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Analysis on the thermal effect of the silicon material induced by laser pulse trains

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ABSTRACT

Laser pulse train *will cause* the temperature accumulation in infrared material. To analyze the thermal damage characteristics of silicon material that induced by different laser pulse trains a practical model has been established. By using the heat conduction equation, the thermal incubation effect in silicon material has been calculated. Furthermore, the temperature accumulation processes caused by different pulse trains are simulated. The results show the temperature variation behavior and the thermal damage characteristics of silicon material clearly.

1. Introduction

Infrared detection system has been applied wildly in space laser communication, optoelectronic countermeasure, environmental monitoring and so on. To some extent, its normal operation is the crucial factor for the high-efficiency working of infrared system. The infrared material can be damaged because of the obvious thermal effect caused by the increasing power density of incident laser. So it's necessary to analyze and evaluate the characteristics of infrared material in extreme working conditions to avoid melting, gasification or breakdown. For instance, in the free-space-communication (FSO) system, to increase pulse laser energy is a relatively simple and feasible way to reduce error rate as well as to enhance signal-to-noise ratio and transmission efficiency. Hence, to avoid the damage of detector is one of the important factors in infrared detection technique for the laser with gradually enhanced energy.

In the 1970s, damage on infrared detector induced by both long and short pulse laser was investigated by Kruer et al. [1,2]. Generalized thermal model for infrared semiconductor materials was presented. In the 1980s, Meyer [3,4] has studied laser damage thresholds of multiple infrared detector materials with numerical models and experiments, presented the dynamic nature of the material's optical and transport properties with the change of temperature and laser-generated carrier density, which has a significant effect on the heating process, particularly for the short pulse laser. Later, Lietoila et al. [5] carried out more detailed investigations focusing on the influence of temperature rise and carrier concentration on silicon induced by nanosecond pulse laser. With the introduction of ultra-fast laser technology, studies about induced damage on infrared materials have attracted many interests [6–9]. Surface damage morphology and laser damage threshold of infrared detector materials induced by repetitive pulse laser in different frequency or pulse numbers have been studied [10–12]. In many practice cases, pulse train outputs in various forms. However, previous researches mainly focused on monotonous repetitive pulse laser, which cannot explain and predict damage performance of photoelectric materials properly. Therefore, to study the modulated pulse train is necessary. In this paper, we revealed the thermal effect on silicon induced by repetitive pulse train and modulated pulse train and made comparison with the repetitive pulse laser.

2. Theoretic analysis model

We research thermal effects on the irradiated material before phase change by multi-pulsed laser with a pulse width of 20 ns and a wavelength of 1.064 μm. The temperature variation of a sample that illuminated by pulsed laser can be described by thermal conduction equation as follows,

$$\rho c \frac{\partial T(z,t)}{\partial t} = k \frac{\partial^2 T(z,t)}{\partial z^2} + S \quad (1)$$

where $T(z, t)$ represents the temperature distribution at time t and depth z. ρ, c, and K are density, specific heat and thermal

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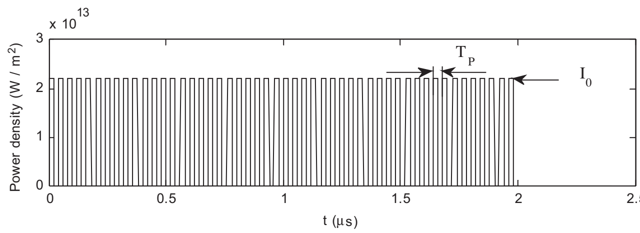

Fig. 1. Power density distribution of RPL at time t, f_P = 25 MHz, N_P = 50.

conductivity of the material respectively. S is the rate of heat supplied to the material per unit time per unit volume, which is described as

$$S = (1 - R)\alpha I(t)\exp(-\alpha z), \tag{2}$$

where R is the reflectivity, α is the absorption coefficient, $I(t)$is the distribution of power density at t.

To make the problem manageable, we make an assumption that no convection and radiation from the surface and the power density, which distributes regularly at the surface, is a constant independent of time, the initial and boundary conditions are given as

$$T(z, 0) = T_0, \tag{3}$$

$$k\frac{\partial T(0, t)}{\partial t} = 0 \tag{4}$$

$$T(L, t) = T_0 \tag{5}$$

where T_0 = 300 K is ambient temperature.

Power density distribution of repetitive pulse laser (RPL) at time t is shown in Fig. 1. Pulse number is N_P. Pulse repetition rate is f_P. Pulse repetition period is $T_P = 1/f_P$. I_0 is the peak power density.

Another form of pulse train is named periodic pulse train (PPT), which power density distribution is shown in Fig. 2. The number of pulse trains is N_{PS}. The repetition rate of the pulse train is f_{PS}. The repeat period of the pulse train is $T_{PS} = 1/f_{PS}$.

Define A as the function of time t, for its value is 1 when the laser is irradiating the silicon, otherwise, the value is 0. Then, A can be described as

$$A(t) = \begin{cases} 1, (j-1)\cdot T_{PS} + (i-1)\cdot T_P \le t \le (j-1)T_{PS} + (i-1)\cdot T_P + \tau \\ 0, (j-1)\cdot T_{PS} + (i-1)\cdot T_P + \tau < t < (j-1)T_{PS} + i\cdot T_P \end{cases} \tag{6}$$

where $i = 1, 2, \ldots, N_P$, $j = 1, 2, \ldots, N_{PS}$. τ is pulse width. Power density distributions of RPL and PPT can be expressed as $I(t) = A(t)\cdot I_0$.

Modulated pulse train (MPT) showed in Fig. 3, modulation frequency is f and $T = 1/f$ is modulation period. $I_{0\sin}$ signed in the figure is the peak power density of the MPT.

Power density distributions of MPT can be expressed as:

$$I_{\sin}(t) = A_{\sin}(t)\cdot I_{0\sin} \tag{7}$$

where $A_{\sin}(t) = \left|\sin(wt)\right|\cdot A(t)$.

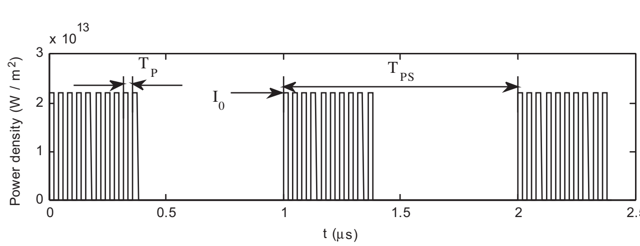

Fig. 2. Power density distribution of PPT at time t, f_P = 25 MHz, f_{PS} = 1 MHz, N_P = 10, N_{PS} = 3.

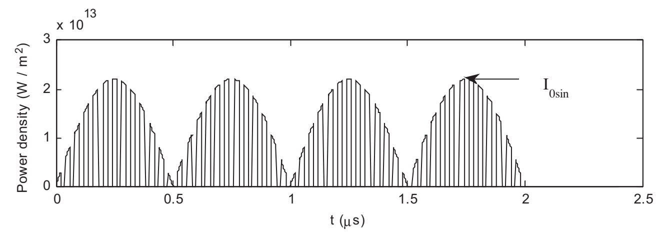

Fig. 3. Power density distribution of MPT at time t, f_P = 25 MHz, N_P = 50, f = 2 MHz.

Table 1
Thermal parameters for silicon.

$\rho/\left(\text{g/cm}^3\right)$	c [J/(g K)]	k [W/cm K]	α (cm)	R
2.33	0.72	299/(T – 99)	50	0.33

If the total energy before and after modulate kept constant, $I_{0\sin}$ is calculated by:

$$\int I_0\cdot A(t)\,dt = \int I_{0\sin}\cdot A_{\sin}(t)\,dt \tag{8}$$

3. Thermal effect on silicon irradiated by RPL, PPT, and MPT

The thermal physical parameters of silicon are listed in Table 1, and which are used to calculate the temperature evolutions at the center of laser spot and z = 0 by numerical simulation. Thermal effects on silicon irradiated by RPL, PPT, and MPT will be investigated in the following sections.

3.1. Temperature rising on silicon induced by RPL

Fig. 4 shows the temperature evolutions on silicon irradiated by RPL. For keeping the surface temperature under the melting point, which marked as the horizontal line in this figure, peak power density of the laser should be less than 2.89×10^{13} W/m^2 while its pulse repetition rate is 15 Hz and pulse number is 15. We can found that, the temperature of silicon gradually increases to a peak at the end of a laser pulse irradiating, and then declines. The peak temperature increases along with the increase of pulse number due to the energy absorbed by silicon exceed the loss, which is named as thermal accumulation. This phenomenon gradually weakens as the number of pulse increases until it vanishes because of the energy absorption and the loss reaches a balance state, meanwhile, peak temperature tends to saturation. Peak temperature achieves the saturation at tenth pulse.

As shown in Fig. 5, the peak temperature vs the pulse number induced by a 40 Hz RPL which peak power density is 8×10^{12} W/m^2

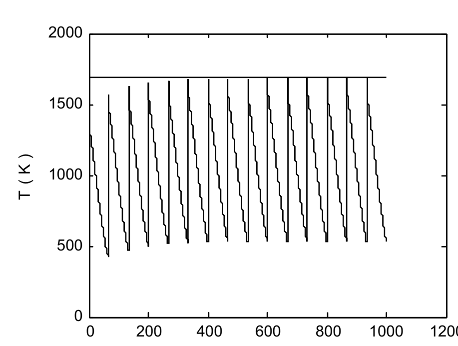

Fig. 4. Temperature evolution on silicon irradiated by RPL at f_P = 15 Hz, $I_0 = 2.89 \times 10^{13}$ W/m^2.