Dynamic Behaviors of PbS Irradiated by Laser Pulse

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Abstract— PbS detector is known as an important infrared (IR) detector which is widely used. The study of laser irradiation on PbS is important in military and commercial area. When the PbS sample is irradiated by laser pulse, the temperature rises in the sample. As the power density of the laser pulse increases, transient phase transformation may occur. In this paper, we will simulate the temperature field in PbS, and discuss the dynamic behaviors of PbS irradiated by laser pulse.

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1. INTRODUCTION

In recent years, the study of laser irradiation on semiconductor has attracted growing attention. It is suggested that the temperature rises when the sample is irradiated by laser beam. When the power density increases to sufficient quantity, various permanent effects may occur in the semiconductor, such as melting, vaporization, removal of material from the sample surface.

PbS detector which is known as a kind of infrared (IR) detector was first used in world war II. It causes more and more attention then, and is widely used in military and commercial area. PbS detector works in the wave band of 1–3 µm.

In this paper, we will discuss the dynamic behavior in PbS sample which is irradiated by laser pulse, by simulating the temperature field.

2. HEAT CONDUCTION EQUATION

It is indicated in previous research work that the intermediate mechanisms of energy transformation from laser to sample heating can be neglected, if

1. The diffusion length of free carriers before recombination is shorter than the light penetration depth or the heat diffusion length during pulse duration.
2. Free carrier absorption is negligible compared with lattice (band-to-band)-absorption.
3. The lifetime of free carriers is shorter than pulse duration.

The heat conduction equation is still valid here.

We presume,

1. The properties of the materials don’t change in this course.
2. There is no energy loss caused by surface radiation and convection.

The transient temperature distribution can be determined by solving the heat conduction equation,

\[ \frac{dT}{dt} = \frac{K}{\rho c_p} \nabla^2 T + \frac{Q}{\rho c_p} \]  \hspace{1cm} (1)

\( T \) is the transient temperature of the material, \( \rho \) is the density of the material, \( K \) is the thermal conductivity, \( c_p \) is the specific heat, \( Q \) is the interior heat source.

The diffusion length in the material is

\[ L_T = \sqrt{2k\tau_L} \]  \hspace{1cm} (2)

\( k \) is the thermal diffusivity, \( \tau_L \) is the duration of laser pulse. In our experiment, the duration of the laser pulse is very short (\( \tau_L = 30\,\text{ns} \)), \( k = 0.077\,\text{cm}^2\,\text{s}^{-1} \) for PbS. The diffusion length
$L_T = 6.79 \times 10^{-5}$ cm. It is much smaller than the radius of the laser beam. In consequence, the heat conduction course can be simplified to one-dimension heat conduction course.

$$\frac{dT}{dt} = K \frac{d^2T}{dx^2} + Q$$

(3)

In one-dimension condition, $Q$ is defined as

$$Q = (1 - R)I_0e^{-x/\delta}/\delta$$

(4)

$R$ is the reflectivity of the material, $I_0$ is the power density of the laser beam, $\delta$ is the heat diffusion depth.

The boundary conditions of the one-dimension heat conduction equation is

$$-K \frac{\partial T}{\partial t}|_{x=0} = \alpha(T - T_0)$$

(5)

$$T(x, t)|_{x=\infty} = \text{const.}$$

(6)

$$T(x, t)|_{t=0} = \text{const.}$$

(7)

$T_0$ is the initial temperature. It is room temperature here, $T_0 = 293K$. And the constant in Equations (6) and (7) correspond to 293K.

We suppose the absorption coefficient is very large, the Equation (3) can be approximate to

$$T(x, t) = \frac{2(1 - R)I_0}{K} \cdot \frac{\sqrt{D t} \cdot \text{erfc}\left(\frac{x}{\sqrt{2D t}}\right)}{\pi}$$

(8)

The surface temperature can be approximate to

$$T(0, t) \approx \frac{2(1 - R)I_0}{K} \cdot \frac{\sqrt{D t}}{\pi} = 2(1 - R)I_0 \left(\frac{t}{K \rho c_p \pi}\right)^{1/2}$$

(9)

Thus the time when melting occurs can be determined by

$$t_m = \frac{\pi K \rho c_p T_m^2}{4(1 - R)^2 I_0^2}$$

(10)

3. NUMERICAL SOLUTION

The calculation and experiment are carried out on PbS sample. The physical parameters of PbS are shown in Table 1. We presume the duration of the laser beam is 30 ns (FWHM), the wavelength is 1.06 $\mu$m, the power density is $I = 1.14 \times 10^8$ W $\cdot$ cm$^{-2}$. The calculated results of the transient temperature field in the sample of PbS is shown in Fig. 1.

Figure 1: The transient temperature field in the sample of PbS at the power density of $1.14 \times 10^8$ W $\cdot$ cm$^{-2}$. 
Table 1: The physical parameters of PbS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho$</td>
<td>7.6 g·cm$^{-3}$</td>
</tr>
<tr>
<td>Thermal conductivity $K$</td>
<td>0.03 W·cm$^{-1}$·K$^{-1}$</td>
</tr>
<tr>
<td>Specific heat $c_p$</td>
<td>0.0511 J·g$^{-1}$·K$^{-1}$</td>
</tr>
<tr>
<td>Reflectivity $R$</td>
<td>0.31</td>
</tr>
<tr>
<td>Melting temperature $T_m$</td>
<td>1387 k at 1 atm</td>
</tr>
</tbody>
</table>

4. CONCLUSION

In this paper the transient temperature field in detector material of PbS is simulated. The melting behavior in the sample is also analyzed by numerical calculation. The result is proved by experiments on PbS sample. It is reasonable to believe the thermal model used in this paper is appropriate and the result is correct.

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