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Simulation of the Si-CCD irradiated by millisecond pulse laser

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ABSTRACT

Based on the Fourier heat conduction equation and the thermoelastic equation, the thermal-stress coupling model of the Si-CCD irradiated by millisecond pulse laser was established, the time-space distribution of the temperature field and the stress field on the Si-CCD was calculated. The results show that: the damage firstly occurred in the color filter layer; increased the laser energy density, part of the microlens and the color filters were missing; then continued to increase the laser energy density, the photosensitive area in the N-Si layer was melting; when the channels in the N-Si layer were damaged, the Si-CCD was under functional loss. In this paper, the simulation results were consistent with the experiment results.

1. Introduction

Since 1990s, native and foreign experts and scholars have carried out a lot of research on the performance degradation and the permanent failure of the Si-CCD. The experimental results are rich and varied, but the theoretical results are not enough. The existing models are shown as follows: the thermal-stress coupling model of the Si-CCD irradiated by nanosecond pulse laser [1], the thermal model of the MOS array irradiated by short pulse laser [2], the thermal-stress coupling model of the MOS pixel irradiated by millisecond pulse laser [3,4], the thermal-stress coupling model of the shielding aluminum film irradiated by mixed frequency laser [5–7], the thermal model of the silicon substrate irradiated by nanosecond pulse laser [8,9], and the thermal-stress coupling model of the silicon substrate irradiated by continuous laser [10,11]. The millisecond pulse laser had the advantages of the high peak power and the difficulty in producing a plasma-shielding phenomenon. In this paper, the simulation of the Si-CCD irradiated by millisecond pulse laser was studied, and the time-space distribution of the temperature field and the stress field on the Si-CCD under different laser energy densities were calculated, providing the theoretical support for laser damage and laser protection.

2. Simulation method

Since the laser has focused on the photosensitive area by the microlens layer, the vertical CCD was shading theoretically. Even if the laser irradiated the vertical CCD, the shading structure protected the vertical CCD from the laser. Therefore,

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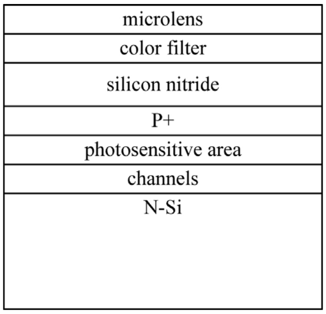

Fig. 1. The sectional structure diagram of the Si-CCD.

the geometric model of the Si-CCD is simplified as follows: the length and width of the Si-CCD are 4.8 mm and 3.6 mm respectively; the microlens layer, the color filter layer, the silicon nitride layer and the N-Si layer's thickness are 2 μm, 5.5 μm, 3 μm and 570 μm respectively. The sectional structure diagram of the Si-CCD is shown in Fig. 1.

The thermal-stress coupling model of the Si-CCD irradiated by millisecond pulse laser is established and the following assumptions are made: the initial temperature is 300 K; the interface of any two layers meets the continuous conditions of heat flow and temperature; the adiabatic condition and the free boundary condition are applied to all boundaries; the Si-CCD is an absolute elastic body(the stress-strain relation of the material is applied to Hooke's law).

When the Si-CCD is irradiated by millisecond pulse laser, the expression of the Fourier transient heat conduction equation is as follows:

$$\rho_j c_j \frac{\partial T_j(x,y,z,t)}{\partial t} - \sum_i \frac{\partial}{\partial i}\left(k_j \frac{\partial T_j(x,y,z,t)}{\partial i}\right) = \rho_j c_j L_j \frac{\partial f_{sj}}{\partial t} + Q_j \quad (\mathrm{i}=\mathrm{x,y,z}) \tag{1}$$

In the formula, $T_j(x, y, z, t)$ represents the time-space distribution of the temperature in the j layer, ρ_j, c_j, k_j, L_j, f_{sj} and Q_j represent the density, the specific heat capacity, the thermal conductivity, the latent heat, the solid fraction and the heat source in the j layer respectively.The expression of the heat source can be described as:

$$Q_j = 0.678 * I_0 * A_j * \alpha_j * e^{-\frac{(x^2+y^2)}{2*r^2}} * e^{-\alpha_j z} \tag{2}$$

In the formula, 0.678 is the transmission of the K9 optical window under 1064 nm laser, I_0 is the central power density of the laser, A_j and α_j represent the absorption rate and the absorption coefficient in the j layer respectively, r is the spot radius of the laser.

The thermoelastic equations, coupled with the heat conduction equation, are as follows:

$$\Delta^2 u_{xj} + \frac{1}{1-2\mu_j}\frac{\partial \varepsilon_j}{\partial x} - \frac{2(1+\mu_j)}{1-\mu_j}\beta_j \frac{\partial T_j(x,y,z,t)}{\partial x} = 0 \tag{3}$$

$$\Delta^2 u_{yj} + \frac{1}{1-2\mu_j}\frac{\partial \varepsilon_j}{\partial y} - \frac{2(1+\mu_j)}{1-\mu_j}\beta_j \frac{\partial T_j(x,y,z,t)}{\partial y} = 0 \tag{4}$$

$$\Delta^2 u_{zj} + \frac{1}{1-2\mu_j}\frac{\partial \varepsilon_j}{\partial z} - \frac{2(1+\mu_j)}{1-\mu_j}\beta_j \frac{\partial T_j(x,y,z,t)}{\partial z} = 0 \tag{5}$$

In the formula, u_{xj}, u_{yj} and u_{zj} represent the displacements on the x, y and z directions in the j layer respectively, ε_j, μ_j and β_j represent the volume strain, the Poisson's ratio and the thermal expansion coefficient in the j layer respectively.

The physical parameters of each layer on the Si-CCD are as follows: the melting point of the microlens layer is 513 K, the melting and boiling points of the color filter layer are 429 K and 693 K respectively, the melting point of the silicon nitride layer is 2173 K, the melting and boiling points of the N-Si layer are 1687 K and 2628 K respectively. In addition, the material parameters of each layer have nonlinear properties, including the thermal conductivity, the density, the specific heat capacity, the absorption rate, the absorption coefficient, the Poisson's ratio, the thermal expansion coefficient and the Young's modulus.

3. Results and analysis

3.1. Analysis of the temperature field

The relationship between the temperature of the central point on the Si-CCD and the depth direction under different energy densities was as shown in Fig. 2, and Fig. 2(b) was the partial enlarged detail of Fig. 2(a). The microlens layer, the color filter layer and the silicon nitride layer's maximum temperature rise appeared in the upper surface, the maximum