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Shock-induced optical emission and high-pressure phase transformation of sapphire

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ABSTRACT

Emission from sapphire window material was measured by spontaneous spectroscopic and multi-wavelength pyrometer techniques. The spectral distribution as a function of wavelength fit well to the grey-body spectrum. We analyzed the emissions and discovered that they arise from shear banding, which is a typical thermal radiation. It was found that the color temperature of shocked sapphire changes linearly and regularly with stress increases from 40 GPa to 59 GPa but becomes monotonic for stresses from 87 GPa to 120 GPa. The change in behavior indicates that a shock-induced phase transformation occurs between 59 GPa and 87 GPa.

1. Introduction

Sapphire has been widely used as a window material in dynamic shock-wave experiments [1–3]. It is commonly used with shock-compression experimental methods such as VISAR, which measure the history of material velocity induced by a shock wave. The first such experiment was performed by Barker and Hollenbach [4] who used a number of materials including sapphire and observed that shock-induced luminescence and transparency were lost in sapphire. Fat′yanov et al. [5] reported that the duration of optical transmission decreased with increasing stress along different crystal orientations using light transmission measurement techniques. The data showed that light transmission in shocked sapphire crystals depends on time, stress, and orientation because of the different manifestations of the nature of inelastic deformation. It was suggested that the decrease in shear strength might be caused by substantial shock-induced micro-structural damage. Mashimo et al. [6] measured the Hugoniot relation of sapphire up to 110 GPa and reported a phase transition at 79 GPa. Sebban et al. [7] used a multi-wavelength pyrometer and bismuth-sapphire targets to study the emitted light from shock-induced sapphire. Their results indicated that the thermal flux originating from the bismuth dominates only at early time stages when the shock breaks out at the bismuth-sapphire interface. The observed radiances vary linearly with time as the shock propagates with a constant velocity inside the crystal and creates a volume of shocked sapphire that grows linearly with time. The authors extracted a grey-body temperature from the eight obtained radiances as the pressure climbed up to 30 GPa at a temperature of 4000 K. Kondo [8] reported the results of shocked-sapphire emission at shock pressures between 15.6 GPa and 84.7 GPa. The data reveal a constant emission temperature that changes monotonically with increasing pressure. These temperatures were larger by an order of magnitude than those estimated by thermodynamic considerations. Hare et al. [9] took short-duration exposure images and spectra of the optical emissions from shock-compressed single-crystal sapphire along different orientations. Their publication posits that the choice of sapphire crystal orientation is important to obtain maximum optical transparency under shock compression. They also did a gray-body fit to the emission results, which demonstrated an apparent temperature of 4780 K when shocking c-plane sapphire to 45 GPa. This temperature was in very good agreement with Kondo′s results but was also higher than the melting temperature. They concluded that the emission source was shear banding but did not explain how the temperature could be so far above the melting curve. Kwiatkowski and Gupta [10] studied optical spectra in the range of 0.45 μm to 0.65 μm for sapphire shocked above the HEL. They found that the spectrum was too narrow to be considered gray-body due to the extinction, which is most likely caused by scattering. In earlier studies, shock-induced emission was the main cause of the loss of optical transparency in crystals such as SiO_2, NaCl, $CaSO_4 \cdot 2H_2O$

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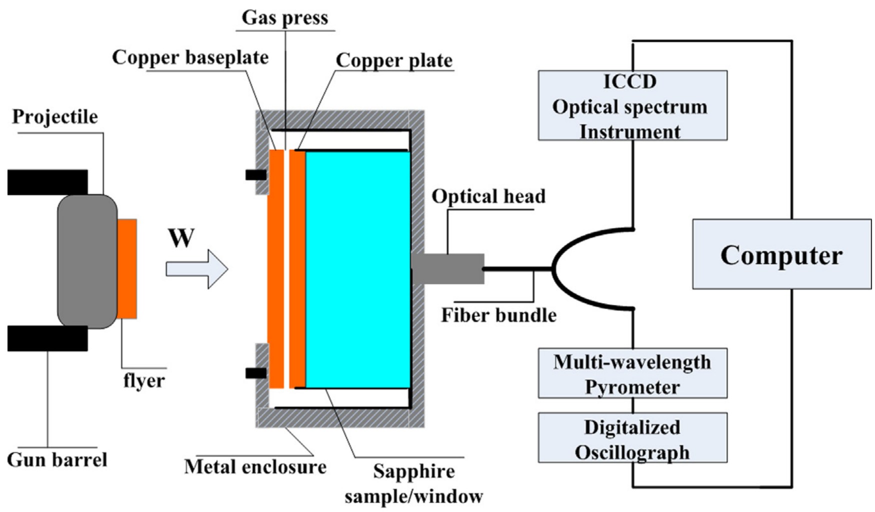

Fig. 1. Experimental setup.

and $CaCO_3$. Kondo and Ahrens [11–12] observed low-level heterogeneous optical emissions from shocked transparent minerals, but the apparent color temperatures are a factor of 2 to 10 greater than the Hugoniot temperature. In another paper, Ahrens and Schmidt [13] determined that the shock-induced color temperatures were in agreement with the corresponding melting temperatures in the pressure range of phase changes by studying MgO and $CaAl_2Si_2O_8$; they believe the thermal radiation came from a heterogeneous hot zone.

Sapphire is believed to be one of the major constituents of the Earth′s mantle. Understanding the phase diagram is very important to developing a dynamic model of the mantle wherein sapphire is mixed. To date, many theoretical and experimental results regarding the polymorphic phases of sapphire have been reported. However, few studies have been performed concerning the pressure-dependent melting line of sapphire. The scarcity of such studies is due to the difficulty of making observations of melting behavior at the elevated temperatures involved. Although many studies have been conducted on the transparency and light emission properties of sapphire under shock loading, conclusions about the radiation mechanism and radiation color temperature data were different for different studies. In this paper, we focus on the optical properties of c-cut sapphire above its HEL from 40 GPa to 120 GPa.

2. Description of experimental methods

In our experiment, we introduced three improvements to help obtain pure light emission from shocked sapphire. First, oxygen-free copper was chosen as the metal material to be mounted on the forward surface of the sapphire in the experiment because of its relatively low radiation characteristics and excellent ductility. Second, a uniform press was executed using a mechanical press along with compressed gaseous media to make the gap between the polished copper and sapphire surfaces as small as possible. The purpose of this design was to improve the quality of the direct-contact interface between copper and sapphire so that the hot layer could not recede from the metal/sapphire contact interface. Finally, we applied a light absorbing material around the wall of the target cavity to eliminate stray light, and we decreased the fiber measuring scope.

The c-cut sapphire sample used in our experiment had an initial density of 3.988 g/cm^3. Other Hugoniot parameters were C_0=8.729 km/s, λ=1.0 and γ_0=1.30 [14]. The samples were cut into 24-mm-diameter disks with a thickness of 8 mm, and they were polished to an optical finish on both sides. Plane shock waves were generated using a copper flyer accelerated by a 25-mm-bore two-stage light-gas gun. The basic experimental configuration is shown in Fig. 1. The shock impacted normally the specially designed target, which was composed of the copper base plate and a c-sapphire window. The optical head received the shock-induced emission, and the light was transmitted to the pyrometer and the ICCD optical spectrum instrument via an optical fiber bundle with a temporal resolution of approximately 5 ns. The fiber bundle was fixed at the center of the back surface. Each pyrometer channel′s wavelengths were centered at 488 nm, 509 nm, 533 nm, 589 nm, 650 nm, 702 nm, 779 nm and 809 nm, respectively. The output voltage from the pyrometer and the instantaneous spectrum from the ICCD were calibrated with a standard bromine-tungsten lamp for each shot. The shock pressures in sapphire were calculated with an impedance matching method [15]. The related Hugoniot parameters of copper were ρ_0=8.930 g/cm^3, C_0=3.933 km/s, λ=1.5 and γ_0=1.96 [16]. The flyer velocities were measured by an electromagnetic technique with uncertainties of approximately 0.5%.

3. Results and discussion

A reproduction of a typical pyrometer record for one shock compression experiment is shown in Fig. 2. In this experiment, sapphire sample disks were used. After impact, the pyrometer signals rise linearly with time, which indicates that the emission derives totally from the sapphire. Because the emission of the copper surface is too weak [17] to contribute compared to the genuine emission of sapphire, it does not change with time. Therefore, the radiation that is observed to increase with time must arise from the volume of the sapphire. The luminousness of sapphire is close to 100% at ambient temperature and pressure in the spectral range of 0.2–54.0 μm [18]. According to the model in Boslough′s study [19], our result represents a case in which there is no significant interface contribution and the initial transparent absorption of the sample is zero. The temperature and emissivity are determined by fitting the measured spectral radiances at all wavelengths to the Planck equation (gray-body model):

$$I(\lambda, Ts) = \varepsilon \cdot c_1 \lambda^{-5} [\exp(c_2/\lambda Ts) - 1]^{-1} \quad (1)$$

where $I(\lambda, Ts)$ is the measured intensity at the wavelength λ, the emissivity ε is assumed to be constant, Ts is the temperature, and