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Heating process and damage threshold analysis of Au film coated on Cu substrate for femtosecond laser

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ABSTRACT

The heating processes of a two-layer film assembly of Au padded with Cu irradiated by femtosecond laser pulse are studied using a two-temperature model. It is found that the chosen substantially influence the energy transport, and consequently the temperature variation, and thermal equilibrium time. At the same laser fluence, the different thickness of gold film leads to a change of gold surface temperature. By choosing the thickness of the gold layer in the two-layer film assemblies, the damage threshold of the gold film can be maximized. The results can be used to optimize the damage threshold of gold coating optical components.

1. Introduction

The physics of femtosecond laser heating of gold films has been the focus of scientific research for many years due to the large number of applications [1–4]. Gold coating optical multilayer thin films are important components in many optoelectronic devices. Especially in the field of femtosecond laser, the gold film surface is irradiated by femtosecond laser, the lattice temperature of the substrate metal rises due to the absorption of the incident laser in the gold surface region. Moreover, the lattice temperature rise becomes crucial for the thickness of the metal layer. This is because of larger electron heat flux across the metal layers, which results in nonuniform expansion of each layer. Investigation of the temperature distribution in each layer during laser irradiation becomes important for steady operation. Several papers on the subject have been published in the recent years [5–8]. They suggested that the substrate layer reduced the increase of the surface temperature significantly during femtosecond laser heating. But they did not particularly discuss the effect of the top-layer thickness with regard to the temperature redistribution. In addition, during the processes of interaction between the laser beam and the gold surface, the photo-induced excitation of phonon subsystem effectively interacting with the plasmons and nonlinear optical effects [9,10] are very weak compared with the heating process. So these factors can be ignored.

In here, we performed a series of numerical simulations of femtosecond laser processing of Au film deposited on Cu substrate with 1000 nm thikness, using the finite difference method. The distributions of electron temperature and lattice temperature were considered. The calculated results showed that the thickness of gold layer had a very important influence for the distribution of the film temperature.

2. Mathematical model

The theoretical method to investigate the ultrashort laser-metal interaction is the well-known two-temperature model (TTM). The model has a long history [11]. The TTM describes the evolution of the temperature increase due to the absorption of a laser pulse within the solid and is applied to model physical phenomena like the energy transfer between electrons and lattice occurring during the target–laser interaction [12]. Therefore the expressions for the time evolution of the temperatures read [2,13,14]:

$$C_e\frac{\partial T_e}{\partial t}=\frac{\partial}{\partial x}\left(k_e\frac{\partial T_e}{\partial x}\right)-G(T_e-T_l)+S \tag{1}$$

$$C_l\frac{\partial T_l}{\partial t}=\frac{\partial}{\partial x}\left(k_l\frac{\partial T_e}{\partial x}\right)+G(T_e-T_l) \tag{2}$$

where t is the time, x is the depth, C_e is the electron heat capacity, C_l is the lattice heat capacity, k_e is the electron thermal

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conductivity, T_e is the electron temperature, T_l is the lattice temperature, G is the electron lattice coupling factor [15], and S is the laser heat source. The heat source S can be modeled with a Gaussian temporal profile [16]:

$$S=\sqrt{\frac{\beta}{\pi}}\frac{(1-R)I}{t_p\alpha}\exp\left[-\frac{x}{\alpha}-\beta\left(\frac{t-2t_p}{t_p}\right)^2\right] \tag{3}$$

where R is the target reflection coefficient, t_p is the full-width at the half maximum (FWHM) with the linear polarization, α is the penetration depth including the ballistic range, I is the incident energy, $\beta=4\ln(2)$.

The electron heat capacity is proportional to the electron temperature when the electron temperature is less than the Fermi temperature as $C_e=\gamma T_e$ [17] and $\gamma=\pi^2 n_e k_B/2T_F$. n_e is the density of the free electrons, k_B is the Boltzmann's constant. As the temperature changes, the variety of the lattice heat capacity is relatively small, we take it as a constant.

A relationship between the electron relaxation time and electron–electron scattering time $1/\tau_{e-e}=AT_e^2$ and electron-lattice scattering time $1/\tau_{e-l}=BT_l$ for electron temperatures below the Fermi temperature is given by $1/\tau=1/\tau_{e-e}+1/\tau_{e-l}=AT_e^2+BT_l$. The expression for the heat conductivity can be written as $k_e=k_{e0}BT_e/(AT_e{}^2+BT_l)$ [18], k_{e0}, A and B are represent the material constants. Many of the ultrafast laser heating analyses have been carried out with a constant electron–lattice coupling factor G. Due to the significant changes in the electron and lattice temperatures caused by high-power laser heating, $G=G_0(A(T_e+T_l)/B+1)$[4,19] should be temperature dependent. G_0 is the coupling factor at room temperature. The lattice thermal conductivity is therefore taken as 1% of the thermal conductivity of bulk metal since the mechanism of heat conduction in metal is mainly by electrons [3]. As the temperature changes, the variety of the lattice heat conductivity is relatively small, we take it as a constant.

Consider a one-dimensional two-layered thin film, the schematic view of the laser heating is shown in Fig. 1. The thickness of the top layer (Au) is l. The thickness of the substrate layer (Cu) is a constant of 1000 nm.

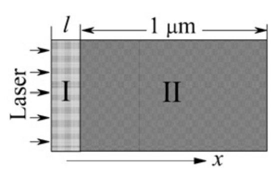

Fig. 1. The schematic of a two-layered film. The thickness of Au is l. The thickness of Cu is 1000 nm.

3. Results and discussion

The typical spatial and temporal distributions of lattice temperature are presented in Fig. 2. The thickness of gold coating layer is 40 nm, 60 nm, 80 nm, and 100 nm, respectively. Accordingly, in the simulation process, the laser wavelength is 800 nm, and the pulse duration is 100 fs. The laser fluence is 2000 mJ/cm^2, and surface reflectivity of gold is $R=0.974$. Table 1[20–24] lists the values of thermal physical parameters of the two noble metals used in these calculations. Fig. 3 shows the variation of the

Table 1
Thermal and optical physical parameters for the two noble metals.

	Au	Cu
G_0 (10^{17} J m^{-3} s^{-1} K^{-1})	0.21	1.0
γ (J m^{-3} K^{-2})	68	97
k_{e0} (J m^{-1} s^{-1} K^{-1})	318	401
C_l (10^6(J m^{-3} K^{-1})	2.5	3.5
α (10^{-9} m)	13.7	12.2
A (10^7 s^{-1} K^{-2})	1.18	1.28
B (10^{11} s^{-1} K^{-1})	1.25	1.23
T_m (°C)	1064	1085

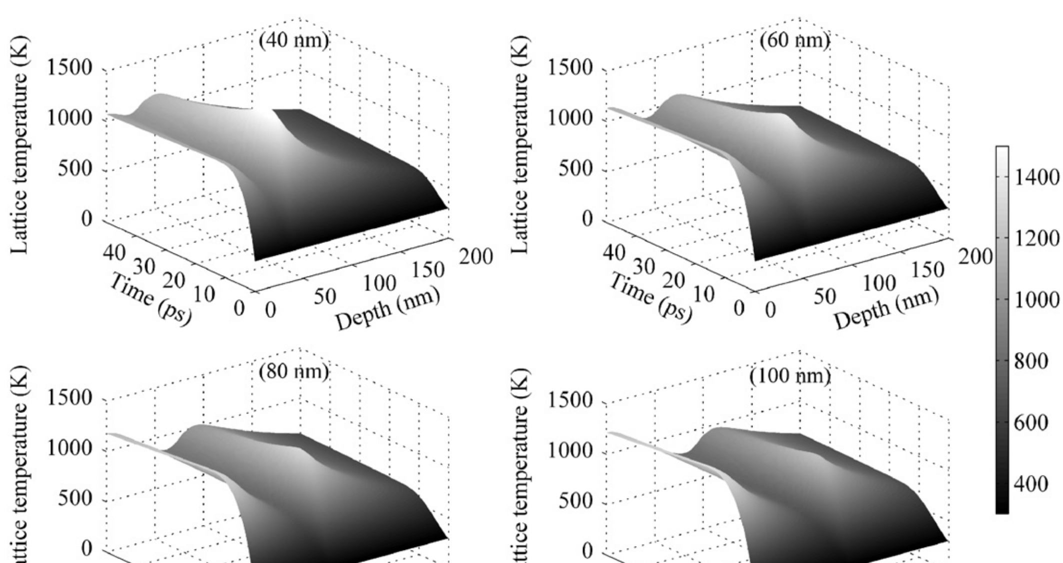

Fig. 2. The distributions of lattice temperatures. The thickness of Au is 40 nm, 60 nm, 80 nm, and 100 nm, respectively. The laser fluence is 2000 mJ/cm^2.