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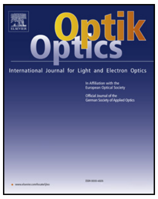

Original research article

A universal theoretical model for thermal integration in materials during repetitive pulsed laser-based processing

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ABSTRACT

In laser-based techniques such as laser processing, knowledge of the thermal integration process and temperature distribution in materials is the basis for process parameters optimization and product quality control. This work presents a universal theoretical model to study the repetitive pulsed laser-induced thermal integration in materials. Using the Green function method, the analytical solution formula for temperature field induced by laser pulses is mathematically deduced based on the Fourier heat transfer theory. Effects of two key parameters of laser pulses, i.e. the pulse spacing to pulse width ratio (t_c/t_h) and the intensity ratio (I/I_0) on thermal integration are studied. Results reveal that for a given I/I_0, thermal integration is mainly controlled by the t_c/t_h ratio, and the peak temperature difference induced by adjacent laser pulses drops exponentially as the t_c/t_h ratio (< 25) increases linearly. For a given cooling period ($t_c/t_h = 1$), the peak temperature difference induced by adjacent laser pulses changes linearly with the ratio of I/I_0. Therefore, temperature distribution in target materials can be tuned by adjusting I/I_0 or t_c/t_h of laser pulses. Furthermore, the analytical solution formula is applied to model temperature distribution in SiGe thin solid films and fused silica irradiated by pulsed laser.

1. Introduction

Thermal integration in materials induced by pulsed laser has become a very important question since the high repetition frequency laser has been widely used in modern high-tech industries [1–3]. For instance, pulsed laser is widely employed in field of laser-supported cutting, welding, drilling and surface processing technologies [4–8]. Besides, pulsed laser also finds new applications in fields of thin solid film deposition techniques [9–11], the 3-D printing technology [12,13] and the antique surface cleaning processes [14].

Laser-material interaction process involves many complex physical phenomena [15–19], such as photon energy absorption, thermal diffusion and integration, material melting and cooling. For nanosecond laser irradiation, thermal effects play a crucial role in the heating of materials and the eventually melting and cooling process [20]. Pulsed laser-induced thermal integration in target materials is the basis for laser processing applications. Thermal integration is also a restriction factor in some situations since it will cause damage in materials. Therefore, thermal integration in materials during pulsed laser irradiation has aroused increasing interests in recent years [21–23].

In the case of pulsed laser, the integration process consists of successive heating and cooling cycles. The thermal integration

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mainly depends on the pulse shape, pulse repetition rate and laser intensity. Mendham, *et al.* [24] studied the influence of variation of temporal pulse shape on laser heating in clusters, suggesting that the temporal profile of the laser pulse played a crucial role in the laser-induced heating. Kalyon et al [25] investigated the effect of variation of pulse parameter on the closed form solution of repetitive laser pulse heating process. They found that the maximum surface temperature increased rapidly once the cooling period between the consecutive pulses was reduced.

Mathematically, the heating process can be expressed by the Fourier heat conduction differential equation with the boundary and initial conditions [26–30]. The resolution of this partial differential equation is normally carried out by numerical methods, such as finite differences and finite elements methods [31–33]. However, numerical methods can not reveal the physical meaning and relations between laser parameters and the heating process. Analytical approaches provide a way to solve this problem, among which the Green function method is quite attractive because it can obtain the temperature field without losing the physical aspects involved in the heating process.

In the present study, the Green function method is used to analytically solve the Fourier thermal conduction equation which describes the temporal thermal integration in materials induced by repetitive nanosecond laser pulses. Successive heating and cooling cycles are considered in the analysis. Non-dimensionalized formula is used to analyze the effects of the ratio of pulse spacing (cooling period, t_c) to pulse width (heating period, t_h) and the intensity ratio of laser pulses (I/I_0) on the thermal integration process. The derived formula is then applied to model temperature distribution in SiGe thin solid film and fused silica glass irradiated by pulsed laser. We attempt to clarify the relationship between laser pulse parameters and thermal integration process. We present an analytical formula for studying temperature field in materials irradiated by laser pulses.

2. Modeling of pulsed laser heating

2.1. Thermal model description

A fraction of the incident laser energy is absorbed by the irradiated material, and the deposited energy leads to the formation of temperature field.

The physical assumptions for the model are listed as follows:

i) The model only considers the quasi-steady heat conduction problem. The initial thermal history of the irradiated material is neglected, as can be seen in a number of previous analytical models [34,35].
ii) The target material is taken as a semi-infinite body and the surface of the material is adiabatic. This assumption results from the fact that the laser beam size is very small relative to the material and the heat losses by convection and radiation are negligible compared to heat conduction within the material during the time of laser irradiation.
iii) The properties of the irradiated material, such as thermal conductivity, thermal diffusivity and reflectivity, are isotropic and independent of temperature. Phase change of the target material is not considered in this work.

2.2. Analytical formulation

For mathematical formulation, a Cartesian geometry system is employed; the *x-y* plane of the coordinate system lies on the surface of the target materials and the origin coincides with the center of the laser beam.

In general form, the heat conduction differential equation for one laser heating pulse can be written as:

$$\partial^2 T(\vec{r}, t)/\partial\vec{r}^{\,2} + g(\vec{r}, t)/k = (1/\alpha) \times \partial T(\vec{r}, t)/\partial t$$
$$0 < \vec{r} < \infty\ ,\ t > 0 \qquad (1)$$

with the boundary conditions:

$$-\,k \times \partial T(\vec{r}, t)/\partial z = 0,\ z = 0,\ t > 0, \qquad (2)$$

and:

$$\partial T(\vec{r}, t)/\partial z = 0,\ z = \infty\ ,\ t > 0, \qquad (3)$$

with the initial condition:

$$T(\vec{r}, 0) = T_0,\ \ t = 0, \qquad (4)$$

where the thermal conductivity k, the thermal diffusivity $\alpha = k/\rho c$, the density ρ, the specific heat c, the heat source in the solid $g(\vec{r}, t)$, and the initial temperature T_0, are independent of temperature.

The surface heating source can be formally expressed as:

$$g(x, y, z, t) = A \times (1 - r_f) \times I_0 \times Exp\left[-\frac{x^2}{R_x^2} - \frac{y^2}{R_y^2}\right] \times f(t) \qquad (5)$$

where A is the material absorptivity, r_f is the reflectivity, I_0 is the peak laser intensity, R_x is the beam radius at x direction, R_y is the