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Thermal Diffusivity of Olivine and Garnet Single Crystals

Masahiro Osako

Department of Science and Engineering, National Science Museum, 3–23–1 Hyakunincho,
Shinjuku-ku, Tokyo, 169 Japan

Abstract Thermal diffusivities of natural olivine and garnet single crystals have been measured from 300 K to around 550 K by an Ångström method. The olivine with a composition of $Fo_{93}Fa_7$ has the anisotropy in thermal diffusivities, which are $2.53 \times 10^{-6}\ m^2 s^{-1}$, $1.52 \times 10^{-6}\ m^2 s^{-1}$, and $2.21 \times 10^{-6}\ m^2 s^{-1}$ at 300 K along the a-, b-, and c-axes respectively. The garnet with a composition of $Prp_{34}Alm_{57}Sps_1Grs_8$ has a thermal diffusivity of $1.18 \times 10^{-6}\ m^2 s^{-1}$ at 300 K.

Key words: thermal diffusivity, olivine, garnet, Ångström method

1. Introduction

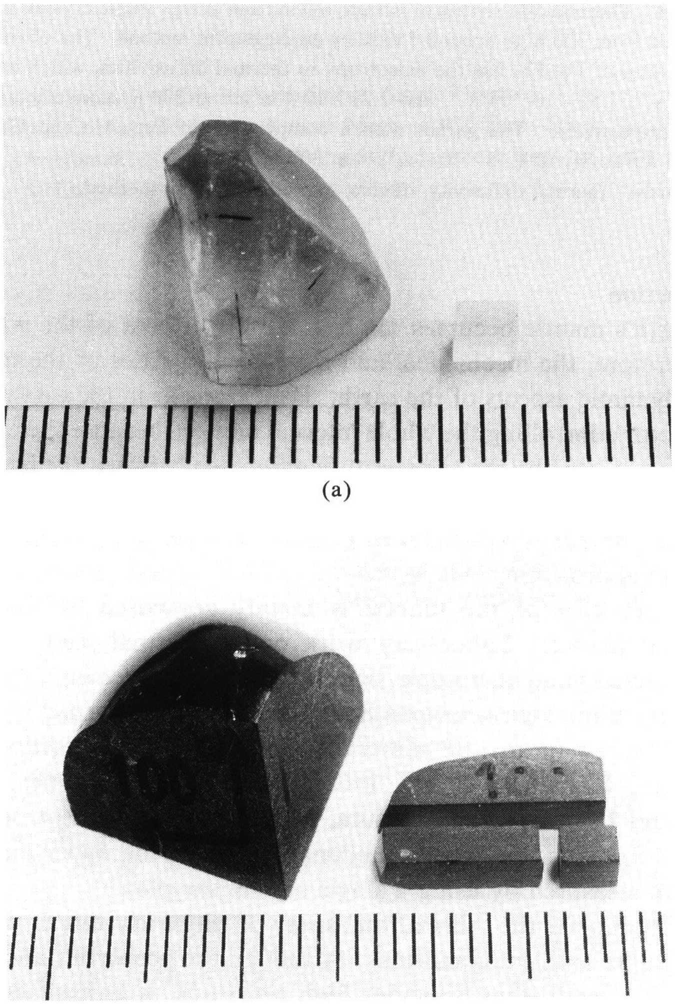
The earth's mantle occupies more than 80 per cent of the whole earth by volume, therefore, the mechanical and thermal properties of the mantle largely affects the dynamic aspects of the earth. Heat transfer in the earth's mantle is a principal factor controlling the whole internal motion, because the earth is a huge heat engine generated by the temperature difference between the hot interior and the cold surface. Estimating the distribution of thermal conductivity or thermal diffusivity in the earth by laboratory measurements on mantle materials is a practical tool approaching this issue.

The upper part of the mantle is mainly composed of silicates olivine, pyroxene and garnet. Laboratory work on geothermal study of the mantle should be started from thermophysical property measurements for these materials. To date some measurements have been made on thermal conductivity or thermal diffusivity of mantle materials under ambient condition or at high pressure (*e.g.*, Kanamori *et al.*, 1968; Fujisawa *et al.*, 1968; Horai, 1971; Schloessin and Dvorak; 1972, Katsura, 1995), however, anisotropy in thermal diffusivities of olivine, the most abundant mineral in the upper mantle, has not been directly measured by using a single crystal sample.

This note reports the thermal diffusivity of single crystals of natural olivine and garnet under ambient conditions. Although the properties under conditions ongoing in the earth, that is, under high pressures, is indispensable for earth sciences, the values at zero pressure are still important, because the result is needed as a check for measurements at high pressures.

2. Experimental

An idiomorphic olivine from northern Pakistan was cut into a rectangular parallelepiped shape so that each edge pointed to the crystallographic a-, b- or c-axis. The accuracy in the edge alignments was within 0.5 degrees, which was confirmed by an X-ray diffractometer. The composition of this olivine is 93% forsterite and 7% fayalite by molar fraction. The initial edge lengths of the


(a)

(b)

Fig. 1. (a) The olivine single crystal used in this work. A cut sample for thermal diffusivity measurement is on the right. (b) The crack-free lump of garnet from India (left); The supplier had given a polish. A small sample (right) was cut out for the measurement.

sample were 3.10 mm for the a-axis direction, 1.77 mm for the b-axis and 2.68 mm for the c-axis. These were finally reduced to 2.96 mm, 1.77 mm and 2.45 mm for the directions of a-, b- and c-axes respectively because of cutting away small cleavages occurred at the corner. Figure 1 shows the olivine sample used in this measurement.

The natural garnet used in this measurement is from India, but the exact locality is not known. This garnet has a molar composition of 34% pyrope, 57% almandine, 1% spessartine and 8% grossular. A rectangular parallelepiped sample of 3.12 mm × 2.42 mm × 2.41 mm was cut out, so that all the edges were parallel to the crystallographic axes, ⟨100⟩. Of these edges the longest one (3.12 mm) was used for the measurement. The lump of garnet and the cut sample are also shown in Figure 1.

A modified Ångström method (Kanamori *et al.*, 1969; Osako, 1991) has been applied for thermal diffusivity measurements. Figure 2 shows the sample attached to the heater generating a periodic temperature wave. The sample and two thermocouples at the ends are fixed with silver coating material. In this study thin alumel-chromel thermocouples with a diameter of 0.05 mm were used

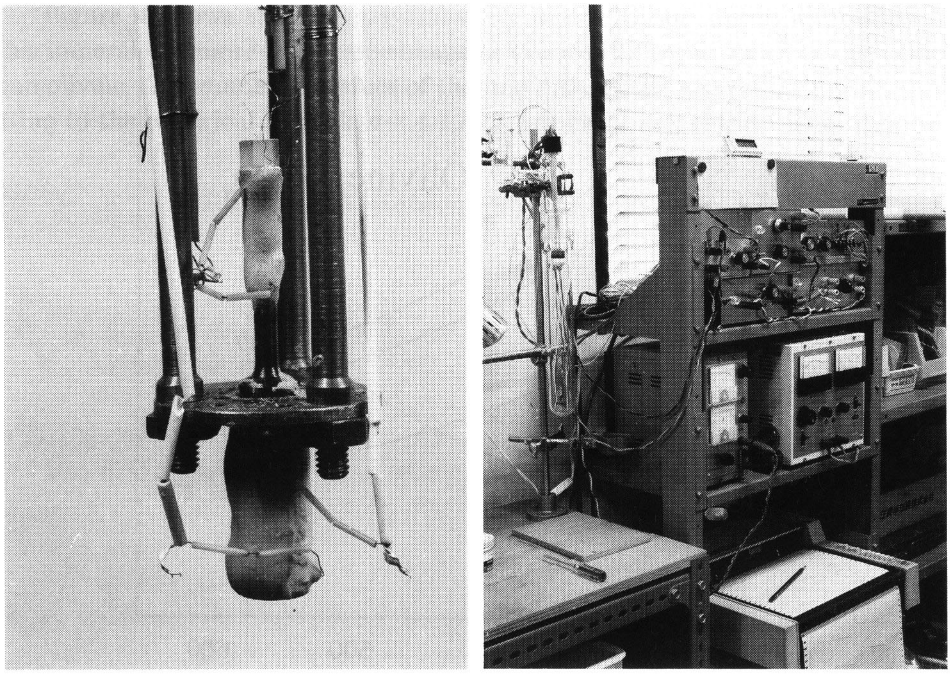

(a) (b)

Fig. 2. (a) The olivine sample attached to a small heater. The sample and two thermocouples are fixed with silver coating material. A small furnace is installed at the bottom. (b) The sample assembly is placed in the vacuum vessel as seen on the left.

in order to reduce heat loss disturbing the measurement for the small samples. The heating period ranged from 1.2 s to 7 s. Power into the heater was changed from 0.03 W to 5 W to make variation in the ambient temperature of the sample. A small furnace attached to the bottom was worked at higher temperatures. Measurements were made in a vacuum vessel not to be disturbed by air convection.

3. Results and discussion

(1) Olivine

Figure 3 shows the anisotropy in thermal diffusivities of the olivine versus temperature for the three crystallographic axes. Over the temperature range investigated the olivine has highly anisotropy in thermal conduction: the thermal diffusivity along the a-axis is the highest value, along the c-axis is 13 per cent lower, and along the b-axis is the lowest, 60% of that along to the a-axis at 300 K. So the thermal conductivity is combined to the thermal diffusivity by multiplying the heat capacity per unit volume, this difference means directly the anisotropy in the thermal conductivity of the olivine. To obtain numerical results an empirical formula, $a=A+B/T$ is fitted to each data, where a is thermal diffusivity, T is the

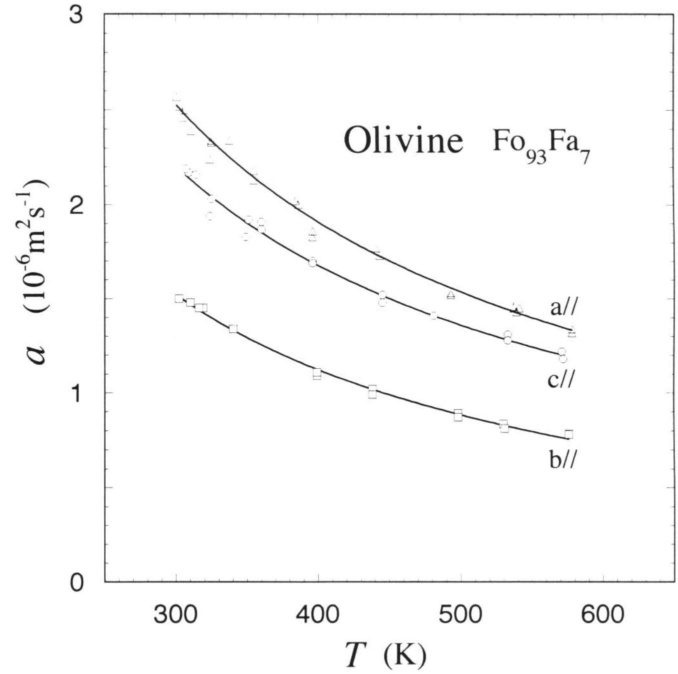


Fig. 3. Thermal diffusivities (a) of olivine as a function of the absolute temperature (T). The symbols $a_{//}$, $b_{//}$ and $c_{//}$ denote the direction of a-, b- and c-axes respectively. The curves are fitted for the formula of $a=A+B/T$.

absolute temperature. The numerical values of thermal diffusivities at various temperatures and the coefficients A and B are listed in Table 1.

Kanamori *et al.* (1968) measured the thermal diffusivity of an olivine of $Fo_{82}Fa_{18}$ for the direction of c-axis. Their result at 300 K shows 16% smaller value than that in the present study for the same crystallographic axis. This discrepancy cannot be suspicious because the thermal conductivity, in consequence thermal diffusivity, has the composition dependence in forsterite-fayalite join (Horai, 1971). According to his estimate the thermal conductivity of olivine increases 15% as the composition changes from 82% to 93% of Fo.

Chai *et al.* (1996) obtained the thermal diffusivity of $Fo_{86}Fa_{14}$ olivine and orthopyroxene for the three crystallographic axes by a microscopic method. They distinguished the anisotropy in the thermal diffusivity of these orthorhombic minerals. As to the order of anisotropy in the thermal diffusivity their results agree with that of the present study. However, their absolute values might be of reconsideration, because they checked the measurement by comparing the results with those for olivines of different compositions in other literature despite the strong composition dependence in the thermal diffusivity.

(2) Garnet

Figure 4 shows the thermal diffusivity of the garnet versus temperature. This mineral has more moderate change in thermal diffusivity with temperature than olivine. The numerical values of thermal diffusivities and the coefficients for fitting to the empirical formula $a=A+B/T$ are listed in Table 1. The thermal

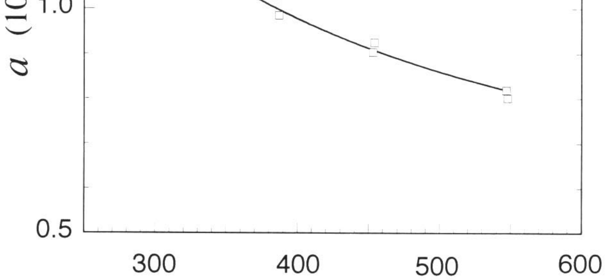


Fig. 4. Thermal diffusivities (a) of garnet as a function of the absolute temperature (T). The curve is fitted for the formula of $a=A+B/T$.

Table 1. Thermal diffusivity of olivine and garnet.

	Thermal diffusivity, a (10^{-6} m^{2}s^{-1})							Coefficients of $a=A+B/T$	
	Temperature, T (K)							A (10^{-6} m^{2}s^{-1})	B (10^{-6} m^{2}s^{-1}K)
	300	350	400	450	500	550	600		
Olivine ($Fo_{93}Fa_7$)									
$a_{//}$	2.53	2.18	1.91	1.70	1.54	1.40	1.29	0.04(0.05)	747(17)
$b_{//}$	1.52	1.29	1.12	0.99	0.88	0.80	0.72	−0.07(0.02)	478(9)
$c_{//}$	2.21	1.90	1.68	1.50	1.36	1.24	1.15	0.09(0.05)	634(19)
Garnet ($Prp_{34}Alm_{57}Sps_1Grs_8$)									
	1.18	1.06	0.98	0.91	0.86	0.82		0.39(0.02)	236(9)

The symbols $a_{//}$, $b_{//}$ and $c_{//}$ denote the direction of a-, b- and c-axes respectively.
Figures in the parenthesis express errors in the coefficients.

diffusivity at 290 K, 1.2×10^{-6} m^{2}s^{-1} coincides with that extrapolated to zero pressure in high pressure measurements using a different method for a similar garnet sample (Osako and Ito, 1997). On the other hand this value is 10% higher than those reported by Knanmori *et al.* (1968) for two garnet samples. As the chemical compositions of their samples were different to that used in the present study, and their extrapolations to 300 K seem to have uncertainties because of scatters in the data points, comparing data would have no decisive conclusion. In any case the thermal diffusivity of silicate garnet would be affected little by composition, and its temperature dependence is more moderate than other mantle minerals. This is also seen in another measurement on mantle minerals using policrystalline samples (Osako, 1991).

4. Conclusion

The olivine has high isotropy in thermal diffusivity or thermal conductivity. This may bring effect on the temperature distribution in the upper mantle if the preferred orientation exists. Such anisotropy in another important mantle mineral, pyroxene has already been examined by Schloessin and Dvorak (1972) under high pressure, however, measurements for double-check are in difficult situations because of lack of appropriate pyroxene samples.

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