The infrared-induced temperature distributions of solid D_2 ices

Bi Peng(毕 鹏)[a)b)], Xie Duan(谢 端)[a)], Lin Wei(林 伟)[a)], Wang Kai(王 凯)[a)], Liu Jiang-Ping(刘江平)[a)b)], Tang Yong-Jian(唐永建)[a)], Yang Xiang-Dong(杨向东)[b)], and Lei Hai-Le(雷海乐)[a)†]

[a)] *Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang* 621900, *China*
[b)] *Institute of Atomic and Molecular Physics, Sichuan University, Chengdu* 610065, *China*

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A specific-wavelength infrared (IR) light ($\lambda = 3140$ nm) was irradiated into a solid D_2 ice prepared in a cylinder target cell. The temperature in the solid D_2 ice oscillated periodically with a high amplitude when irradiated by the IR light. The temperature oscillation has been well explained based on the two-dimensional heat transfer theory plus the IR-irradiation effect. The transmission optical imaging reveals that such a temperature oscillation is favorable to recrystallize the solid D_2 ice from multicrystal to quasi single crystal. This suggests an efficient method to layer the solid hydrogen-isotope ice for the inertial-confinement-fusion (ICF) experiments.

Keywords: heat transfer, solid deuterium, infrared irradiation

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1. Introduction

To achieve ignition and burn in inertial-confinement-fusion (ICF) experiments,[1–7] one critical challenge is to form a very smooth (roughness less than 1 μm) and uniform deuterium–tritium (D–T) ice layer covering the internal surface of a spherical capsule. The natural heating from the β decay of tritium can redistribute the solid D–T ice towards a smooth layer, but such a layer is typically a multicrystalline surface and not perfectly smooth. Some material techniques, such as epitaxial growth, are used to get a smooth or flat surface finish, but they are not available for ice layering in ICF experiments. A novel method[8] using a heat flux normal to the gas–solid interface to reduce the surface roughness of multicrystalline D_2 films has been investigated by Collins in 2001. When a heat flux deposits on a solid D_2 ice, it causes sublimation and recondensation from the thicker to thinner regions. At the same time, many high index crystal planes with higher specific surface energies are exposed in the heat flux heating process. In fact, the fundamental mechanism of smoothing solid D_2 ices is dependent on the competition between the decreasing overall bulk thermal energy due to the temperature gradient driven by the heat flux and the increasing surface energy from the high index surface plane. In short, the temperature distribution caused by the heat flux plays an important role in this process. Similarly, infrared (IR) irradiation as a heat flux can be used in ice layering experiments. Based on our previous studies, the IR-induced temperature distribution of a solid D_2 ice is investigated by both experiment and theory in this paper.

2. Experiments

By using the planar cryotarget system shown in Refs. [9] and [10], the solid D_2 ice was grown from the vapor phase by cooling through the triple-point temperature[11] T_{tp} (the triple-point temperature of deuterium in the standard condition) in a target cell (see Fig. 1). The target cell, a cylinder cavity with a diameter about 3.0 mm and a length about 1.6 mm, was mounted on the second-stage cold head of a Gifford–McMahon (G–M) crycooler. Each end of the target cell was sealed with a 0.4 mm thick quartz disk. The whole experimental process was examined by transmitted $\lambda = 855$ nm optical imagings. As schematically shown in Fig. 1, an infrared system was coupled to the planar-cryotarget system to irradiate the solid D_2 ice. A monochrometer was used to select a definite-wavelength IR light. Details of the experimental setup were elucidated in Ref. [9].

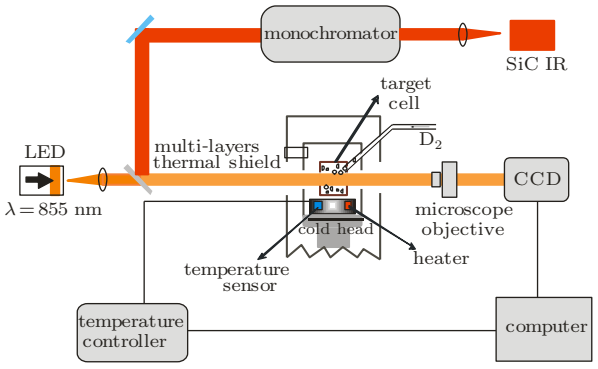


Fig. 1. (color online) Experimental setup.

3. Results

In our previous studies,[12] a strong absorption peak was found at 3140 nm by measuring the IR absorption spectra of

†Corresponding author. E-mail: hailelei@caep.ac.cn

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liquid D_2 at different temperatures. In the present experiment, the incident IR light is selected to be 3140 nm in wavelength and 100 μW in power. As shown in Fig. 2(a), the dark area indicates that no $\lambda = 855$ nm light can pass through the initial solidified D_2 due to its diffused reflection. This is commonly believed to be related to the surface roughness and the boundaries between misaligned crystallites produced during the initial random nucleation and rapid crystal growth. The initially dark image of the solid D_2 becomes transparent during the IR heating, as shown in Figs. 2(b)–2(f). It implies that the solid D_2 irradiated by the special IR light exhibits a tendency from the multiple crystalline to a quasi single crystal with fewer grain boundaries, fewer other defects, or smoother surfaces to reduce the diffused reflection and enhance the transmittance. As shown in Fig. 3, the transmittance and the spatial distribution of the solid D_2 ice change with its temperature adjusted to the set point (18.62 K) with the help of a heater (see Fig. 1), which can change its power when the temperature is above or below the set one. In this way, the temperature of the solid D_2 ice without IR irradiation oscillates around 18.62 K with a 50 mK amplitude, as shown in Fig. 3(a). Obviously, when irradiated by the special IR light, the temperature oscillates with a higher amplitude and even abruptly increases to T_{tp}, as shown in Fig. 3(b).

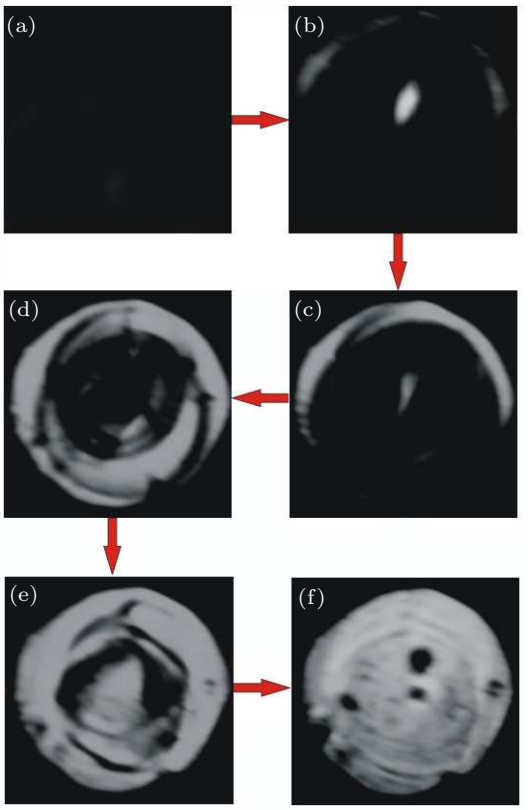


Fig. 2. Transmitted optical images of solid D_2 ice at 18.62 K after IR irradiation time of (a) 0 s, (b) 60 s, (c) 330 s, (d) 710 s, (e) 1030 s, and (f) 2242 s; the IR irradiation is 3140 nm in wavelength and 100 μW in power.

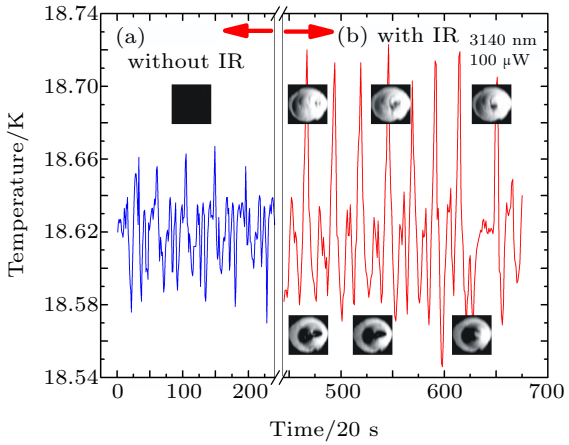


Fig. 3. (color online) Temperature of the cold head, the insets show transmitted optical images of the solid D_2 ice at different time ((a) without and (b) with IR heating).

4. Analysis and discussion

The temperature changes obviously due to the special IR irradiation as shown in Fig. 3. The IR-induced temperature distributions of the solid D_2 ice can be calculated by using the heat transfer theory. Since the whole experimental process is in a high vacuum environment, the convective heat transfer can be ignored. The radiative one is also ignored due to its small contribution to heat transfer. The temporal and spatial evolution of temperature can be determined by a simple conductive heat transfer model[13]

$$\rho C_P \frac{\partial T(x,y,t)}{\partial t} = k\left(\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2}\right) + Q_{IR}(x,y), \quad (1)$$

where T is the temperature in units of Kelvin, and $Q_{IR}(x,y)$ is the IR volumetric heating rate in units of W/m^3. As shown in Fig. 4, x and y denote the spatial directions parallel to and perpendicular to the IR light incident direction, respectively. An implicit finite difference method is applied in the temperature computation, in which the time iterative step Δt is 1 s and the spatial iterative step Δh is 10 μm. In the incident IR light direction, the transmitted IR power can be written as a function of x

$$I(x) = I_0 \exp(-\alpha x), \quad (2)$$

$$\mathrm{d}I(x) = -\alpha I_0 \exp(-\alpha x)\,\mathrm{d}x, \quad (3)$$

$$Q_{IR}(x)V = I(x-\Delta x) - I(x) = \Delta I(x) \approx \alpha I_0 \exp(-\alpha x)\Delta x = \alpha \Delta x I(x), \quad (4)$$

where I_0 is the incident IR light power at $x = 0$, V is the volume at the position x, and α is the absorption coefficient of the material. In our experiment, the absorption coefficients[12] of solid D_2 and quartz are 1.02 cm^{-1} and 1.55 cm^{-1}, respectively. Some intrinsic parameters[14] of solid D_2 and quartz are shown in Table 1. The intrinsic temperature oscillation is considered as a sinusoid with an amplitude of 50 mK .

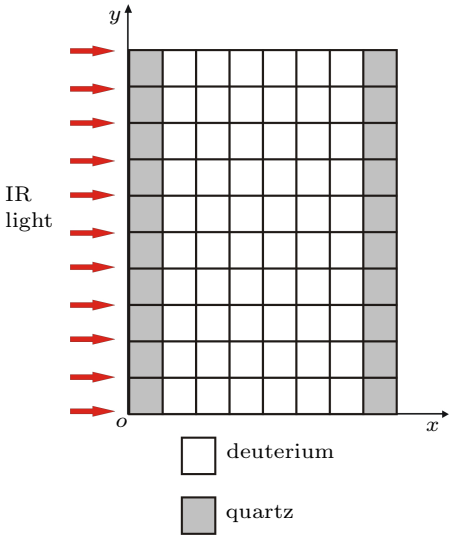


Fig. 4. (color online) Grid divisions of the target cell in the Cartesian coordinate.

Table 1. Some intrinsic parameters of solid D_2 and quartz.

	ρ/kg·m^{-3}	C_P/J·kg^{-1}·K^{-1}	k/W·m^{-1}·K^{-1}
Solid D_2	196.7	5158.1	0.124
Quartz	2650	9734.3	0.15

Figure 5 shows the two-dimensional distributions of temperature in the solid D_2 ice as a function of IR irradiation time corresponding to Fig. 2. The initially transparent area (Fig. 2(b)) indicates that the central parts of the solid D_2 ice reach a higher temperature earlier than the fringe ones as shown in Figs. 5(b) and 6(b). Then the transparent area expands as the IR irradiation time increases (Figs. 2(c) and 5(c)). When the temperature of the whole solid D_2 ice oscillates abruptly up to T_{tp} (Fig. 5(f)), the transmittance is the strongest (Fig. 2(f)). So the transmittance is mostly determined by the temperature distributions.

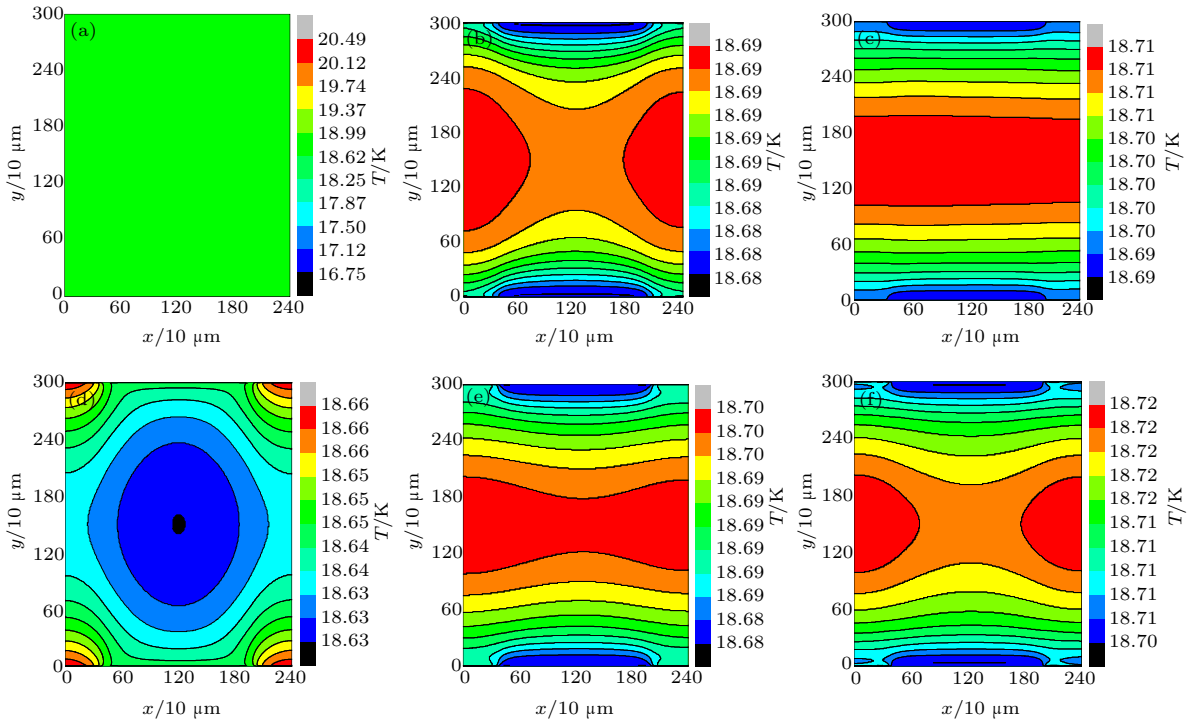


Fig. 5. (color online) Theoretical temperature fields of the solid D_2 ice as a function of irradiation time (corresponding to Fig. 2) (a) 0 s, (b) 60 s, (c) 330 s, (d) 710 s, (e) 103 s, and (f) 2242 s.

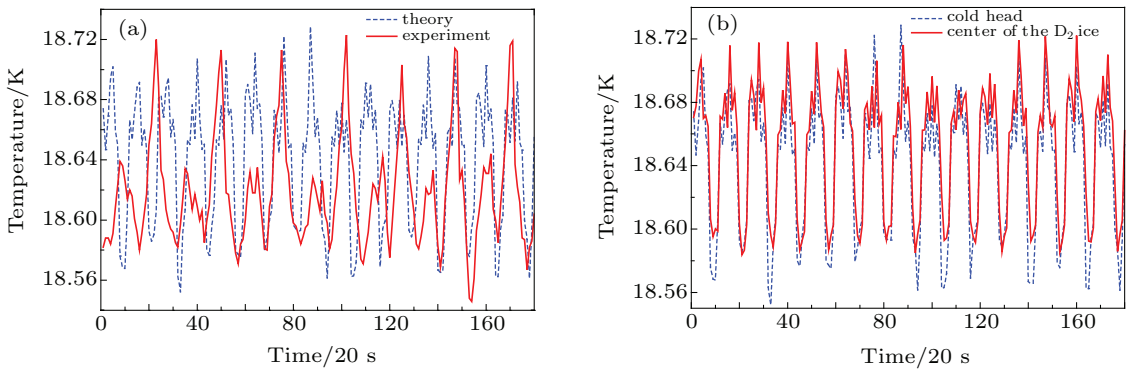


Fig. 6. (color online) Theoretical and experimental temperatures of the solid D_2 ice irradiated by the $\lambda = 3140$ nm IR light with 100 μW power. (a) Theoretical and experimental data of cold head (around the solid D_2 ice), (b) theoretical results in different positions of the solid D_2 ice.

The variations of temperature distributions are mostly determined by the cold head temperature which represents the average temperature of the solid D_2 ice and has an intrinsic oscillation. However, the multicrystalline D_2 cannot easily transform to a quasi single crystal by such an intrinsic temperature oscillation as shown in Fig. 3(a). When irradiated by the special IR light, the solid D_2 ice absorbs heat and makes a feedback to the cold head. That is why an abrupt temperature increase appears in Fig. 3(b). It is deduced that the temperature variations shown in Figs. 5 and 6 are dependent on the heat accumulation caused by the IR irradiation and the intrinsic cooling effects of the cryocooler. As shown in Fig. 6(a), the theoretical data for the temperature of the cold head as a function of time are in good agreement with the experimental ones. By the recurrent process revealed in Fig. 3, the solid D_2 can repair its own microstructure through such temperature oscillations. A single-crystal D_2 is expected when the D_2 recrystallization takes place after a sufficiently long IR irradiation time.

In our experiment, the temperature oscillation range can be controlled by the incident IR power. Experiments indicate that too high or too low IR power is not good for the D_2 redistribution. Therefore, a suitable incident IR power is favorable to control the temperature variations and good for the D_2 recrystallization. In conclusion, a transparent and uniform ice inside of a microshell is expected to form in future ICF experiments by using the heat effects of the IR irradiation.

5. Summary

Solid D_2 ice has been prepared and heated by $\lambda = 3140$ nm IR light. The two-dimensional heat transfer theory well explains the temperature variations of the solid D_2 ice after irradiation by the IR light. It is found that the heat effect of the IR irradiation on the solid D_2 is good for forming a transparent D_2 ice. At the same time, a suitable temperature oscillation to form such solid D_2 can be controlled by modulating the incident IR power.

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