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Lattice thermal conductivity of $MgSiO_3$ perovskite and post-perovskite at the core–mantle boundary

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ABSTRACT

Thermal conductivity is essential for controlling the rate of core heat loss and long-term thermal evolution of the Earth, but it has been poorly constrained at the high pressures of Earth's lowermost mantle. We measured the lattice component of thermal diffusivity, heat transport by scattering of phonons, of both $MgSiO_3$ perovskite (Pv) and post-perovskite (PPv) at high pressures of up to 144 GPa and at room temperature. Lattice thermal conductivity of Pv-dominant lowermost mantle assemblage obtained in this study is about 11 W/m/K, while PPv-bearing rocks exhibit ~60% higher conductivity. Since such Pv value is comparable to the conventionally assumed lowermost mantle conductivity, our findings do not significantly alter but support the recent notion of high core–mantle boundary heat flow along with a young inner core and high temperatures in the early deep Earth.

1. Introduction

Heat in the Earth's interior is transported dominantly by convection in the mantle and core, and by conduction at thermal boundary layers. The thermal conductivity of the bottom thermal boundary layer of the solid mantle determines the magnitude of heat flux from the core, and is intimately related to instability of the boundary layer and the formation of mantle plumes, the long-term thermal evolution of both mantle and core, and the driving force for generation of the geomagnetic field (see Lay et al. (2008) for a review). Core heat loss has been estimated quantitatively from the temperature gradient in the boundary layer, inferred from recent seismological and mineral physics studies, and the thermal conductivity of the lowermost mantle (Hernlund et al., 2005; Lay et al., 2006; van der Hilst et al., 2007; Tateno et al., 2009a). However, the thermal conductivity (κ) and diffusivity ($D=(\kappa/\rho Cp)$, where ρ is density and Cp is specific heat at constant pressure) have been poorly constrained at high pressure.

The lattice thermal diffusivity of $MgSiO_3$ Pv, a primary mineral in the Earth's lower mantle, has only been measured at 1 bar and 26 GPa (Osako and Ito, 1991; Manthilake et al., 2011). Its pressure dependence therefore remains uncertain, although some predictions have been made based on theoretical modeling (Hofmeister, 2008; Manthilake et al., 2011) and first-principles calculations (de Koker, 2010). The value of $MgSiO_3$ PPv, a high-pressure polymorph of $MgSiO_3$ Pv, has only been speculated (Hofmeister, 2007a). Recent experiments on $Ca_{1-x}Sr_xIrO_3$ analogs showed that the thermal conductivity (or diffusivity) of PPv is nearly twice as high as that of the Pv phase (Keawprak et al., 2009; Cheng et al., 2011; Hunt et al., 2012). Previous estimates of the lower mantle thermal conductivity ranged widely between 5 and 30 W/m/K (e.g., Manga and Jeanloz, 1997; Hofmeister, 2008), and it has been often assumed to be 10 W/m/K (Stacey, 1992).

Here we measured the lattice thermal diffusivity of $MgSiO_3$ Pv and PPv over the entire lower mantle pressure range of up to 144 GPa and at room temperature using newly developed pulsed light heating thermoreflectance technique in a diamond-anvil cell (DAC) (Fig. 1). Combined with an externally heated DAC technique, high-temperature diffusivity measurements on Pv was also performed at 70 GPa up to 436 K. Our results yield a Pv-dominant lowermost mantle conductivity of about 11 W/m/K, comparable to the conventionally assumed value of 10 W/m/K proposed by

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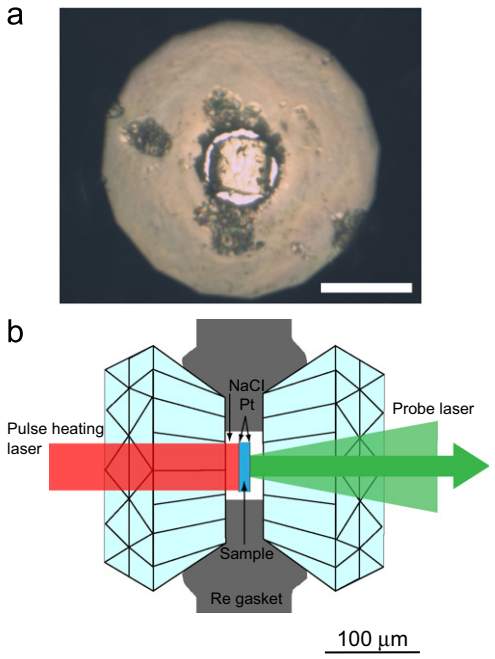

Fig. 1. Microscopic image and schematic drawing of the sample in a DAC. (a) Optical image of the Pv sample at 50 GPa in a DAC. Scale bar, 100 μm. (b) Schematic drawing of the sample configuration for thermoreflectance measurement. After the Pt film on one side was heated by pulsed laser (red), the heat was transported by conduction through the sample to the Pt film on the other side. Such heat diffusion time was determined from the change in reflectivity of the latter Pt film, which was monitored by continuous-wave laser (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Stacey (1992). We also found that PPv-bearing rock exhibits ~60% higher conductivity than Pv-dominant one, in good agreement with the recent results on $Ca_{1-x}Sr_xIrO_3$ analogs (Keawprak et al., 2009; Cheng et al., 2011; Hunt et al., 2012). However, enhanced conductivity of PPv does not significantly affect the estimate of core heat flow based on the double-crossing model. Our findings support the recent estimates of high heat flux across the core–mantle boundary (Labrosse et al., 2007; Lay et al., 2008).

2. Experimental methods

2.1. Sample preparation and high-pressure generation

We used polycrystalline $MgSiO_3$ Pv as a sample, which was synthesized at 25 GPa and 2073 K in a multi-anvil apparatus prior to the thermal diffusivity measurements. The Pv structure was confirmed by Raman spectroscopy. It was polished on both sides and thinned to about 10 μm in thickness by using Ion Slicer Ar ion-milling device (JEOL EM-09100IS) (Tateno et al., 2009b). Since complete transformation from Pv to PPv was found to be difficult when using Pv as the starting material, we also used $MgSiO_3$ gel starting material for the measurements of PPv. Such gel starting material was also used for the Pv measurement at 108 GPa. The gel was completely dehydrated beforehand by heating to 1273 K for 1 h in a furnace.

The sample plate was coated with sputtered platinum (Pt) film (initial thickness of 800 nm) on both sides for laser heating and thermoreflectance measurement. It was loaded into a hole in rhenium gasket, together with NaCl layers that served as both a pressure medium and thermal insulator against the diamond anvils (Fig. 1a). We then compressed the sample at room temperature in a DAC with 150, 200 or 300-μm culet anvils. Pressure was determined based on the Raman spectrum of the diamond anvil after thermal annealing (Akahama and Kawamura, 2004). The overall uncertainty in pressure may be less than 10%.

Each time before the thermoreflectance measurement, the sample was annealed by heating with a multi-mode Nd:YAG laser or a fiber laser to ~1800 K excluding below 22 GPa where $MgSiO_3$ Pv is thermodynamically unstable. PPv was synthesized directly from the gel starting material by heating with a fiber laser to 2000 K for 60 min. Phase identification was made by synchrotron X-ray diffraction measurements at BL10XU of SPring-8 (Fig. 2). The Pv sample did not change its crystal structure after the thermal annealing at 110 and 144 GPa.

2.2. Pulsed light heating thermoreflectance measurement and estimate of sample thickness at high pressure

The lattice thermal diffusivities of both $MgSiO_3$ Pv and PPv were measured in a DAC using the pulsed light heating thermoreflectance technique. The thermoreflectance measurement was made at a single pressure condition of interest in each run, except those at 11 and 22 GPa were performed upon decompression from 31 GPa. The 50–100 μm area of the Pt film was heated from one side by a pulsed Nd:YAG laser with a pulse duration of 2 ns (Fig. 1b). The increase in temperature due to pulsed heating was estimated to be less than 10 K. The applied heat was conducted through the sample to the Pt film on the opposite side. The temperature rise after the pulse heating was monitored as a change in reflectivity of that Pt film (Fig. 3). The reflectivity was probed by a linearly-polarized continuous-wave diode laser beam (782 nm in wavelength), which was focused to about 30 μm area of the Pt film in this study. Further details may be found in Yagi et al. (2011).

The high-temperature thermoreflectance measurements were also conducted on Pv to 436 K at 70 GPa. We employed an externally-heated DAC with a cylindrical furnace using AlChrom-O wire. Temperature was measured by Alumel–Chromel (K-type) thermocouple, which was placed very close to the sample. The total temperature uncertainty may be less than 5 K.

The thickness of both sample and Pt at high pressure (d_{sample} and d_{Pt}) was estimated after the thermoreflectance measurement

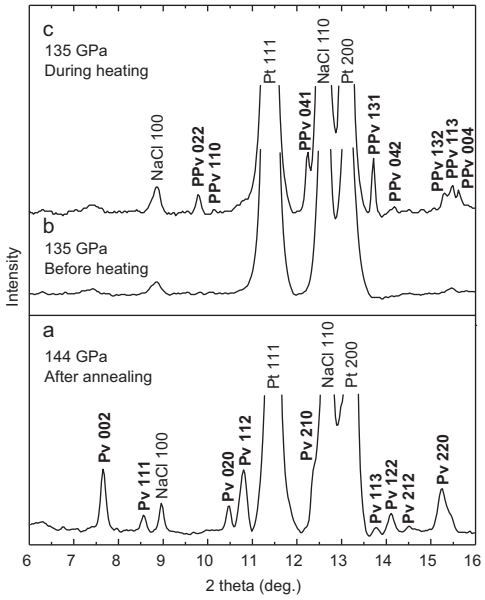

Fig. 2. XRD patterns of sample at high pressure and temperature. (a) Pv at 144 GPa and 300 K after thermal annealing, (b) amorphous gel sample before heating at 135 GPa and 300 K, and (c) PPv at 135 GPa and 2000 K during laser heating. Pt, platinum; NaCl, pressure medium. Background was subtracted.