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A critical point model with three Lorentzian terms for interband transition was proposed to describe temperature-dependent reflectivity (R) and absorption coefficient (α) for copper irradiated by ultrashort-pulsed lasers of wavelength 200–1000 nm. After validated with experimental data at room temperature, it was incorporated into a two-temperature model to study ultrafast laser-material interactions. The dynamic changes of optical properties R and α, distributions of laser heat density, electron and lattice temperature, and phase changes of a copper film were investigated. Comparing with the experimental data of average absorption showed that the proposed two-temperature model together with the critical point model can simulate satisfying results for temperature-dependent R and α. The drastic changes in R and α could alter laser energy deposition in a heated target, leading to different thermal responses than those predicted with constant R and α at room temperature. © 2011 American Institute of Physics. [doi:10.1063/1.3662897]

I. INTRODUCTION

In the last two decades, a new wave of research in physics, chemistry, bioscience, and materials science has been driven by the rapid advancement of ultrashort-pulsed laser technology.1–5 Among the theoretical studies on ultrafast laser-material interaction, the two-temperature model (TTM) pioneered by Anisimov6 has been widely employed or modified7–9 for simulating non-equilibrium thermal transport. In addition to models themselves, thermophysical and optical properties are the key factor that governs solution accuracy. The former controls thermal transport and temperature distributions in a heated medium, while the latter dictates laser energy deposition that influences the thermal response.

The three thermophysical properties of electrons involved in TTMs reported for a wide range of temperature so far are quite convincing. For example, Anisimov and Rethfeld10 proposed a semiempirical formula for electron thermal conductivity (κe) adequate even for temperatures greater than Fermi temperature. Based on the electron density of state (DOS) and the effect of thermal excitation of electrons,11 Lin and Zhigilei12,13 calculated electron heat capacity (Cν) and electron-phonon coupling factor (G) up to 50 × 103 K. On the other hand, the optical properties, surface reflectivity (R), and absorption coefficient (α), have received less attention. Either the values at room temperature (RT) or arbitrarily assumed were frequently applied in TTM modeling. To calculate temperature-dependent R and α, Eskey14 and later Jiang and Tsai15 included the Fermi smearing effect in the Drude model.16 To improve the Drude model for the dielectric permittivity, Sim et al.17 adjusted the electron collision rate to match R at RT for wavelength (λ) 1053 nm. Fisher et al.18,19 modified the Drude model by including interband transition effect to evaluate R and α for aluminum18 and copper.19 Fairly good comparisons of their model with experimental data for average absorption were demonstrated. Recently, Ren et al.20 employed a Lorentz-Drude oscillator model with one Lorentzian term to study temperature-dependent R and α for gold. They pointed out that use of constant R and α at RT in a TTM could significantly underestimate laser energy deposition in a metal target when laser fluence exceeds the melting threshold. In addition, the resulting laser heat density would not follow exponential decay dictated by Beer’s law.

In this paper, a critical point model21 with three Lorentzian terms for interband transition is proposed to evaluate the dielectric permittivity of copper for wavelength 200–1000 nm. After the model is validated by comparing R and α with experimental data at RT,22 it is incorporated into a TTM to study the transient optical and thermal response for a copper film irradiated by an ultrashort laser pulse. The temperature-dependent thermophysical properties employed are suitable over a wide range of temperature. The average values of the simulated absorption are compared with experiment data.19 The laser heat density, the non-equilibrium evolutions of electron and lattice temperature, and the rapid solid-liquid (S-L) and liquid-vapor (L-V) phase change are investigated and discussed.

II. DIELECTRIC FUNCTION MODELS

Attempts have been made to determine optical properties R and α at RT in the range from UV to near infrared. For example, Rakic et al.23 employed a Lorentz-Drude model with five Lorentzian terms to reflect interband transition effect. Comparing with experimental data indicated their model was not precise enough in the vicinity of 2.2 eV for copper where the interband transition takes place. Based on the Drude model, Etchegoin21 proposed a critical point model with two Lorentzian terms to calculate the permittivity for gold. Later, Vial et al.24 found that the critical point model can be fairly good for silver also.

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In the present work, the critical point model with three Lorentzian terms is proposed to evaluate temperature-dependent \( R \) and \( \alpha \) for copper. The critical point model with interband transition is written as

\[
\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_D^2}{\omega^2 + \Gamma_0^2} + \sum_{p=1}^{n} \frac{B_p \Omega_p}{(\Omega_p - \omega - i\Gamma_p) + (\Omega_p + \omega + i\Gamma_p)}
\]

\[
= \varepsilon_1(x, t) + i\varepsilon_2(x, t),
\]

where \( \varepsilon_\infty \) is dielectric constant, \( \omega_D \) plasma frequency, \( \omega \) laser frequency, \( \gamma \) damping coefficient which equals reciprocal of electron relaxation time \( (\tau_e) \), \( n \) number of oscillators, \( B \) a weighting factor, and \( \Omega, \phi, \) and \( \Gamma \) energy of gap, phase, and broadening, respectively.

The parameters in Eq. (1) for copper with \( n = 3 \) are best fitted with \( \tau_e = 10.0 \) fs using a simulated annealing method.\(^{25}\) The results are listed in Table I. Figures 1 and 2 compare \( R \) and \( \alpha \) at RT obtained by the three optical models with experimental data\(^{22}\) for \( \lambda = 200–1000 \) nm. Apparently, the proposed critical point model with three Lorentzian terms computes quite satisfying results, compared to the Drude model\(^{16}\) and Rakic et al.\(^{23}\)

The electron relaxation time is often expressed in the form

\[
\tau_e = \frac{1}{B_p T_l + A_c T_e^2},
\]

where \( T_e \) and \( T_l \) are electron and lattice temperature, respectively; \( A_c \) and \( B_l \) are constants to be determined. The first term in the denominator represents electron-phonon collision rates \( (v_{e,ph}) \), and the second term the electron-electron collision rates \( (v_{e,e}) \). In fact, the electron-phonon collision rate depends on both \( T_e \) and \( T_l \)\(^{18}\)

\[
v_{e,ph} = \frac{\Xi^2}{8\pi^2 k_F^2 \rho s} m_{opt} \left\{ \int_0^{\phi} e^{\phi_q} + e^{-\phi_q} d\phi_q + \eta \int_0^{\phi} e^{\phi_q} - e^{-\phi_q} d\phi_q + q_b \left( e^{\phi_q} + e^{-\phi_q} \right) \left( e^{\phi_q} - 1 \right) (e^{\phi_q} - 1)
\]

\[
= \frac{2(k_F)^3 - d_b^2}{4} - 4\eta q_b^2 k_F^2 \left( e^{\phi_q} - 1 \right) (e^{\phi_q} - 1)
\]

where \( \phi_q = \beta_q hq, \phi_e = \beta_e hq, \phi_l = \beta_l hq, \phi_c = \beta_c hq, \) \( k_F \) Fermi velocity, \( \rho \) density, \( s \) longitudinal sound velocity, \( m_{opt} \) effective electron mass, \( m_e \) mass of an electron, \( q \) the phonon wave vector, \( \beta_q = T_q/k_B, \beta_e = T_e/k_B, \) and \( \eta = 2m_{opt}/h \). The first two terms on the right-hand side of Eq. (3) are only significant for low temperature and can be neglected for RT and above. Using the similar method as Fisher et al.\(^{18}\) the two parameters are found to be: \( \Xi = 3.99 \) eV, \( q_b = 8.97 \times 10^9 \) m\(^{-1}\) for copper with \( m_{opt} = 1.39 m_e \). In this work, the term \( B_p T_l \) in Eq. (2) is replaced with the above collision rate \( v_{e,ph} \) multiplied by a factor of 3.54 for which the electron relaxation time is 10.0 fs at RT.

---

**TABLE I. Parameters in the critical point model fitted for copper.**

<table>
<thead>
<tr>
<th>( \varepsilon_\infty )</th>
<th>( \omega_D (\text{rad/s}) )</th>
<th>( \Gamma (\text{rad/s}) )</th>
<th>( B_1 )</th>
<th>( \Phi_1 )</th>
<th>( \Omega_1 (\text{rad/s}) )</th>
<th>( \Gamma_1 (\text{rad/s}) )</th>
<th>( B_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.686</td>
<td>1.34 \times 10^{16}</td>
<td>0.99 \times 10^{14}</td>
<td>0.562</td>
<td>-8.185</td>
<td>3.205 \times 10^{15}</td>
<td>0.404 \times 10^{15}</td>
<td>27.36</td>
</tr>
<tr>
<td>( \Phi_2 )</td>
<td>( \Omega_2 (\text{rad/s}) )</td>
<td>( \Gamma_2 (\text{rad/s}) )</td>
<td>( B_3 )</td>
<td>( \Phi_3 )</td>
<td>( \Omega_3 (\text{rad/s}) )</td>
<td>( \Gamma_3 (\text{rad/s}) )</td>
<td>0.226</td>
</tr>
</tbody>
</table>

---

**FIG. 1.** (Color online) Reflectivity at RT versus wavelength calculated by different models.

**FIG. 2.** (Color online) Absorption coefficient at RT versus wavelength calculated by different models.
The optical properties $R$ and $\alpha$ can be determined from Fresnel function \(^{16}\)

$$R(x, t) = \frac{(f_1(x, t) - 1)^2 + f_2(x, t)}{(f_1(x, t) + 1)^2 + f_2(x, t)}; \quad \alpha(x, t) = \frac{2 \omega f_2(x, t)}{c},$$

where $c$ is light speed in vacuum, and the normal refractive index $f_1$ and extinction coefficient $f_2$ are functions of $\varepsilon_1$ and $\varepsilon_2$:

$$f_1(x, t) = \sqrt{\frac{\varepsilon_1 + \sqrt{\varepsilon_1^2 + \varepsilon_2^2}}{2}}, \quad f_2(x, t) = \sqrt{-\frac{-\varepsilon_1 + \sqrt{\varepsilon_1^2 + \varepsilon_2^2}}{2}}.$$  \hfill (5)

Figure 3 shows the calculated reflectivity $R$ as a function of temperature ($T = T_i = T_e$) for copper. The reflectivity $R$ decreases with temperature, especially for longer wavelengths. The monotonic trend is not always found for $\alpha$ as shown in Fig. 4. In the ultrafast laser heating the values of $R$ and $\alpha$ are determined by nonequilibrium electron and lattice temperatures.

III. TWO-TEMPERATURE MODEL

Consider a free standing copper film of thickness $L$ and initial temperature $T_i$ irradiated by a flat-top laser pulse of fluence $J_o$ on the front surface ($x = 0$). The laser pulse is Gaussian in time with full width at half maximum (FWHM) $t_p$. For simplicity, the problem is approximated to be one dimensional.

Thermal conductivity of lattice is usually neglected in a TTM for pure metals due to the fact that it is much smaller than that of electrons. When a phase change from solid to liquid occurs, the lattice thermal conductivity, however, should be considered. Thus, the TTM is given as follows: \(^{8}\)

$$C_i \frac{\partial T_i}{\partial t} = \frac{\partial}{\partial x} \left(k_i \frac{\partial T_i}{\partial x} \right) - G(T_e - T_i) + S(x, t),$$

\hfill (6)

where $C$ is heat capacity, $k$ thermal conductivity, $G$ electron-phonon coupling factor, and $S$ laser heat density. The subscript $e$ and $i$ denote electron and lattice, respectively. The laser heat density in Eq. (6) is given by \(^{20}\)

$$S(x, t) = 0.94 \sqrt{\frac{1 - R(0, t)}{t_p} J_o \alpha(x, t)} \exp \left[-\int_0^x \frac{\alpha(x, t) dx}{2.77 \left(\frac{t}{t_p}\right)^2} \right],$$

\hfill (8)

in which $x$ is spatial coordinate, $t$ is time, and $R(0, t)$ is surface reflectivity.

To model melting and evaporation in metals, all the electron thermophysical properties should be valid over a wide range of temperature. Figure 5 shows the data \(^{13}\) of heat capacity for copper calculated by taking the derivative of the
total electron energy density with respect to electron temperature.\(^2\) In numerical analysis, an explicit function that can accurately describe properties would be more useful. Thus, we fit the data as

\[
C_e(T_e) = \begin{cases} 
117.47 T_e, & T_e < 2 \times 10^3 K \\
-2.049 \times 10^4 - 26.64 T_e + 0.0996 T_e^2, & 1.122 \times 10^{-5} T_e^3 + 5.735 \times 10^{-10} T_e^4, & 2 \times 10^3 K \leq T_e \leq 50 \times 10^3 K \\
-1.524 \times 10^{-14} T_e^5 + 2.044 \times 10^{-19} T_e^6 - 1.094 \times 10^{-24} T_e^7, & 2 \times 10^3 K \leq T_e \leq 50 \times 10^3 K 
\end{cases}
\] (9)

with units in Jm\(^{-3}\)K\(^{-1}\). The accuracy of the curve-fitted polynomial function can be seen in Fig. 5.

Figure 6 shows the data\(^3\) of electron-phonon coupling factor for copper, computed based on the assumption that the square of the absolute electron-phonon scattering matrix element, when summed over scattering angles, is independent of the electron states.\(^11,12\) Again, the data are curve-fitted to be

\[
G(T_e) = \begin{cases} 
0.56 \times 10^{17}, & T_e < 2,750 K \\
1.341 \times 10^{17} - 1.407 \times 10^{14} T_e + 5.988 \times 10^{10} T_e^2 - 7.93 \times 10^6 T_e^3, & 2,750 K \leq T_e \leq 50 \times 10^3 K \\
+ 55.2 T_e^4 + 0.023272 T_e^5 + 6.041 \times 10^{-7} T_e^6 - 9.529 \times 10^{-12} T_e^7, & 2,750 K \leq T_e \leq 50 \times 10^3 K \\
+ 8.377 \times 10^{-17} T_e^8 - 3.15 \times 10^{-22} T_e^9, & 2,750 K \leq T_e \leq 50 \times 10^3 K 
\end{cases}
\] (10)

with units in Wm\(^{-3}\)K\(^{-1}\). The results are shown in Fig. 6.

The electron thermal conductivity proposed by Anisimov and Rethfeld\(^10\) is in the form

\[
k_e = \chi \frac{(\partial e^2 + 0.16)^{5/4}(\partial e^2 + 0.44)\phi_e}{(\partial e^2 + 0.092)^{1/2}(\partial e^2 + \eta \partial_1)},
\] (11)

where \(\phi_e = T_e/T_F\) and \(\partial_1 = T_1/T_F\) with \(T_F\) denoting Fermi temperature; \(\chi\) and \(\eta\) are constant. For copper, \(T_F = 8.16 \times 10^4 K, \chi = 377 \text{ Wm}^{-1} \text{ K}^{-1}\), and \(\eta = 0.139.\)

From solid state, the bulk thermal conductivity \((k_{eq})\) is the sum of electronic component \((k_e)\) and lattice component \((k_l)\). For pure metals, \(k_l\) is much smaller than \(k_e\) because free electrons conduct the majority part of heat. In this work, \(k_l\) is taken to be 1% of \(k_{eq}\) for copper.\(^27\) The temperature-dependent bulk thermal conductivity, specific heat, and mass density of copper in solid and liquid phase are listed in Table II.

The rapid melting induced by ultrashort pulse laser is controlled by nucleation dynamics at the interface, as oppose to by interfacial energy balance for conventional melting process. The S-L interface can be heated well above the melting point during a rapid melting process, in which case the solid becomes superheated. Similarly, the interface can be cooled far below the melting point in the rapid solidification process, in which case the liquid becomes undercooled. It is assumed that the maximum S-L interface velocity is equal to the speed of sound of the liquid phase and that the fraction of the sites on interface where rearrangement of atoms can occur is unity. These two assumptions are valid for metals.\(^28,29\) For ultrafast evaporation, the velocity of dynamic evaporation is limited by the characteristic speed of sound on the liquidus line according to superheating kinetics of volume vaporization and shock wave theory. To simulate those phase changes, the numerical algorithms proposed by Zhang and Chen\(^30\) for rapid melting/re-solidification processes and those proposed by Huang et al.\(^31\) for non-equilibrium, superheating process of evaporation are adopted.

The initial temperature of electrons and lattice are set to be

\[
T_e(x, -2l_p) = T_l(x, -2l_p) = T_i.
\] (12)

Adiabatic boundary conditions on both sides of a heated target have been assumed in most of the existing works for ultrafast laser heating. In this paper, radiation heat loss on the front surface is considered. The boundary conditions are as follows:

\[
\frac{\partial T_e(0,t)}{\partial x} = \frac{\partial T_e(L,t)}{\partial x} = \frac{\partial T_l(L,t)}{\partial x} = 0; \quad k_l \frac{\partial T_l(0,t)}{\partial x} = \sigma c(T_s - T_\infty),
\] (13)

FIG. 6. (Color online) Temperature-dependent electron-phonon coupling factor of copper.
where $\sigma$ is Stefan-Boltzmann constant, $\varepsilon$ is emissivity, and $T_{\text{surf}}$ is surface temperature of lattice which becomes L-V interface temperature when evaporation takes place.

IV. NUMERICAL RESULTS AND DISCUSSION

The electron energy equation, lattice energy equation, and equations for the rapid S-L and L-V phase change are solved using a finite difference method. The iteration solution procedures can be found in reference 30 for the S-L phase change and 31 for the L-V phase change. The numerical simulations are performed for a copper film of $1 \mu$m thickness irradiated by a laser pulse of $\lambda = 800$ nm. The initial temperature is set at 300 K. A value of $0.12/\text{C}^2 10^6 \text{K}/\text{C}^0 2$ is chosen for $A_e$ to fit the experimental data for the 50-fs laser pulse, and then is used for all the simulations.

Figure 7 shows the average absorption for four pulse lengths, 50 fs, 150 fs, 500 fs, and 1 ps, where the average absorption of the target is calculated by

$$A = \frac{\int_{2r_p}^{2r_p} S(x,t)dx}{\int_{2r_p}^{2r_p} I(t)dt},$$

with $I(t)$ being the laser intensity before it reaches the target

$$I(t) = 0.94 \frac{J_o}{t_p} \exp\left(-2.77 \frac{t}{t_p}^2\right).$$

It can be seen from Fig. 7 that the present approach correlates the average absorption quite well with experimental data, compared to the other theoretical result. The laser intensity at which the average surface absorption begins to significantly change depends on laser pulse length; for example, about $1.0 \times 10^{12}$ W/cm$^2$ for the 500-fs pulse and $4.0 \times 10^{13}$ W/cm$^2$ for the 50-fs pulse. Under the same peak laser intensity ($I_o$), a longer laser pulse would have higher absorption because it contains more laser energy. However, the difference becomes inconsequential when intensities are low, for example, $I_o < 1.0 \times 10^{11}$ W/cm$^2$ for the four pulses. At those intensities the induced electron and lattice temperature would not be high enough to significantly alter $R$ and $\alpha$.

Variations of $R$ and $\alpha$ at the front surface during the laser irradiation are illustrated in Fig. 8. The normalized laser profile and electron relaxation time are also presented in the figure for convenience. In this simulation, the pulse length is

\[\text{TABLE II. Thermophysical and optical properties of copper.}\]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Solid ($s$)</th>
<th>Liquid ($l$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat, $c_p$ (J/kg·K)</td>
<td>$313.7 + 0.324 T_l - 2.687 \times 10^{-4} T_l^2 + 1.257 \times 10^{-3} T_l^3$</td>
<td>510.1</td>
</tr>
<tr>
<td>Latent heat of fusion, $h_m$ (kJ/kg)</td>
<td>510.1</td>
<td></td>
</tr>
<tr>
<td>Molar weight, $M$ (kg/kmol)</td>
<td>63.55</td>
<td></td>
</tr>
<tr>
<td>Boiling temperature, $T_b$ (K)</td>
<td>2835</td>
<td></td>
</tr>
<tr>
<td>Melting temperature, $T_m$ (K)</td>
<td>1357</td>
<td></td>
</tr>
<tr>
<td>$R$ at RT for $\lambda = 800$ nm</td>
<td>0.958</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ at RT for $\lambda = 800$ nm (m$^{-1}$)</td>
<td>78.80</td>
<td></td>
</tr>
<tr>
<td>Density, $\rho$ (kg/m$^3$)</td>
<td>$8.94 \times 10^3$</td>
<td></td>
</tr>
</tbody>
</table>

\[\text{FIG. 7. (Color online) Average absorption for different laser pulse lengths with } \lambda = 800 \text{ nm.}\]

\[\text{FIG. 8. (Color online) Variations of reflectivity and absorption coefficient at the front surface during laser irradiation: } t_p = 150 \text{ fs, } \lambda = 800 \text{ nm, and } I_o = 6.0 \times 10^{13} \text{ W/cm}^2.\]
150 fs and the peak laser intensity is $6.0 \times 10^{13}$ W/cm$^2$. It appears that the electron relaxation time decreases with time due to the electron and lattice temperature rise. As a result, both $R$ and $\alpha$ decrease during laser irradiation. The decrease in $R$ makes the target absorb more laser energy while the decrease in $\alpha$ alters the distribution of laser heat density inside the target, see Eq. (8).

Figure 9 plots the spatial profiles of the laser heat density $S(x,t)$ at $t = 0.1$ ps for four intensities. For low laser intensity, the laser heat density basically follows exponential decay since $\alpha$ remains almost the same. Nonetheless, the exponential decay no longer exists for higher laser intensity, except for the deeper part of material where $\alpha$ is not significantly affected.

For example, for the case of $I_o = 8.0 \times 10^{13}$ W/cm$^2$ shown in Fig. 9, the laser heat density decays much slower with a plateau present in the region $10 \text{nm} < x < 25 \text{nm}$.

Figure 10 shows the time evolutions of electron and lattice temperature at the front surface of the copper film heated by the 150-fs laser pulse with $J_o = 1.5$ J/cm$^2$. Both $T_e$ and $T_l$ predicted with dynamic $R$ and $\alpha$ are higher than those predicted with constant $R$ and $\alpha$ at RT. The simulated peak $T_e$ and $T_l$ are 21,187 K and 4,132 K versus 16,158 K and 2,936 K, respectively. It can be seen in Fig. 10 that $T_e$ becomes equal to $T_l$ at about $t = 7.9$ ps. After that, $T_e$ is even lower than $T_l$. The difference keeps increasing until $t = 17.4$ ps and then decreasing until the thermal equilibrium is established at about $t = 3$ ns. The non-equilibrium between $T_e$ and $T_l$ during this stage is governed by two competing mechanisms: diffusion of electron thermal energy into the deeper part of electrons and energy exchange between electrons and the lattice. Obviously, the former is predominating here. The difference between $T_e$ and $T_l$ depends on laser fluence. The higher the fluence is, the larger the difference is.

The melting process is depicted in Fig. 11. Melting begins from the front surface at $t = 335$ fs and re-solidification starts after the maximum melting depth (38.3 nm) is reached at $t = 130.7$ ps. Then, the solid-liquid interfacial velocity becomes negative and the interface moves back toward the front surface. Evaporation can be seen in Fig. 11 where the final location of the front surface is not at $x = 0$. When the property $R$ and $\alpha$ at RT are employed, the simulated maximum melting depth is only 22.1 nm and no evaporation is found.

V. CONCLUSIONS

A critical point model with three Lorentzian terms for interband transition was proposed to describe temperature-dependent reflectivity and absorption coefficient for copper irradiated by ultrashort-pulsed lasers of wavelength 200–1000 nm. It was shown, from the comparison with experimental data, that this optical model characterizes very well the optical properties $R$ and $\alpha$ at room temperature. After the model validation, it was incorporated into a two-temperature model to study ultrafast laser-material interaction. All the thermophysical properties considered in this work are valid for a wide range of temperatures. The dynamic changes of $R$ and $\alpha$ during laser irradiation, distributions of laser heat density, electron and lattice temperature, and phase changes of a copper film caused by
ultrashort-pulsed lasers were investigated. Comparing the model prediction with experimental data for the average absorption reveals that the proposed TTM model along with the critical point model can simulate satisfying results for temperature-dependent $R$ and $a$. Under the same peak laser intensity, a longer laser pulse results in higher energy absorption, except for very low intensity. For an ultrashort laser pulse with high laser fluence, both $R$ and $a$ could drastically decrease, leading to different laser energy deposition, both in magnitude and spatial distribution. As a result, the simulated thermal responses could be different than those predicted with constant $R$ and $a$ at RT. Therefore, transient $R$ and $a$ should be considered in the modeling of ultrashort laser heating, especially when melting in the material occurs. This study can be extended to other pure metals since their optical and thermophysical behaviors are similar, respectively.