Sound velocity measurements of hcp Fe-Si alloy at high pressure and high temperature by inelastic X-ray scattering

TAKANORI SAKAIRI1, TATSUYA SAKAMAKI1, EIJI OHTANI1,2,*, HIROSHI FUKUI3,4, SEIJI KAMADA5, SATOSHI TSUTSUI6, HIROSHI UCHIYAMA6, and ALFRED Q.R. BARON4

1Department of Earth and Planetary Materials Science, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan
2VS. Sobolev Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences, Koptyuga Ave. 3, Novosibirsk 630090, Russia
3Center for Novel Material Science under Multi-Extreme Conditions, Graduate School of Material Science, University of Hyogo, Kamigori, Hyogo 678-1297, Japan
4Materials Dynamics Laboratory, RIKEN SPring-8 Center, Sayo, Hyogo 679-5148, Japan
5Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai 980-8578, Japan
6Japan Synchrotron Radiation Research Institute (JASRI), Hyogo 679-5198, Japan

ABSTRACT

The sound velocity of hcp Fe0.89Si0.11 (Fe-6wt% Si) alloy was measured at pressures from 45 to 84 GPa and temperatures of 300 and 1800 K using inelastic X-ray scattering (IXS) from laser-heated samples in diamond-anvil cells (DACs). The compressional velocity (v_p) and density (ρ) of the Fe-Si alloy are observed to follow a linear relationship at a given temperature. For hcp Fe0.89Si0.11 alloy we found v_p = 1.030 (±0.008) × ρ − 1.45 (±0.08) + [3.8 × 10^4(T − 300) × (ρ − 15.37)], including non-negligible temperature dependence. The present results of sound velocity and density of hcp Fe0.89Si0.11 alloy indicates that 3–6 wt% of silicon in the inner core with additional amount of Ni can explain the compressional velocity (v_p) and density (ρ) of the “preliminary Earth reference model” (PREM), assuming a temperature of 5500 K and that silicon is the only light element in the inner core.

Keywords: Sound velocity, Fe-Si alloy, high pressure, high temperature, inelastic X-ray scattering, inner core, Birch’s law, silicon

INTRODUCTION

The profile of the density and sound velocity of the Earth’s deep interior has been modeled by seismological observations leading to the creation of the preliminary Earth reference model (PREM, Dziewonski and Anderson 1981). The Earth’s inner core is considered to be mainly composed of iron-nickel alloy with small amount of light elements to account for the core density deficit (Birch 1964). We can constrain the composition of the core by comparing sound velocity and density data of Fe and Fe alloys with PREM. Therefore, sound velocity measurements of Fe and Fe-light element alloys have been performed under high-pressure conditions using various methods, such as shock wave experiments (e.g., Brown and McQueen 1986), inelastic X-ray scattering (IXS) (e.g., Antonangeli et al. 2010; Mao et al. 2012; Ohtani et al. 2013; Sakamaki et al. 2016), nuclear resonance inelastic X-ray scattering (NRIXS or NIS) (e.g., Antongiorgi et al. 2003). It is generally accepted that, as a first approximation, there is a linear relationship between density and sound velocity, i.e., Birch’s law (Birch 1961; Antonangeli and Ohtani 2015). We used the expression “Birch’s law” for the linear dependence of the sound velocity on density at a constant temperature, even when the temperature effects are important. However, the effect of temperature on Birch’s law is not yet well understood. Thus additional data on temperature dependence, especially for Fe alloys with light impurities, are important to allow understanding of the core composition.

Silicon is one of the major candidates for light elements in the Earth’s core. The sound velocity of Fe-Si alloy at room temperature has been measured by several methods such as NRIXS (NIS) (Lin et al. 2003) and IXS (Badro et al. 2007; Mao et al. 2012), however, the results have not been consistent. Using NRIXS (NIS) to investigate hcp Fe0.86Si0.15 alloy, Lin et al. (2003) reported that dissolution of silicon in metallic iron increases both the compressional velocity and shear velocity of iron alloys at high pressure. Using IXS to investigate FeSi at room temperature, Badro et al. (2007) suggested that the incorporation of small amounts of silicon, 2.3 wt%, might account for the geophysical observations including the PREM sound velocity of the inner core. In contrast, the work of Mao et al. (2012) using IXS to investigate hcp Fe0.85Si0.15 alloy at 300 K suggests the PREM inner core matches a velocity profile of iron with 8 wt% Si. On the other hand, Liu et al. (2016) suggested that the PREM inner core can be explained by 5 wt% Ni, and with Si being a “major” light alloying element based on the combined measurements of IXS and NRIXS for hcp-Fe and hcp-Fe0.86Ni0.14Si0.04 at room temperature and high pressure.

Sound velocity measurements of hcp Fe-Si alloy at high pressure and temperature have not been reported yet and certainly may impact these discussions. Here we report the sound velocity of hcp Fe0.89Si0.11 (Fe-6wt% Si) alloy up to 84 GPa and 1800 K based on IXS measurements, including the effect of temperature on the sound velocity of the alloy. In this context, we discuss the silicon content of the Earth’s inner core.