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Pulsative heating of silicon thin film resembling laser pulses

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ABSTRACT

Thermal response of thin films under pulse heating, resembling laser pulses, is considered and the semi-analytical solution of phonon radiative transport is presented. Temperature pulsation is introduced at the film edge resembling the laser pulses and silicon thin film is used as the film material. Since the film thickness is comparable to the mean free path of silicon, equation for radiative phonon transport is incorporated in the analysis. Temperature findings from the semi-analytical solution are compared to that obtained from the numerical solution. Equivalent equilibrium temperature is introduced to quantify the phonon intensity distribution in the film. It is found that equivalent equilibrium temperature obtained from the semi-analytical solution agrees well with its counterpart obtained from the numerical simulations. The semi-analytical solution correctly predicts the temperature jump at the film edges. The semi-analytical solution reduces the computation efforts significantly in terms of run time and memory size, which are required for the numerical simulations. Temporal distribution of temperature inside the film at various locations does not follow exactly the temperature pulses introduced at one edge of the silicon film.

1. Introduction

The thin films are widely used in micro-electronics industry [1] and thermal management of thin films remains critical for efficient operation of the micro-electronic devices. The thermal energy transfer is mainly associated by the non-equilibrium transport processes and the phonon transport governs the thermal energy transfer in the film if the film thickness reduces to become comparable to the mean free path of the film material. The phonons emitted under the thermal disturbance undergo scattering in the film and the formulation of the phonon scattering and transport is possible via incorporating the Boltzmann transport equation. The wave nature of the thermal energy transport in thin films is formulated through the hyperbolic wave equation incorporating the phase lag model [2] and electron kinetic energy approach [3]; however, the phonon scattering at the film boundaries are overlooked in these model studies. The phonons suffer from boundary scattering, which causes reduction of phonon intensity at the boundaries. This phenomenon gives rise to a temperature jump at the film boundaries and interfaces. Consequently, thin film response to the phonon transport under the thermal disturbance is not possibly formulated using the differential form of the classical wave equations. The Boltzmann transport equation provides comprehensive solution for the phonon transport in the thin films. However, some difficulties are encountered towards solving the Boltzmann transport equation; in this case, some simplifications are introduced, such as relaxation time approximation [4]. This arrangement reduces the Boltzmann transport equation to the equation for phonon radiative transport. The phonon radiative transport equation provides reasonably correct solution of the phonon intensities for low temperature ranges [4]. The numerical solution of the phonon radiative transport equation with the appropriate boundary conditions becomes feasible. However, the computational efforts required to simulate the phonon intensity distribution is significant in terms of the numerical code development, memory size, and run-time. On the other hand, a semi-analytical solution of phonon radiative transport equation becomes fruitful towards reducing the computational efforts. Since the process of phonon transport is transient in nature and the transient analysis of equation for phonon radiative transport becomes essential. Particularly, investigation of thermal response of the thin films becomes fruitful when the pulsative thermal disturbance is introduced at the film edge.

Considerable research studies were carried out to examine phonon transport in thin films. A study on the phonon radiative transport in silicon and aluminum thin films was carried out by Mansoor and Yilbas [5]. They showed that equivalent equilibrium temperature in the silicon film resulted from the frequency

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dependent solution of phonon radiative transfer equation decayed sharper than that obtained from the frequency independent solution. A study on the phonon transport in thin nanostructured silicon membranes was considered by Liang et al. [6]. The findings revealed that the thermal conductivity of the membrane was reduced due to phonon back scattering from the nanostructures having the pore boundaries. The phonon transport across nanoscale curved thin films was studied by Mansoor and Yilbas [7]. They demonstrated that phonon intensity decay along the film arc length was sharper than that corresponding to film horizontal axis. This is more evidenced in the inner radius region of the film. Lowering the arc angle of the film enhanced the phonon intensity decay in the close region of the film edge. The laser irradiation of curved aluminum film and phonon transport was examined by Mansoor and Yilbas [8]. They indicated that electron temperature showed a similar behavior of the laser pulse intensity along the film length. However, electron temperature did not demonstrate similar behavior of the laser pulse temporarily. The lattice Boltzmann scheme for the formulation of the phonon transport was proposed by Guo and Wang [9]. They showed that it was possible to demonstrate, through the Chapman–Enskog expansion, the phonon lattice Boltzmann equation under the gray relaxation time approximation recovered the classical Fourier's law in the diffusive limit. A study on the radiative phonon transport in relation to laser heating of thin silicon and aluminum films was carried out by Mansoor and Yilbas [10]. They demonstrated that equivalent equilibrium temperature increased gradually in the aluminum film; however, it decayed sharply at the silicon interface during same period. Equivalent equilibrium temperature reduced due to the presence of thermal boundary resistance at the aluminum interface. The dissipative particle dynamics study of phonon transport in thin films was carried out by Zhang et al. [11]. They showed that temperature jump took place at the interfaces of the film edges due to boundary scattering. The radiative phonon transport across a nano-size gap located at the interface of the aluminum and the silicon thin films were examined by Yilbas and Ali [12]. The findings revealed that laser pulse heating resulted in differences in electron and lattice temperatures; in which case, electron temperature attained higher values than that of the lattice temperatures. The boundary scattering at the interface also reduced the lattice temperature. The ballistic phonons transported higher rate of thermal energy across the gap as compared to that of the thermal radiation. A model study for the quasi-ballistic phonon heat conduction in multi-dimensional geometry was carried out by Allu and Mazumder [13]. They showed that, at low temperature the ballistic phonons governed the thermal transport characteristics and the Fourier heating model did not predict correct temperature in the film. For short heating durations, all models other than the Boltzmann transport equation exhibited significant error. The lattice Boltzmann method for phonon transport was investigated by Nabovati et al. [14]. They indicated that, at the ballistic regime, the effect of directional discretization was significant on the phonon transport characteristics for two dimensional films, regardless of the lattice used. The radiation heat transfer and phonon transport in silicon thin films was studied by Wong et al. [15]. The findings revealed that temperature gradient become sensible when the ultra-short radiative pulses of a strong power density was introduced at the edges. The transient ballistic–diffusive phonon transport in two-dimensional domains was examined by Hamian et al. [16]. They indicated that as the Knudsen number (Kn) attained larger values heat transport was governed by the ballistic phonons. In addition, the ballistic nature of phonon behavior influenced the boundary scattering and temperature jump at film edges. The thermal transport in thin films with presence of the aluminum dot was studied by Ali et al. [17]. They showed that the decay of temperature in the region of the dot was sharp due to the emitted phonons scattering at the dot edges. Phonon transport incorporating the ballistic–diffusive in the silicon nano-films was investigated by Dong et al. [18]. They proposed a model predicting the thermal conductivity with the film size. The model predictions agreed with the molecular dynamics simulations. The ballistic transport had different effects on the heat conduction in the in-plane or cross-plane directions, which caused the anisotropy of thermal conductivity of nano-films. Such anisotropy was also size dependent and vanished with the increase of film thickness. A study on the phonon radiative transfer in porous nanostructures was carried out by Li et al. [19]. They showed that for certain aspect ratios, the scale factor dominated the thermal conductivity, and the thermal conductivity of nanostructure was significantly influenced by the phonon scattering. In nanostructures with staggered arrangement pores, the phonons were prevented from transporting through the film material. The phonon transport in a silicon film and logistic characteristics were examined by Yilbas and Mansoor [20]. They demonstrated that the averaged heat flux behaved like S-curve with heating time and the S-curve behavior changed as the film width altered; in which case, the attainment of the quasi-steady heat flux remained short for the small width films. Phonon transport in silicon–silicon and silicon–diamond thin films was studied by Mansoor and Yilbas [21]. The findings revealed that temperature predictions attained larger values at the interface of silicon films in silicon–silicon films than that corresponding to silicon–diamond films. The thermal transport in the aluminum thin film and the effect of film thickness on the transport characteristics were investigated by Yilbas and Mansoor [22]. They demonstrated that temperature predictions from the Boltzmann equation were different than those obtained from the two-equation model for small film thicknesses; however, increasing film thickness lowered temperature difference. Temperature predictions of the two-equation model remained higher than those predicted from the Boltzmann equation, which was particularly true in the region of the high temperature film edge.

Although analytical solution for the radiative phonon transport equation was presented previously [2,23], the main focus was to formulate the phonon intensity distribution for steady state heating situation [23] or transient uniform temperature disturbance from the film edges [23]. The analytical solution pertinent to thermal disturbance due to temperature oscillation at the film edge was left for future study. In most of practical applications, the transient thermal disturbance is created at the film edges in the form of pulses. The numerical solution of such conditions and formulation of phonon response to pulsation in a thin film is challenging. On the other hand, semi-analytical solution of phonon radiative transport equation is fruitful because of minimization of the requirements of excessive computational efforts. Consequently, in the present study, a semi-analytical solution of equation for phonon radiative transport pertinent to phonon transport in a thin film is presented for the condition that temperature pulsation at one edge of the film was introduced. The orthogonality properties of trigonometric functions are incorporated to formulate the coefficients for the semi-analytical solution of the resulting transport equation. Silicon thin film is considered and the step-input temperature pulsation within 301 K to 300 K at one edge of the film is incorporated in the analysis. The phonon intensity distribution inside the film is quantified through equivalent equilibrium temperature. Equivalent equilibrium temperature represents the average energy of all photons around a local point and it is equivalent to the equilibrium temperature of those phonons if they redistribute adiabatically to an equilibrium state.