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Laser short-pulse heating of an aluminum thin film: Energy transfer in electron and lattice sub-systems

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ABSTRACT

Laser short-pulse heating of an aluminum thin film is considered and energy transfer in the film is formulated using the Boltzmann equation. Since the heating duration is short and the film thickness is considerably small, thermal separation of electron and lattice sub-systems is incorporated in the analysis. The electron–phonon coupling is used to formulate thermal communication of both sub-systems during the heating period. Equivalent equilibrium temperature is introduced to account for the average energy of all phonons around a local point when they redistribute adiabatically to an equilibrium state. Temperature predictions of the Boltzmann equation are compared with those obtained from the two-equation model. It is found that temperature predictions from the Boltzmann equation differ slightly from the two-equation model results. Temporal variation of equivalent equilibrium temperature does not follow the laser pulse intensity in the electron sub-system. The time occurrence of the peak equivalent equilibrium temperature differs for electron and lattice sub-systems, which is attributed to phonon scattering in the irradiated field in the lattice sub-system. In this case, time shift is observed for occurrence of the peak temperature in the lattice sub-system.

1. Introduction

Non-equilibrium energy transfer in thin metallic films, due to short duration of thermal excitation from an irradiated field, results in thermal separation of the electron and the lattice sub-systems. Electrons absorb energy from the irradiated field and increase their excess energy in the electron sub-system. Through electron–phonon coupling, energy transfer occurs from electron sub-system to the lattice sub-system. Since the radiation absorption takes place locally in the irradiated film, electron energy distribution in the electron sub-system becomes non-uniform. This in turn results in non-uniform energy transfer within the lattice sub-systems. However, phonons are the main heat carriers in the lattice sub-system and the phonon scattering governs the thermal energy transport in the sub-system. Since the wave nature of the phonon behavior is important for the thermal energy transport, the first principle solution of the problem using the Boltzmann equation becomes necessary to predict correct temperature rise in the lattice sub-system when the metallic thin film is subjected to a short-pulse irradiation. In order to assess the energy transfer in the electron sub-system, modified Boltzmann equation can be used, in which case, a source term incorporating the volumetric absorption and electron–phonon coupling can be introduced. Although the modification of the Boltzmann equation provides physical insight into the energy transport characteristics in the electron sub-system, verification of the formulation is essential. In this case, the reduction of the modified Boltzmann equation to the telegraph equation becomes essential.

Considerable research studies were carried out to examine energy transport in thin films. Radiative phonon transport in silicon and collisional energy transfer in aluminum films due to laser short-pulse heating was studied by Mansoor and Yilbas [1]. They demonstrated that lattice site temperature rise was gradual in the aluminum film in the late heating period and the thermal boundary resistance lowered lattice site temperature considerably in the region of the aluminum interface. Microscale transport in aluminum thin film was investigated by Yilbas and Mansoor [2]. They incorporated small temperature disturbance across the thin film and formulated electron temperature rise during the thermal disturbance. The effect of internal polarized monochromatic acoustic phonon emission on heat dissipation at nanoscale was examined by Wong [3]. He indicated that monochromatic transverse acoustic-phonon emission within the film resulted in higher local peak temperature than that of longitudinal acoustic-phonon emission with an identical volumetric power generation. Non-equilibrium acoustic phonon propagation in diamond films was studied by Sharkov et al. [4]. The findings revealed that phonon transport had a diffusive character for the film thicknesses within

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Nomenclature

I	Particle intensity (W/m^2)
I^o	Equilibrium particle intensity (W/m^2)
v	Particle speed (m/s)
t	Time (s)
x	Distance along the *x*-axis (m)
z	Distance along the *z*-axis (m)
G	Electron–phonon coupling constant (W/m^3/K)
C	Volumetric heat capacity (J/m^3/K)
S	Laser volumetric heat source term in the EPRT (W/m^3)
R	Reflectance (fraction of the laser intensity reflected from the surface)
J	Laser pulse energy (J)
t_p	Pulse duration (s)
L_x	Length of film along the *x*-axis (m)
L_z	Length of film along the *z*-axis (m)
q''_x	Heat flux along the *x*-axis (W/m^2)
q''_z	Heat flux along the *z*-axis (W/m^2)
T	Thermodynamic temperature (K); Equivalent equilibrium temperature (K)
Kn	Knudsen number
k	Thermal conductivity (W/m/K)
Δt	Time step (s)

Greek letters

θ	Polar angle (radian)
ϕ	Azimuthal angle (radian)
Λ	Mean-free-path (m)
α	Absorption coefficient (m^{-1})
τ	Relaxation time (s)

Subscripts

p	Phonon
e	Electron

250–350 μm range. The combined analysis of phonon and electron heat transfer mechanism on thermal conductivity for nano-fluids was carried out by Avsec [5]. He introduced the mathematical model representing the analytical calculation of phonon and electron heat transfer and analyzed the thermal conductivity for nano-fluids. The influence of mechanical strain on thermal conductivity of nanoscale aluminum films was investigated by Lee et al. [6]. They showed that mechanical strain decreased the mean free path of the thermal conduction electrons, primarily through enhanced scattering at the moving grain boundaries. A review on ultra-short laser interaction with a solid surface was presented by Gamaly and Rode [7]. They described the material response from the first principles, aiming to establish analytical scaling relations, which linked the laser pulse characteristics with the properties of the material and discussed the influence of the laser polarization on the material ionization. Phonon thermal transport was studied by Chernatynskiy and Phillpot [8]. They indicated that the approach introduced was in consistent with ab initio determination of the thermal conductivity in the pure crystals and they also discussed the effects of various defects on thermal conductivity. Modeling of femtosecond laser damage threshold on the two-layer metal films was presented by Chen et al. [9]. They showed that it was possible to maximize the damage threshold of the gold film surface by altering the thickness ratio of the gold layer and the substrate layer in the two-layer film assembly. Near-field radiative heat transfer across a pore substrate and its effects on thermal conductivity was investigated by Li et al. [10]. They demonstrated that the smaller the pore diameter, the more significant the near-field radiation effect and the combined thermal conductivities decreased gradually when the pore diameter was increased.

Although thermal characteristics of an aluminum thin film were investigated due to temperature disturbance at the film edges previously [1,2], the source term due to the absorption of the irradiated field was not incorporated in the analysis and this effect was left for the future study. Consequently, in the present study, thermal characteristics of an aluminum thin film when subjected to a short-pulse laser irradiation, resembling the volumetric source, are investigated. The transient response of the film in electron and lattice sub-systems is evaluated using the Boltzmann transport equation. Thermal communication in between electron and lattice sub-systems is incorporated in the model study through introducing the electron phonon coupling parameter. The mathematical formulation is reduced to two-equation model under the quasi-continuum heating regime.

2. Mathematical formulation of energy transport

In metal thin films, thermal separation of electron and phonon sub-systems occur, which requires incorporating the re-structuring of the energy equations in line with the Boltzmann equation. This can be achieved through formulating energy transport in each sub-system using the Boltzmann transport equation. In this case, separate equations for radiative phonon transport (EPRT) for each sub-system needs to be developed. Due to the presence of thermal communication of both sub-systems during the energy transport, the electron–phonon coupling term should be included in the EPRTs of each sub-system. Moreover, the laser heating of the aluminum thin film should be modeled by means of a volumetric heat source term in the EPRT for the electron sub-system. The functional form of the electron–phonon coupling term as well as the volumetric heat source term should be incorporated in such a way that in the diffusive limit, the EPRT is expected to reduce the standard two-temperature model with a volumetric heat generation [11].

2.1. EPRT for phonon sub-system

The proposed modified Boltzmann equation for the energy transport should satisfy the conservation of energy [11] in the lattice sub-system and it can be written as:

$$\frac{1}{v_p}\frac{\partial I_p}{\partial t} + \cos\theta\frac{\partial I_p}{\partial x} + \sin\theta\sin\phi\frac{\partial I_p}{\partial z} = \frac{\frac{1}{4\pi}\iint_{4\pi} I_p \sin\theta d\theta d\phi - I_p}{\Lambda_p} - \frac{G}{4\pi}\left(\frac{1}{C_p v_p}\iint_{4\pi} I_p \sin\theta d\theta d\phi - \frac{1}{C_e v_e}\iint_{4\pi} I_e \sin\theta d\theta d\phi\right) \qquad (1)$$

I_p is the phonon intensity, ν_p is the phonon speed, Λ_p is the phonon mean free path, C_v is the phonon volumetric heat capacity, θ is the polar angle, ϕ is the azimuthal angle, and G is the electron phonon coupling parameter.