Sound wave velocities of Fe$_5$Si at high-pressure and high-temperature conditions: Implications to lunar and planetary cores

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ABSTRACT

Elastic properties of Fe alloys are critical in constraining the compositions of planetary bodies by comparing to the planetary observations. The sound wave velocities and density of an Fe$_5$Si (9 wt% Si) alloy in body-centered cubic (bcc) structure were measured by combining an ultrasonic technique with synchrotron X-ray radiography at pressure (P) and temperature (T) conditions of 2.6–7.5 GPa and 300–1173 K, respectively. At room temperature, it is observed that adding Si to bcc-Fe increases the compressional wave velocity ($v_p$) but decreases the shear wave velocity ($v_s$). At high temperatures, we observed a pronounced effect of pressure on the $v_p$-$T$ relations in the Fe$_5$Si alloy. The $v_p$-density ($\rho$) relationship of the Fe$_5$Si alloy is found to follow the Birch’s law in the $P$-$T$ range of this study, whereas the $v_s$-$\rho$ relation exhibits complex behavior. Implications of these results to the lunar core and the Mercurian core are discussed. Our results imply that adding Si to a pure Fe lunar core would be invisible in terms of $v_p$ but exhibit a decreased $v_s$. Including Si in a sulfur-rich lunar core would display an increased $v_s$ and a decreased $\rho$. Our density and sound wave velocity model provide lower and upper limit for a Si-bearing lunar core if 1–3 wt% Si content of enstatite chondrite is taken as compositional analog. A Si-rich (>9 wt%) Mercurian core model is derived to satisfy newly observed moment of inertia values by Messenger spacecraft.

Keywords: Fe-Si alloy, elastic wave velocity, lunar and planetary cores, high pressure, high temperature

INTRODUCTION

It has been widely accepted that the terrestrial planets (such as the Earth and the Mercury) and their satellites (such as the Moon, Konopliv et al. 1998) possess Fe-dominated cores. One or more light elements (such as O, Si, S, C, and H) may be present in the cores, based on cosmochemical and geophysical considerations (e.g., Anderson and Ahrens 1994; Anderson and Isaak 2002; Badro et al. 2007). Among the potential light elements, Si remains a dominant candidate, based on several constraints. First, it is experimentally demonstrated that Si has a significant solubility in liquid Fe (25 wt% Si at the eutectic at 21 GPa, Kuwayama and Hirose 2004) at high-pressure and high-temperature (high $P$-$T$) conditions (Fischer et al. 2013). Because magma ocean events, which is characterized by the widespread molten Fe and silicate melt, might occur in many inner-solar planetary bodies (such as the Mercury and the Earth) and the Moon, the high solubility of Si in liquid Fe provides a mechanism for Si entering into those planetary cores during the silicate-metal differentiation process (Ricolfleau et al. 2011; Badro et al. 2015). Second, the siderophile element partitioning data strongly support that early accretion of Earth and Mercury occurred under highly reduced conditions (Malavergne et al. 2010; Javoy et al. 2010). Moreover, the gamma-ray spectrometers of the Mercury’s Messenger spacecraft revealed that an amount of 1–4 wt% S could be present on the Mercury’s surface, implying that the oxygen fugacity of the Mercury’s interior is low, with an IW ranging from ~2.6 to ~7.3 (Chabot et al. 2014). The extremely low oxygen fugacity is compatible with the reduced nature of Si. Thus substantial Si could have been incorporated into the cores during the core-mantle segregation.

Pure iron adopts at least three polymorphs at high $P$-$T$, including body-centered-cubic (bcc), face-centered-cubic (fcc), and hexagonal-closed-packing (hcp). The fcc- and hcp-Fe are commonly viewed to be the dominant phases at terrestrial planetary cores, because of their stability fields of the related $P$-$T$ conditions. However, high-pressure experimental and theoretical studies suggested that the addition of Si or Ni in Fe can stabilize the bcc structure at expanded $P$-$T$ conditions (Lin et al. 2002; Dubrovinsky et al. 2007; Vocadlo et al. 2008; Kuwayama et al. 2009). For example, in situ X-ray diffraction experiments on an Fe$_5$Si alloy found a stabilized mixture of bcc and hcp phases up to at least 150 GPa and 3000 K (Lin et al. 2009). Therefore, a bcc structured Fe-Si alloy could be a candidate phase in the cores of terrestrial planets and their satellites.

Sound wave velocity is a critical physical parameter for constraining the planetary core compositions. In conjunction with the seismological observations of the planetary interior, it