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Simultaneous thermal diffusivity and thermal conductivity measurements of mantle materials up to 10GPa

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A one-dimensional transient (pulse) method for thermophysical property measurements has been applied to small samples of mantle materials in a uniaxial split-sphere high-pressure apparatus. Thermal diffusivity and thermal conductivity of fused silica and garnet have been measured. At pressures up to 8.3 GPa the thermal conductivity and the thermal diffusivity of fused silica decreases with increasing pressure. For a principal mantle mineral, garnet, the pressure derivatives of thermal conductivity and the thermal diffusivity are positive: they are 2 per cent of increase per 1 GPa at the room temperature over 5GPa.

[thermal diffusivity, thermal conductivity, earth materials, pulse method, split-sphere apparatus]

1. Introduction

Heat transfer in the Earth's mantle is the one of the important factors for the dynamics of the globe acting as a heat engine generated by the temperature difference between the hot interior and the cold surface. Estimating magnitude of thermal conduction in the earth by experiments for earth's materials is a practical tools of approach to this problem. Needless to say, thermal conductivity or thermal diffusivity measurements should be made at conditions on going in the earth, namely high temperature and high pressure. This needs troublesome experimental environment that controlling heat flow in a sample is difficult because of the surrounding pressure medium. One successful way to avoid this issue is to design a method of measurement using a sample of cylindrical symmetry. However, that method require a comparative large samples for study of the earth's interior; the important mantle minerals including materials obtained only by high pressure synthesis has usually a small, mm-sized volume.

In this report we present a simultaneous thermal diffusivity and thermal conductivity measurements of mantle materials under pressure using a one-dimentional transient (pulse) method. This method is favorable for mantle materials, because samples are small compared to those for other methods using cylindrical symmetry. Of course, this method can be applied to materials which are anisotropic in thermal conductivity. In addition. the heat capacity can be obtained by comparing the thermal diffusivity and the thermal conductivity.

2. Experimental procedure

We have applied a transient method under pressure developed by Dzavadov (1975) to a small samples of mantle materials. Three thin sample disks with equal thickness are stacked. A thin planar heater is installed between the two disks, and a thermocouple is inserted to the other joint of the disks. A electric pulse current is supplied to the heater, and the temperature change in the sample is detected by the thermocouple. Figure 1 shows the schematic diagram of the measurement.

For the condition that temperature is constant at the end of the sample the temperature change (ΔT) at any point in the sample is expressed as

$$\Delta T = A\sum_{n-1}^{\infty}(1/n^2)\sin(n\pi/3)\sin(n\pi x/d)\exp(-n^2Bt)[\exp(n^2B\tau)-1] \quad (t > \tau) ,$$

where the origin of time (t) is the rising point of pulse heating, x is the distance from the end of the sample on the heater side, τ is the width of the pulse current, d is the total thickness of the sample. The thermocouple is placed at $x= 2d/3$.

In this expression A and B are combined with the physical properties as

$$A= 2Wd/\pi^2\lambda S, \text{ and } B = \pi^2 a/d^2,$$

where, a is the thermal diffusivity and λ is the thermal conductivity of the sample, W is the power of the pulse current and S is the cross section of the heater.

The temperature change, ΔT, has a maximum; The parameter B combined thermal diffusivity is determined so that the maximum point of the summation in the ΔT's expression for x= 2d/3 coincides the time at the observed temperature peak for a heating duration, τ. In practice, the sum is cut off to the first 10 terms in the calculation on a personal computer. So thermal conductivity is calculated by using S,W and the observed value of peak temperature.

Measurements have been made in the uniaxial split-sphere high-pressure apparatus, USSA-1000 at the Institute for Study of the Earth's Interior, Okayama University. In this study magnesia octahedrons of 18mm edge length containing Cr_2O_3, were used for pressure medium. The truncation edge length of tungsten carbide anvils was 11 mm. Pressure generated was calibrated by Iizuka (1996) using BiI/II and BIII/IV phase transition for the same gasket and compression-pad design at room temperature.

Figure 2 shows the sample assembly in a octahedral pressure medium. To make uniform heating, a planar heater made of nickel-chromium alloy is cut into groove by photographic etching. The thickness is 0.03mm and the diameter is 3.8mm. The heater has a electric resistance of about 25 ohms. A alumel-chromel thermocouple with a flat cross section of 0.03mmx0.3mm is used. Total thickness of the sample is set to from 0.9mm to 1.1 mm. The electric power supplied to the heater is about 15W and the pulse width (duration) ranged from 2ms to 10ms. Examples of temperature records on a storage oscilloscope are shown in Fig. 3. The uncertainty of the measurement is 7 per cent for thermal diffusivity and 4 per cent for thermal conductivity. These estimates come from the limit of determination in the sample thickness and from the time resolution in record of the temperature profile.

3. Results

(1) Fused silica

Figure 4 shows the pressure effect on thermal diffusivity and the thermal conductivity of fused silica. The total thickness of the sample is 1.050mm. The sample lengths reduced with pressure increase are calibrated by compression data (Schroeder et al., 1990). Thermal diffusivity of fused silica decreases with increasing pressure up to 8.3 GPa at room temperature. This behavior agree with the previous data obtained by a Ångström method using a sample of cylindrical symmetry (Katsura, 1993) .

(2) Garnet

Figure 5 shows the preliminary results of thermal diffusivity and thermal conductivity of natural garnet at 17˚C up to 8.3 GPa. The garnet sample, from India, is classified as almandine, with a composition of $Mg_{0.51}Fe_{2.29}Mn_{0.20}Al_2Si_30_{12}$. The total thickness of the sample is 1.023mm. In calculating the the thermal diffusivity and thermal conductivity at high pressures, the compression of almandine (Sato et al., 1978) is taken account. The cubic symmetry crystal, like garnet is thermally isotropic; The crystallographic axis of the sample was taken to arbitrary direction. The thermal conductivity at lower pressures has good agreement with the previous results for almandine ($3.3Wm^{-1}K^{-1}$, at 23˚C: Horai,1971). Both the thermal diffusivity and the thermal conductivity of the garnet increase with increasing pressure, however, their pressure (P) derivatives are small, namely dlna/dP~ 0.02/GPa and dlnλ/dP~ 0.02/GPa in the pressure range from 5 GPa to 8.2 GPa.

4. Concluding remarks

Using a small samples, this simple method will bring information on the pressure effects of thermal diffusivity and thermal conductivity of mantle materials. The large contrast of thermal conductivity between the sample and the surrounding material could ensure sufficient approximation in the boundary conditions for the measurement. It is well known that thermal conductivity and thermal diffusivity of mantle material s vary large with temperature; Measurements at high temperatures and at high pressures are the next step of this experiment.

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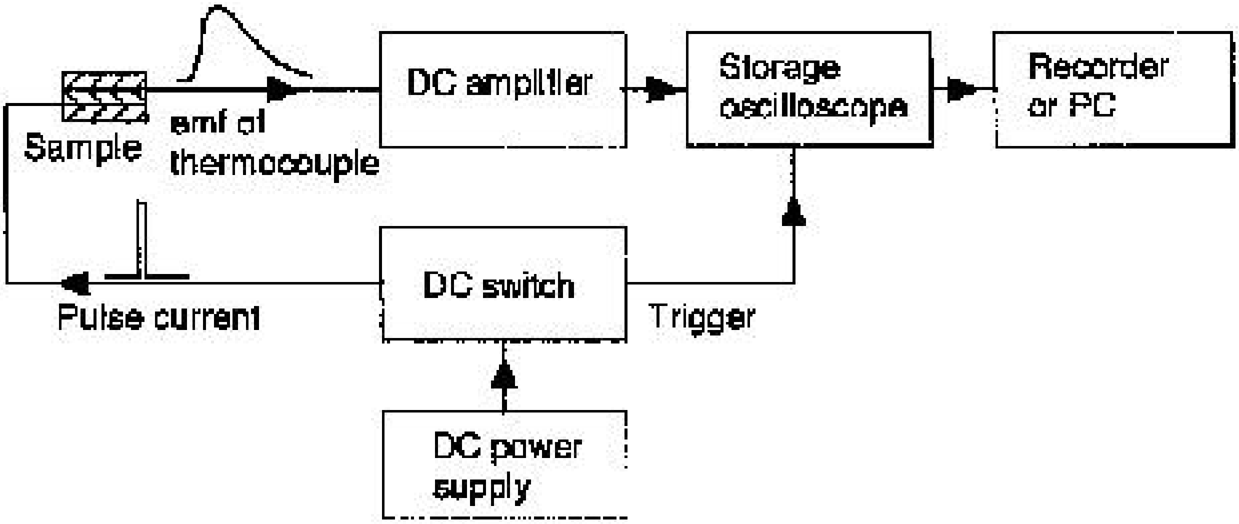

Fig.1. Schematic diagram of the one-dimensional transient (pulse) method of thermal diffusivity and thermal conductivity measurements

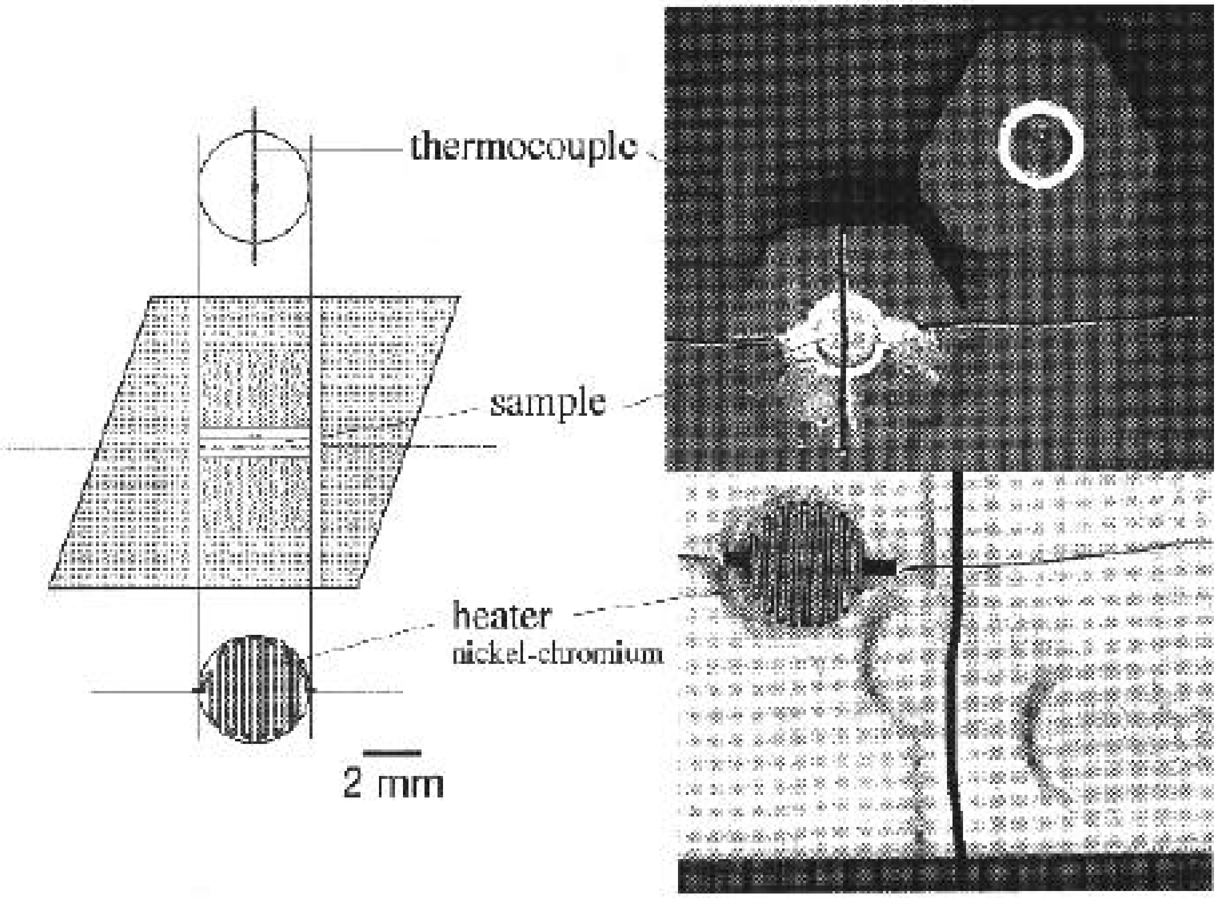

Fig. 2. A sample for a one-dimensional transient method of thermal diffusivity and thermal conductivity measurements in a octahedral pressure medium.

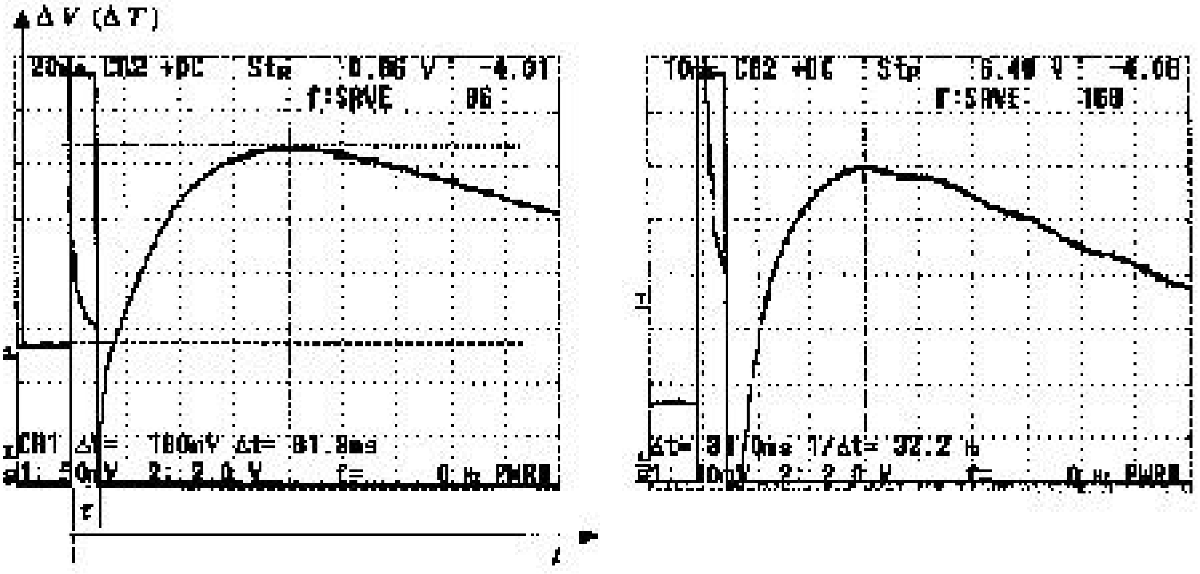

Fig 3. The records of temperature (emf of the thermocouple) on a storage oscilloscope. Left: Fused quartz at 1.9GPa. The sample thickness is 1.050mm at zero pressure. Heating duration is 10.0ms with a power of 11.1W. Right: Garnet at 8.3GPa. The sample thickness is 1.023mm at zero pressure. Heating duration is 5.0ms with a power of 10.0W

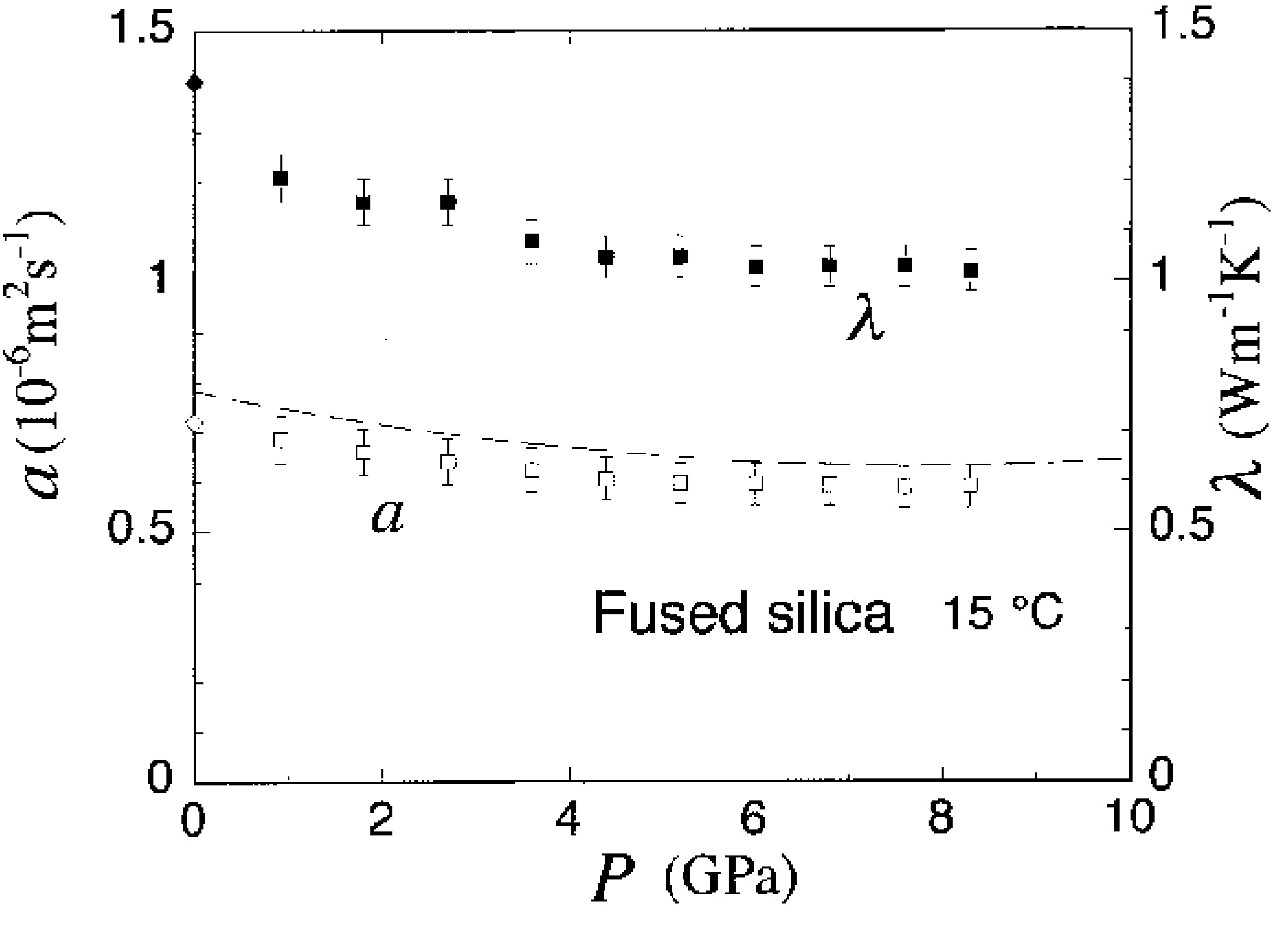

Fig. 4. The thermal diffusivity (open squares) and the thermal conductivity (solid squares) of fused silica as a function of pressure at 15˚C. The error bars express the uncertainties of the measurements coming from the limit of determination in the sample thickness and from the time resolution in record of the temperature profile. The open diamond denotes the thermal diffusivity by Kanamori et al. (1969) at the same temperature under one atmosphere, and the solid diamond is the thermal conductivity at O˚C under one atmosphere (Rika Nenpyo,1997). The dashed line denotes the thermal diffusivity of fused silica at 373K by the Ångström method using cylindrical symmetry (Katsura, 1992).

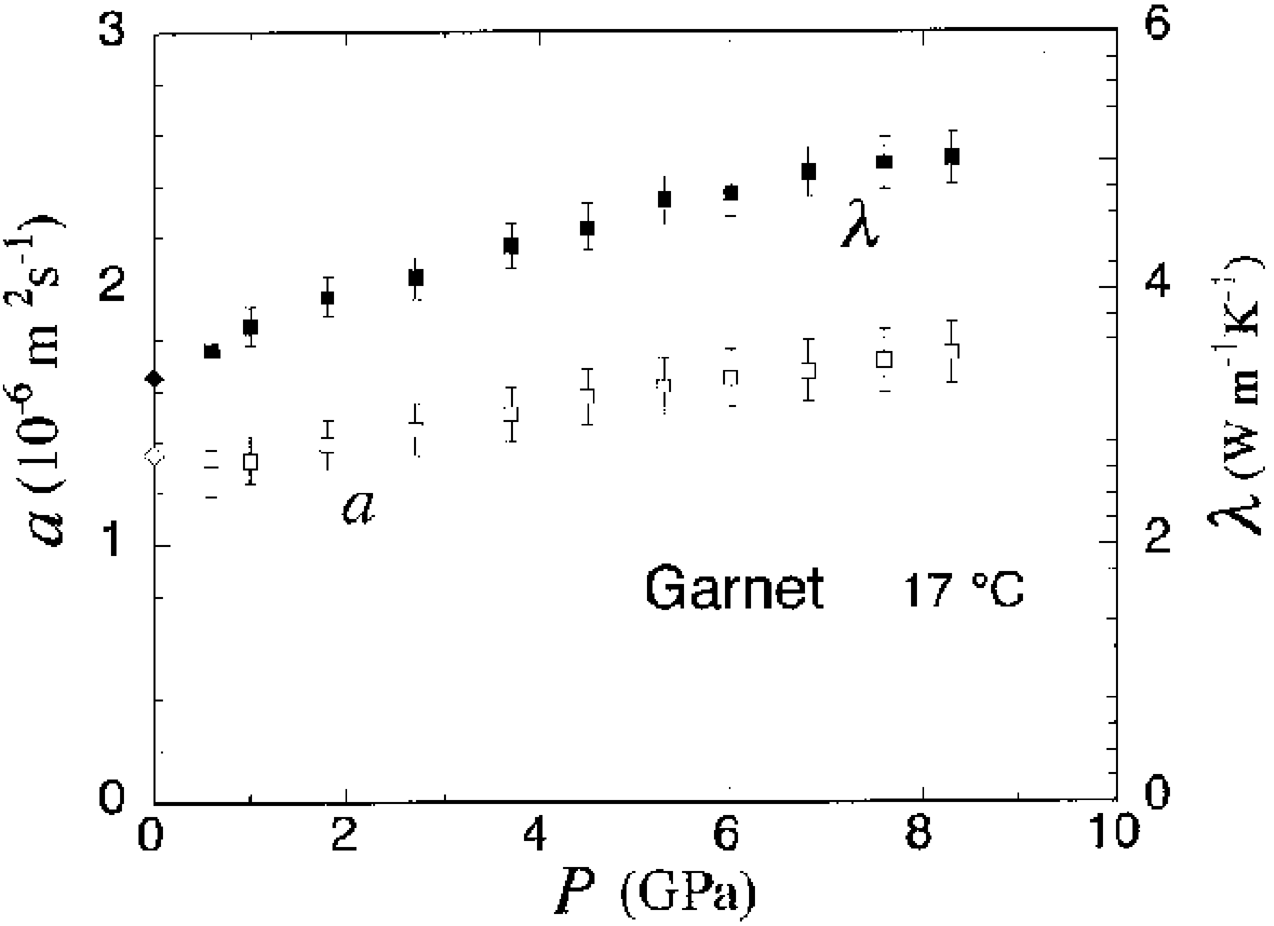

Fig . 5. The thermal diffusivity (open squares) and the thermal conductivity (solid squares) of almandine garnet as a function of pressure at 17˚C. The meaning of the error bars is the same as in Figure 2. The open diamond denote the thermal diffusivity at 290K under zero pressure (Osako, 1991). The solid diamond is the thermal conductivity of natural almandine at 23˚C under one atmosphere (Horai,1971).