takes a specific value, it represents a different theory:

CD theory: $v_0 = \tau_0 = 0,\ n_0 = n_1 = 0$,

LS theory: $v_0 = 0, n_0 = n_1 = 1, \tau_0 > 0$,

GL theory: $n_0 = 0,\ n_1 = 1,\ v_0 \geq \tau_0 > 0$.

The displacement potential functions $\varphi(x,z,t)$ and $\psi(x,z,t)$ are introduced and defined as:

$$u = \frac{\partial \varphi}{\partial x} + \frac{\partial \psi}{\partial z}, \quad w = \frac{\partial \varphi}{\partial z} - \frac{\partial \psi}{\partial x}. \tag{4}$$

For ease of handling, introduce the following dimensionless quantities:

$$\overline{x_i} = \frac{x_i}{C_T\omega^*}, \overline{u_i} = \frac{u_i}{C_T\omega^*}, \overline{\varphi} = \frac{\varphi}{C_T\omega^*}, \overline{\psi} = \frac{\psi}{C_T\omega^*}, \overline{t} = \frac{t}{\omega^*},$$
$$\overline{\tau} = \frac{\tau}{\omega^*}, \overline{T} = \frac{\beta_T T}{\lambda+2\mu}, \overline{\sigma_{ij}} = \frac{\sigma_{ij}}{\mu}, \overline{N} = \frac{\delta_n N}{\lambda+2\mu}, \overline{v_0} = \frac{v_0}{\omega^*},$$
$$\overline{\tau_0} = \frac{\tau_0}{\omega^*}, \overline{e_0a} = \frac{e_0a}{C_T\omega^*}, \overline{\sigma_{ij}} = \frac{\sigma_{ij}}{\mu}, i,j = x,z.$$

Consider the propagation of the wave in the x–z plane. Assuming the incident angle θ is the angle between the x-axis and the z-axis, we can set the solution as follows:

$$\{\varphi, \psi, T, N\} = \{\overline{\varphi}, \overline{\psi}, \overline{T}, \overline{N}\} \mathrm{e}^{\mathrm{i}\xi(x\sin\theta + z\cos\theta) - \mathrm{i}\omega t}, \tag{5}$$

where ξ is the wave number, ω is the frequency.

Substituting Eqs. (5) into non-dimensional Eqs. (1)-(3), we obtain four homogeneous equations:

$$\left(\xi^2 + \alpha\right)\overline{N} - \varepsilon_3 \overline{T} = 0, \tag{6}$$

$$\left(\xi^2 - \mathrm{i}\omega s_1\right)\overline{T} - \varepsilon_2 \overline{N} - \mathrm{i}\varepsilon_1 \omega \xi^2 s_2 \overline{\varphi} = 0, \tag{7}$$

$$\left(\xi^2 - \omega^2 + t_1\xi^2\omega^2\right)\overline{\varphi} - s_3 T(1+t_1\xi^2) + \left(1 + t_1\xi^2\right)\overline{N} = 0, \tag{8}$$

$$\left(\xi^2 - \beta^2\omega^2 + t_1\xi^2\omega^2\right)\overline{\psi} = 0, \tag{9}$$

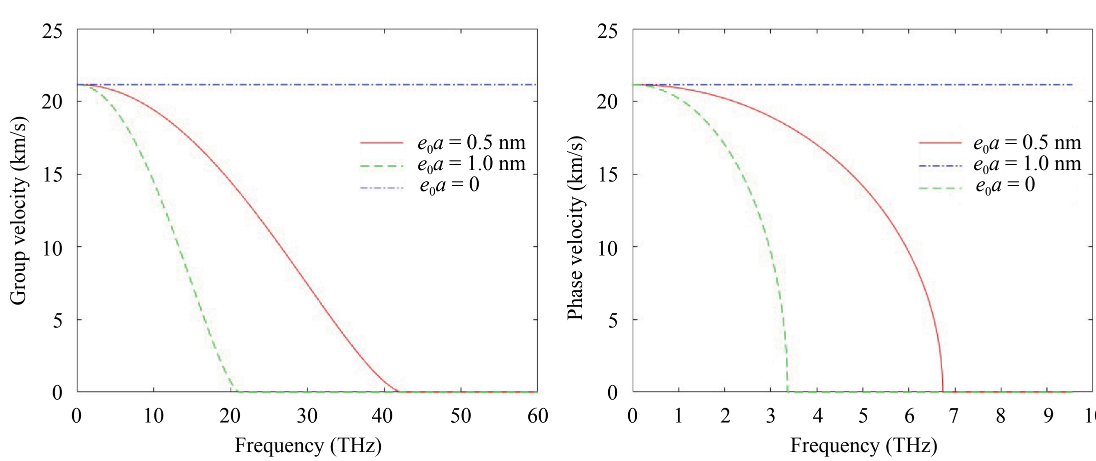

Fig. 1. Group velocity, phase velocity-frequency diagram.