

ANISOTROPIC EVAPORATION OF FORSTERITE IN HYDROGEN GAS. M. Yokoyama¹, A. Takigawa¹, S. Tachibana¹, H. Nagahara¹, and K. Ozawa¹, ¹Department of Earth and Planetary Sciences, University of Tokyo (s52632@geoph.eps.s.u-tokyo.ac.jp).

Introduction: Forsterite (Mg_2SiO_4), one of the major minerals in circumstellar environments and meteorites, plays a key role in physical and chemical evolution of a protoplanetary disc because of its abundance and larger Mg/Si(=2) ratio than that of the solar abundances (~ 1). Astronomical observation has revealed the presence of crystalline forsterite along with enstatite in protoplanetary discs based on spectrum energy distributions (SED) [e.g., 1]. The amount of crystalline silicate appears to increase with evolution of discs and the observed dusts are totally crystalline in some discs [1]. Because interstellar silicates are almost exclusively amorphous [2], amorphous silicate dusts experience crystallization during disc evolution. The heat source for crystallization of amorphous silicates is under a debate and several models have been proposed; radial mixing [3, 4], in situ annealing by a shock [5], destruction of small planetary bodies [6]. Although the mechanism for crystallization may be various, it appears to be evident that crystalline forsterite is an abundant constituent of protoplanetary discs.

Forsterite, which may primarily be amorphous, is expected to evaporate when it is transported to high temperature regions in the disc. Because evaporation of pre-existing dust grains changes the size and shape of the grains, it should change the SED, which is largely dependent on the phase, size, shape of the dust grains and temperature. It is thus important to know the evaporation rate of forsterite that carry the SED.

The evaporation rate of forsterite has been extensively studied in laboratory [7-12], and shown to evaporate congruently in a wide range of conditions. It evaporates anisotropically in vacuum [11, 13]; fastest along the c-axis and slowest along the b-axis. It is thus expected that forsterite evaporates anisotropically in the presence of hydrogen gas, which is a dominant gas species in a protoplanetary disc, as well. If forsterite evaporates anisotropically in hydrogen gas, the SED of protoplanetary discs may change with evaporation of forsterite.

In this study, in order to investigate the evaporation anisotropy of forsterite in hydrogen gas, we conducted experiments on evaporation of forsterite in H_2 gas. The results will be compared with model calculation on the IR spectrum for different shapes of forsterite based on laboratory measurements of the optical constant for different crystallographic orientations of forsterite [14] to evaluate the role of evaporation of forsterite on the evolution of protoplanetary disc.

Experiments: Evaporation experiments were conducted in a vacuum chamber made of stainless steel with a tungsten mesh heater, into which H_2 gas is introduced through an alumina pipe that was connected to a stainless steel pipe at a low-temperature region of the chamber. The chamber was evacuated by a rotary pump and a turbo molecular pump to high vacuum ($\sim 10^{-4}$ Pa). Single crystal of forsterite was cut into rectangular parallelepipeds (about 1 x 3 x 4mm size) for the starting material. A set of three crystals with largest area vertical to one of the a-, b-, or c-axes were put together in the furnace for each experiment, in order to assure the same experimental conditions to obtain rate anisotropy with high precision. The samples were pre-evacuated at 500°C and heated at a constant rate to 1535°C, which is the melting temperature of metallic iron. The samples were heated at 1535°C for a desired duration (1.5-30 hours) and were quenched by turning off the heater. Hydrogen gas was introduced in the furnace at 500°C and pressure of hydrogen ($p(\text{H}_2)$) in the chamber during experiments was kept at 10^{-2} -1 Pa by flowing hydrogen gas. Evaporation experiments in vacuum at 1535°C were also carried out for comparison.

Evaporation rates along three crystallographic axes were calculated from the weight losses and the original shapes of three starting materials [8]. The surface microstructures of evaporated samples were observed under an optical microscope and an FE-SEM.

Results: Surfaces microstructures of evaporated samples show notable anisotropy. The characteristic morphological features of the (100) surface are rectangular pits containing dislocations along the a-axis at the cores. The (010) surface contains rectangular pits, and the (001) surface is characterized by the presence of rhomboidal pits and sharp narrow triangular grooves, which are developed along the dislocations running parallel to the a-axis. Although the pit densities and the shapes of the pits are slightly different from those in vacuum, the essential features of surface microstructures are similar to those of vacuum experiments [11].

Evaporation rates of forsterite (V) in hydrogen gas and in vacuum are shown in Fig. 1. It is seen that evaporation rates of forsterite is much faster than those in vacuum and increases with increasing $p(\text{H}_2)$. The evaporation rates seem to increase linearly with $p(\text{H}_2)^{-0.5}$, which is consistent with the results of [12, 15].

It is also clearly seen that the evaporation rate of forsterite in hydrogen gas is anisotropic. The evaporation rate in hydrogen gas is fastest along the c-axis and slowest along the b-axis ($V_c > V_a \geq V_b$). This is consistent with anisotropy of evaporation rates in vacuum [11, 13], but the degree of anisotropy seems to be different from that in vacuum. The V_c/V_b ratio for evaporation in hydrogen gas is ~ 3.0 - 2.8 , while that for evaporation in vacuum is ~ 4.7 . The V_a/V_b ratio seems to decrease with increasing $p(\text{H}_2)$ and vary from ~ 2.8 in vacuum to ~ 1.0 for $p(\text{H}_2)=1$ Pa. The V_c/V_a ratio seems to vary from ~ 1.7 in vacuum to ~ 2.7 for $p(\text{H}_2)=1$ Pa.

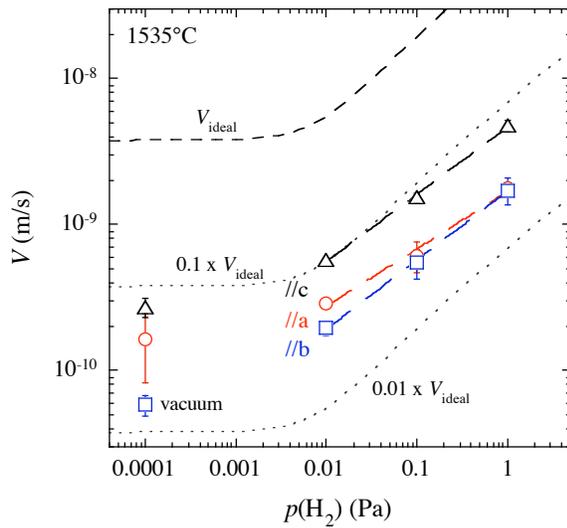


Figure 1. Evaporation rates of forsterite in hydrogen gas along different crystallographic orientations (1535°C). Evaporation rates in vacuum are shown for comparison. The pressure dependence of the ideal evaporation rate of forsterite (V_{ideal}) is also shown with its 10-times and 100-times smaller rates.

Discussion: The evaporation rate of forsterite in hydrogen gas can be expressed by the Hertz-Knudsen equation;

$$V = \frac{\alpha p_{\text{SiO}}^{\text{eq}}}{\sqrt{2\pi m_{\text{SiO}} kT}} \Omega,$$

where $p_{\text{SiO}}^{\text{eq}}$ is the equilibrium vapor pressure of SiO, m_{SiO} is a molecular weight of SiO, k is the Boltzmann constant, T is an absolute temperature, Ω is a molecular weight of forsterite, and α is the evaporation coefficient that expresses kinetic hindrances for evaporation ($0 < \alpha \leq 1$). When α is equal to unity, the maximum evaporation rate is obtained (V_{ideal} in Fig. 1). It has been proposed that α is on the order of 0.1 in a wide range of temperature and $p(\text{H}_2)$ [9]. The evaporation

rates obtained in this study are also $\sim 1/10$ - $1/20$ of V_{ideal} , which is consistent with previous studies [9, 11, 13]. The similar α for evaporation both in vacuum and in hydrogen gas implies that kinetic hindrances for evaporation of forsterite in hydrogen gas are basically the same as those in vacuum, particularly along the c-axis.

The change of anisotropy in evaporation rates along different crystallographic orientations suggests that, even though the kinetic hindrances are similar, there should be changes in atomistic processes of the surface reaction, details of which should be clarified in future studies.

Implication to infrared spectroscopy: Evaporation of forsterite in hydrogen gas ($p(\text{H}_2)$ of ~ 0.1 - 1 Pa) may correspond to that in protoplanetary discs, while evaporation in vacuum may correspond to that under very low-pressure circumstellar environments. Because anisotropy of the evaporation rate is different in hydrogen gas from in vacuum, forsterite grains that experience evaporation in different conditions may have different shapes. The present results indicate that forsterite grains tend to have plate-like shapes in the direction of the c-axis when they evaporate in a high-temperature region of protoplanetary discs, whereas grains that evaporate in circumstellar environments may have a rod-like shape elongating to the b-axis. Such a difference in crystal shapes and/or in sizes results in different shapes of SEDs [14] even if forsterite is a dominant crystalline phase. It is thus quite important to understand anisotropy of evaporation and condensation kinetics of crystalline phases, which may make it possible to evaluate physical and chemical conditions of regions where dust particles were born and survived.

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