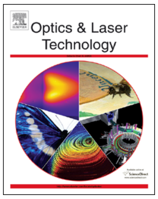
Optics & Laser Technology 58 (2014) 172–176

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec



Analysis of damage threshold on HgCdTe crystal irradiated by multi-pulsed CO_2 laser

Wei Tang [a,b,*], Jin Guo [a], Junfeng Shao [a,b], Tingfeng Wang [a]

[a] State Key Laboratory of Laser Interaction with Matter, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin 130033, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 20 August 2013
Received in revised form
28 September 2013
Accepted 19 October 2013
Available online 10 December 2013

Keywords:
Laser ablation
HgCdTe crystal
Multi-pulsed CO_2 laser

ABSTRACT

Damage threshold for the onset of surface melting was investigated theoretically and experimentally on HgCdTe crystal irradiated by multi-pulsed CO_2 laser. The impact of repetition frequency and irradiation time on damage threshold was analyzed and damage morphology of the crystal was observed by scanning electron microscope (SEM). Thermal accumulate effect is obvious, and damage threshold gradually reduces with the increase of irradiation time and does not depend on laser repetition frequency. Damage threshold calculated by thermal model is in good agreement with the experimental data. Melting and solidification phenomenon were evident on the crystal surface, and the obvious crack which was caused by thermal stress was not found. Theoretical model gives a reasonable explanation on surface morphology changes.

1. Introduction

HgCdTe crystal is a major semiconductor material used for fabrication of infrared photoelectric detector (8–14 μm) because of its high sensitivity and suitable response wavelength. In many applications [1–3], it is very important that the detectors continue to operate at high performance levels. However, HgCdTe crystal irradiated by high power laser happens to easily fracture [4] and melting [5,6], resulting in a permanent damage. Therefore, a number of studies on HgCdTe crystal damaged by CO_2 laser have been reported in recent years [4,7–9]. These researches are mainly focused on continuous-wave (CW) CO_2 laser damage or single pulsed laser damage. Bartoli gave a general theoretical model for laser induced damage of HgCdTe crystal and detector, in which laser was assumed to be Gaussian beam profile and the irradiation was assumed to be uniform [7], and obtained the damage threshold of HgCdTe detector which was irradiated by single pulsed CO_2 laser [8]. Zhao set up experimental installation of HgCdTe crystal damaged by CW CO_2 laser, and got the relationship between damage threshold of the crystal and irradiation time [9]. However, there has been no reported till now on HgCdTe crystal damaged by multi-pulsed CO_2 laser.

In this paper, we not only obtain the relationship between damage threshold and irradiation time, but also set up three-dimensional theoretical model, calculate thermal stress and temperature rising process of the crystal, and analyze the impact of repetition frequency on damage threshold.

2. Experimental set-up

Experimental sample is a p-type $Hg_{1-x}Cd_xTe$ ($x=0.174$) crystal which is cylindrical with thickness 0.63 mm, and radius 8 mm. The polished sample is mounted on the substrate by a thin layer of double-side adhesive tape. Morphology changes in the damaged sample are measured by SEM (Model#: XL30ESEM-FEG). The arrangement of experimental apparatus is schematically shown in Fig. 1.The pulsed laser used in the experiment is a high repetition frequency CO_2 laser operating in a Q-switched mode with a pulse width of 200 ns and a wavelength of 10.6 μm, and laser peak power is 4000 W [10]. Repetition frequency of the laser can be adjusted from 1 Hz to 100 kHz. The laser is operated on near TEM_{00} mode, the beam radius is 6 mm, and divergence angle is 1 mrad.

In our experiment, attenuator is used to adjust laser average power and the polarization of the incident beam needs not to be controlled. The CO_2 laser is divided into two parts by beam splitter. The reflected beam is received by a power meter to monitor laser power. The transmitted beam is focused on the crystal surface by a lens with focal length f of 100 mm. HgCdTe crystal is placed on the

---

[*] Corresponding author at: Changchun Institute of Optics, State Key Laboratory of Laser Interaction with Matter, Fine Mechanics and Physics, Chinese Academy of Sciences, 3888, Dong Nanhu Road, Changchun, Jilin 130033, China. Tel.: +86 135 961 90302.
E-mail addresses: 475531439@qq.com, twei222@163.com (W. Tang).

0030-3992/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlastec.2013.10.023

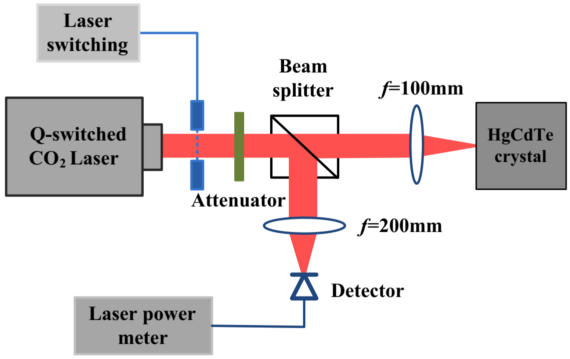


Fig. 1. Schematic diagram of the experimental set-up.

focus plane and the distance between multi-pulsed CO_2 laser and the focus lens is 2 m. Laser switching is used to adjust pulse number, and its exposure time is from 1 ms to 100 s.

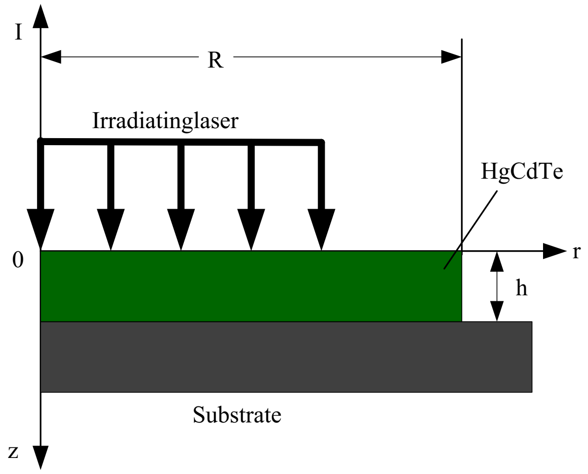


Fig. 2. Physical model of $Hg_{0.826}Cd_{0.174}Te$ crystal irradiated by high repetition frequency CO_2 laser.

3. Theoretical model set-up

Electron-phonon relaxation time of HgCdTe crystal have been found to be 1–2 ps in previous studies, so laser energy coupled to the electrinic system is quickly transferred to the lattice during nanosecond laser irradiation [11]. When pulsed laser is focused on the sample surface, laser energy is absorbed by the sample and its surface temperature will gradually rise on the irradiation with a 200 ns pulse. The problem usually can be simulated with one-dimensional model for single pulsed laser [5,7,12]. However, those one-dimensional models are no longer applied to multi-pulsed laser irradiation at a long irradiation time. Therefore, a three-dimensional thermal model is set up in this paper. We consider that HgCdTe crystal is the optically isotropy material and uniformly irradiated in the model. In addition, considering pulsed CO_2 laser and sample axial symmetry, one of fourth physical model of the sample is set up in Fig. 2.

Temperature distribution of HgCdTe crystal irradiated by multi-pulsed laser is described by three-dimensional heat conduction equation:

$$\rho c(T)\frac{\partial T}{\partial t}=K(T)\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)+Q(r,z,t) \quad (1)$$

where K(T), ρ and c(T) are thermal conductivity, density and specific heat of the material. $Q(r,z,t)$ is the rate of heat supplied to the material per unit time per unit volume and is connected to the peak power density I_0 of the irradiation laser.

$$Q=I_0(1-R_t)\alpha\exp(-\alpha z) \quad (2)$$

where R_t is the reflectivity, and α is the absorption coefficient of $Hg_{0.826}Cd_{0.174}Te$ crystal. HgCdTe absorption coefficient α mainly includes one-photon absorption coefficient α_L and two-photon absorption coefficient β_n [13].

$$\alpha=\alpha_L+\frac{\beta_n I_0}{2} \quad (3)$$

Two-photon absorption (TPA) is the fact that when the energy of high intensity incident photons is more than half of the band gap energy of the semiconductor, the electrons in the valence band (VB) absorb two photons to reach the unoccupied states in the conduction band (CB) [14]. Owing to low peak power density I_0 in our experiment, the absorption caused by TPA is much smaller than one-photon absorption. Therefore, we neglect the influence of TPA and absorption coefficient α is approximately equivalent to one-photon absorption coefficient α_L in our analysis.

Besides, considering the process of laser-material interaction, energy absorbed by the crystal surface is more than energy radiated, thus thermal radiation process is neglected in the model. However, heat convection process must be analyzed owing to a long irradiation time. Therefore, the initial and boundary conditions are given respectively:

$$T(r,h)=T_0 \quad (4)$$

$$-k\frac{\partial T(r,0)}{\partial n}=h_c(T_s-T_0) \quad (5)$$

$$-k\frac{\partial T(R,z)}{\partial n}=h_c(T_s-T_0) \quad (6)$$

where T_0 is room temperature, h_c is heat convection coefficient. Since c、K and α_L of $Hg_{1-x}Cd_xTe$ crystal are mainly dependent on temperature and chemical composition x, the analytic solution of Eq. (1) is not available. Hence, finite element method is used to calculate thermal damage process of $Hg_{0.826}Cd_{0.174}Te$ crystal irradiated by multi-pulsed CO_2 laser in this paper. The main physical properties of $Hg_{0.826}Cd_{0.174}Te$ crystal is shown in Table 1.

4. Experimental results and analysis

4.1. Damage threshold analysis

4.1.1. Repetition frequency

In order to analyze the impact of the repetition frequency, we measure the relationship between damage threshold and repetition frequency by morphology method in our experiment. Experimental results are shown in Fig. 3.

We can found that damage threshold of $Hg_{0.826}Cd_{0.174}Te$ crystal irradiated by different repetition frequencies is mainly the same in Fig. 3. Once laser average power density is more than 0.95 kW/cm^2, the melting damage will occur. Therefore, we argue that damage threshold irradiated by multi-pulsed laser mainly depends on laser average power density, and does not depend on repetition frequency. In order to explain the experimental conclusion, we calculate temperature rising process of $Hg_{0.826}Cd_{0.174}Te$ crystal with different repetition frequencies in the first 5 ms when laser average power densities are 0.95 kW/cm^2. Simulation results are shown in Fig. 4.

We can found that surface temperature gradually rises with the increase of irradiation time and appears two processes of temperature rising and dropping in the single pulse. Though the value

Table 1
Physical properties of $Hg_{0.826}Cd_{0.174}Te$ crystal.

Physical properties	Value	Reference
Melting point T_m	993 K	[5]
Density ρ	7.6 g/cm^3	[5]
Thermal diffusion coefficient of solid K(T)	1.125–4.568 T+11.03 T^2–8.427 T^3(mm^2/s),T(°C/1000)	[15]
Specific heat c(T)	0.058 T+149.76(J/kg K)(300–673 K)	[15]
Thermal conductivity coefficient $k(T)$	$\rho K(T)c(T)$	[15]
Latent heat of melting ΔH	130 J/g	[7]
Reflectivity	0.31	[5]
One-photon absorption coefficient α_L	$\alpha_0 \exp(\delta(E\text{-}E_0)/k/T)$ cm^{-1}	[16]
Two-photon absorption coefficient β_n	4.68 cm/MW	[14]
Thermal expansion coefficient β	4.25×10^{-6}/K	[4]
Elastic module E	5.39×10^{10} N/m^2	[4]
Poisson's ratio	0.41	[17]

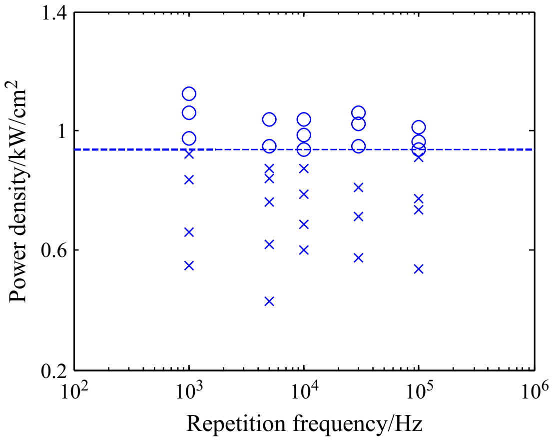


Fig. 3. Relationship between damage threshold and repetition frequency with the irradiation time of 10 s ("x" represents undamaged spots, "o" represents damaged spots).

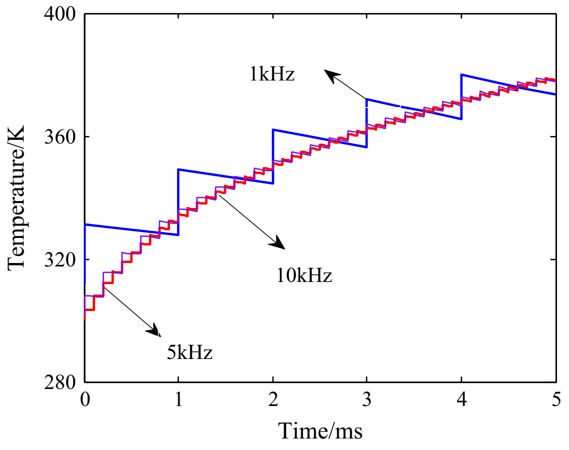


Fig. 4. Temperature rising process with the different repetition frequencies.

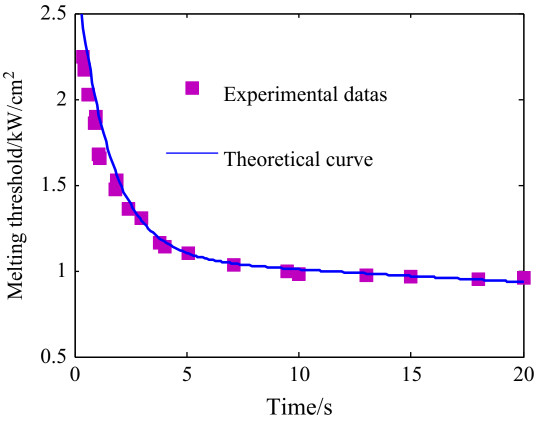


Fig. 5. Experimental results of damage threshold.

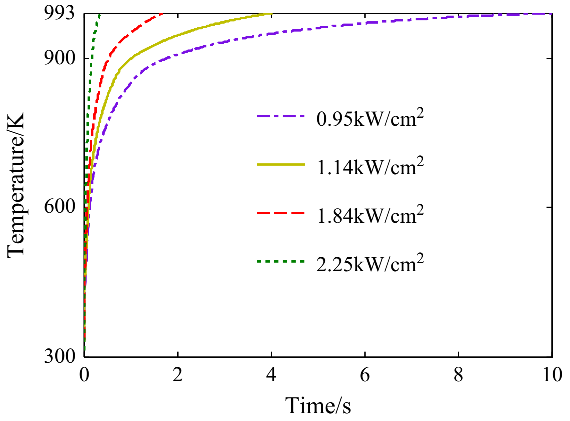


Fig. 6. Temperature rise of $Hg_{0.826}Cd_{0.174}Te$ at the center of the ablation zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of temperature rising caused by high repetition frequency laser is lower in the single pulse, the curve of temperature rising is basically the same with low repetition frequency laser because of its more pulse numbers and the same disappeared heat through thermal diffusion and convection at the same irradiation time. It is a reasonable explanation on previous experimental results.

4.1.2. Irradiation time

The relationship between damage threshold and irradiation time is shown in Fig. 5. Experimental results show that damage threshold of $Hg_{0.826}Cd_{0.174}Te$ crystal irradiated by multi-pulsed CO_2 laser decreases rapidly with the increase of irradiation time in the first 5 s. Damage threshold is 2.25 kW/cm^2 at the irradiation time of 0.4 s, while damage threshold reduces by half at the irradiation time of 5 s.

In addition, it is worth noting that once the irradiation time is more than 10 s, the damage threshold is 0.95 kW/cm^2 and it is not dependant on the irradiation time, that means no matter how long the interaction is, the crystal cannot be damaged with an average power density less than 0.95 kW/cm^2.

In order to approve the experimental conclusions above, we calculate temperature rising progress of the crystal irradiated by different power densities. Numerical simulation results are shown in Fig. 6.

We could note that thermal accumulation effect of HgCdTe crystal is extremely obvious in Fig. 6. Temperature on HgCdTe crystal surface gradually rises with the increase of irradiation time. When surface temperature reaches the melting point, melting damage will occur, and the higher average power density is, the less is the melting time. However, crystal surface temperature will appear in thermal equilibrium if the value of temperature rising is equal to the value of temperature dropping caused by thermal diffusion and convection in the single pulse, such as the purple dot dash line. Hence, it can be well explained experimental phenomenon above that when laser pulse number is more than 10 s, damage threshold was not changed.

Fig. 5 gives theoretical curve (solid line) of damage threshold. It is found that damage threshold calculated by thermal model is in good agreement with the experimental results. When laser peak power density is 0.95 kW/cm^2, temperature distribution of HgCdTe crystal simulated by ANSYS is shown in Fig. 7. We can found that the maximum temperature of the surface is located in the center of laser ablation zone, thermal diffusion occurs on the surface, the temperature gradually declines from the center to the edge of the crystal, thus the temperature gradient is formed on the surface. With the increase of irradiation time, the maximum temperature of the surface is higher, and the temperature gradient is more obvious.

Therefore, we can found that damage mechanism of multi-pulsed laser is different from single pulsed laser in Ref. [8]. When HgCdTe is damaged by single pulsed laser, surface temperature of the crystal will rise rapidly to melting point in the single pulse, and damage threshold mainly depends on energy deposited by unit area. Nevertheless, when HgCdTe is damaged by multi-pulsed laser, surface temperature of the crystal rises gradually due to thermal accumulation effect, and damage threshold mainly depends on average power density and associates with the irradiation time. It is basically consistent with the previous conclusions on CW CO_2 laser in Ref. [9].

4.2. Morphological analysis

Besides melting damage, stress damage is another main way of material damage. Once thermal stress is theoretically greater than the tensile strength of the material, thermal stress damage occurs, resulting in obvious cracks on the crystal surface. Therefore, we measure surface morphology of the crystal damaged by multi-pulsed CO_2 laser. SEM micrographs of the crystal surface damaged are shown in Fig. 8.

We can observe that melting and solidification phenomenon were extremely obvious, and a large number of bulges and pits were found in laser ablation zone. The main reason of the bulges and pits emerging is inhomogeneous of Hg evaporation. The more

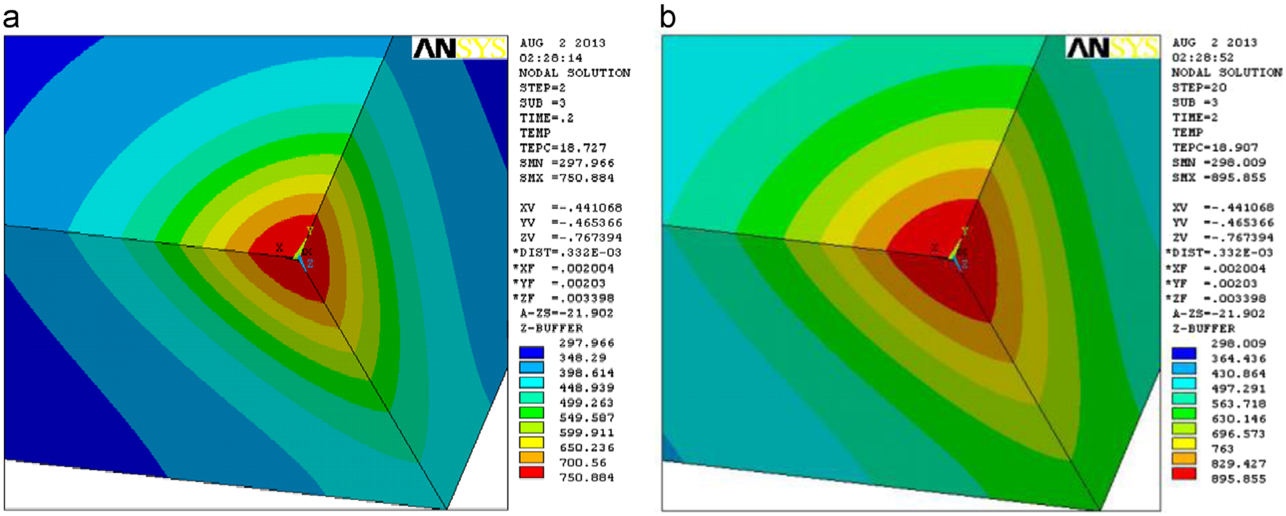


Fig. 7. Nephograms of temperature distribution on the crystal irradiated by different irradiation times. (a) 0.2, (b) 2 s.

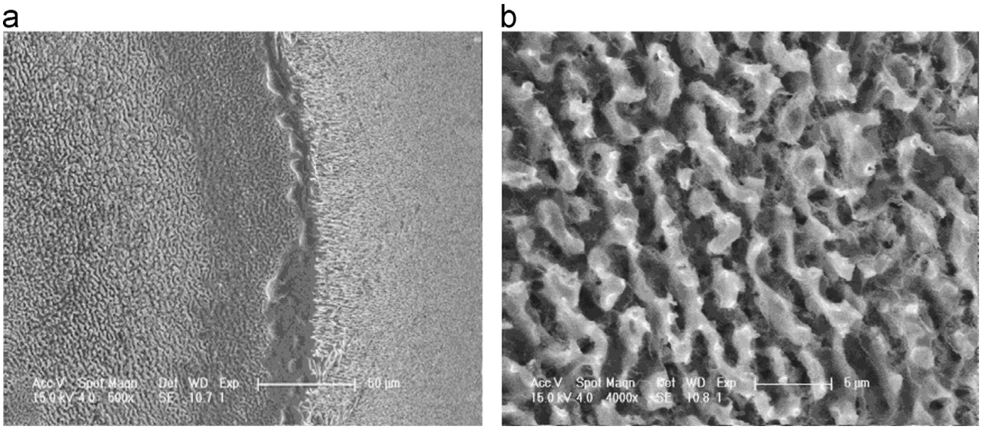


Fig. 8. SEM micrograph of $Hg_{0.826}Cd_{0.174}Te$ crystal. (a) SEM micrograph of the crystal surface (b) SEM micrograph of laser ablation zone.

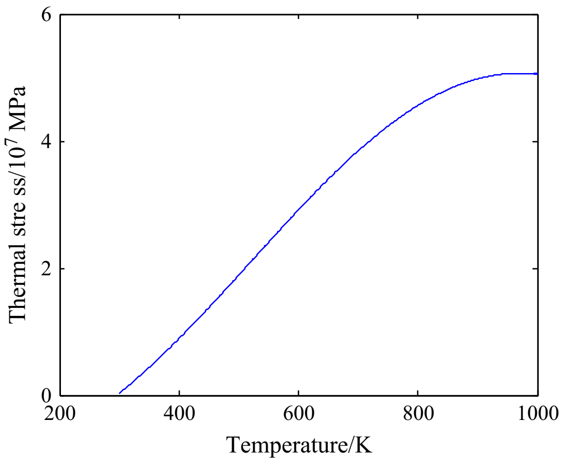


Fig. 9. Thermal stress results of $Hg_{0.826}Cd_{0.174}Te$ crystal.

Hg evaporation edgendered the pits, and the less Hg evaporation engendered the bulges. Hg evaporation is mainly due to the fact that Hg–Te key in HgCdTe crystal is unstable and easily decomposed into Hg and Te when surface temperature is very high. Thus Hg can be evaporated resulting in Hg vacancy because of its low melting points (234 K) and boiling points (629 K). Hg vacancy is the main native defects of HgCdTe crystal.In addition, comparing with surface morphology damaged by single pulsed laser in Ref. [4], we can found that the obvious crack caused by thermal stress was not found on the crystal surface.

In order to explain experimental phenomenon above, we calculate thermal stress of $Hg_{0.826}Cd_{0.174}Te$ crystal irradiated by 2.25 kW/cm^2. Radial deformation of the crystal axis defines zero as structure boundary condition in our analysis. The results are shown in Fig. 9.

We can observe that thermal stresses gradually increase with the increase of the temperature on the crystal surface. The thermal stress on the crystal surface is up to the maximum when the melting damage happens, the value of which is 5×10^7 Pa. In Ref. [4], it is reported that when the maximum thermal stress on the crystal surface is 14.9×10^7 Pa, thermal stress damage of the crystal surface occurs, and an obvious crack emerges throughout laser ablation zone. It is very obvious that the maximum thermal stress caused by multi-pulsed laser is much less than the thermal stress reported by Ref. [4] and not enough to make the crystal crack. This is mainly due to the fact that the crystal surface temperature rapidly rises in an extremely short time, thus the bigger thermal stress is produced in the irradiation zone. Once thermal stress is greater than the tensile strength of the material, the obvious crack will appear in the crystal surface. However, temperature rising is mainly due to thermal accumulation for multi-pulsed laser ablation, the crystal surface temperature slowly rises in the longer irradiation time, and thermal stress caused is smaller and not enough to engender the crack. Therefore, it gives a reasonable explanation that the main method of $Hg_{0.826}Cd_{0.174}Te$ crystal damaged by multi-pulsed CO_2 laser should be melting.

5. Conclusions

In summary, melting damages of $Hg_{0.826}Cd_{0.174}Te$ crystal irradiated by multi-pulsed CO_2 laser were measured in this paper, and temperature rising and thermal stress were calculated by three-dimensional theoretical model. The research results show that thermal accumulate effect of the crystal damaged by multi-pulsed laser is obvious, damage threshold mainly depends on laser irradiation time and does not depends on repetition frequency. Once laser average power density is less than 0.95 kW/cm^2, melting damage will not occur. Furthermore, $Hg_{0.826}Cd_{0.174}Te$ crystal irradiated by multi-pulsed CO_2 laser should be melting damage, melting and solidification phenomenon were evident in the laser ablation zone, and the obvious crack which was caused by thermal stress was not found. In theory, the maximum thermal stress obtained by thermal stress model is only 5×10^7 Pa, which is not enough to engender the crack. It is very reasonable to explain the experimental phenomena. The conclusions of the study have a reference value for HgCdTe crystal in the application of manufacturing infrared detector.

Acknowledgements

The experiment is supported by State Key Laboratory of Laser Interaction with Matter. Experimental equipments are supplied by the Laboratory to guarantee the experiments successfully completed. Furthermore, we also want to thank Shanghai Institute of technical physics for supplying $Hg_{0.826}Cd_{0.174}Te$ crystal.

References

[1] Singh A, Srivastav V, Pal R. HgCdTe avalanche photodiodes: a review. Opt Laser Technol 2011;43(7):1358–70.
[2] Bratt PR, Johnson SM, Rhiger DR. Historical perspectives on HgCdTe material and device development at Raytheon Vision Systems. Proc. SPIE 2009;7298:72982U.
[3] Rogalski A. HgCdTe infrared detector material: history, status and outlook. Rep Prog Phys 2005;68:2267–336.
[4] Cai H, Cheng ZH, Zhu HH, Zuo DL. Fracture mechanisms of $Hg_{0.8}Cd_{0.2}Te$ induced by pulsed TEA-CO_2 laser. Appl Surf Sci 2005;252(5):1685–92.
[5] Chen CS, Liu AH, Sun G, He JL, Wei XQ, Liu M, et al. Analysis of laser damage threshold and morphological changes at the surface of a HgCdTe crystal. J Opt A Pure Appl Opt 2006;8(1):88–92.
[6] Garg A, Kapoor A, Tripathi KN. Comparative study of evolution of laser damage in HgCdTe, CdTe & CdZnTe with nanosecond 1.06 μm wavelength multiple pulses. Proc. SPIE 2003;5273:122–8.
[7] Bartoli F, Esterowitz L, Kruer M, Allen R. Thermal modelling of laser damage in 8–14 μm HgCdTe photoconductive and PbSnTe photovoltaic detectors. J Appl Phys 1975;46(10):4519–25.
[8] Bartoli F, Esterowitz L, Kruer M, Allen R. Irreversible laser damage in ir detector materials. Appl Opt 1977;16(11):2934–7.
[9] Zhao JH, Li XY, Liu H, Jiang RQ, Liu ZHP, Hu ZHH. Damage threshold of HgCdTe induced by continuous-wave CO_2 laser. Appl Phys Lett 1999;74(8):1081–3.
[10] Xie JJ, Guo RH, Li DJ, Zhang CHS, Yang GL, Geng YM. Theoretical calculation and experimental study of acousto-optically Q-switched CO_2 laser. Opt Express 2010;18(12):12371–80.
[11] Garg A, Kapoor A, Tripathi KN, Bansal SK. Laser induced damage studies in mercury cadmium telluride. Opt Laser Technol 2007;39(7):1319–27.
[12] Semak VV, Thomas JG, Campbell BR. Drilling of steel and HgCdTe with the femtosecond pulses produced by a commercial laser system. J Phys D: Appl Phys 2004;37:2925–31.
[13] Cui HY, Li ZF, Liu ZL, Wang C, Chen XS. Modulation of the two-photon absorption by electric fields in HgCdTe photodiode. Appl Phys Lett 2008;92:021128.
[14] Krishnamurthy S, Yu ZG. Accurate evaluation of nonlinear absorption coefficients in InAs, InSb, and HgCdTe alloys. J Appl Phys 2007;101:113104.
[15] Voitsekhovskii AV, Kokhanenko AP, Shulga SA, Smith R. A model for the prediction of radiation defect profiles in the semiconductor target (HgCdTe) subjected to high power short pulsed ion beams. Nucl Instrum Methods Phys Res, Sect B 2005;227:531–44.
[16] Chu JH, Mi ZHY, Tang ZHY. Band-to-band optical absorption in narrow-gap $Hg_{1-x}Cd_xTe$ semiconductors. J Appl Phys 1992;71(8):3955–61.
[17] Wan CF, Luttmer JD, List RS, Strong RL. Piezoelectric effects in HgCdTe devices. J Electron Mater 1995;24(9):1293–7.