Measuring the electrical resistivity of liquid iron to 1.4 Mbar

Molten iron (Fe) is the dominant component of terrestrial cores, and its electrical and thermal conductivities control the dynamics and evolution of terrestrial bodies. Numerous theoretical predictions have been made regarding the electrical and magnetic properties of dense liquid Fe. However, experimental data on the electrical resistivity (the inverse of the electrical conductivity) of liquid Fe at high pressures are sparse compared to those on solid phases (e.g., [1]). Because of the high fluidity and chemical reactivity of molten Fe, it is difficult to conduct experiments in a high-pressure apparatus while maintaining the geometry and purity of the Fe sample. The resistivity of liquid Fe can currently be found in experimental data up to 51 GPa and 2900 K [1], although the pressure-temperature ($P-T$) conditions and data accuracy are not sufficient.

In this study [2], we determined the electrical resistivity of liquid Fe in the pressure range 42–135 GPa using a diamond anvil cell (DAC) combined with two novel techniques. The first, called the sapphire capsule method, is a resistance measurement technique for a liquid Fe sample encapsulated by a sapphire single crystal in a DAC combined with a laser and an internal resistance hybrid heating system. This technique aims to keep the geometry of the Fe sample unchanged during melting and minimize the temperature gradient inside the sample. The instantaneous resistance detection method (Fig. 1) seeks to detect the liquid Fe resistance prior to sample geometry changes by simultaneously measuring the electrical resistance, temperature, and X-ray diffraction (XRD) of Fe melted instantaneously via a single high-power laser shot. A total of nine separate runs using either of these methods were performed at SPring-8 **BL10XU**.

The sapphire capsule method was used in three separate runs conducted at approximately 40 GPa and 70 GPa. In a run, we compressed the sapphire-encapsulated Fe sample to 44 GPa at 300 K and then performed simultaneous high $P-T$ resistance and XRD measurements to determine melting conditions. At the melting temperature of 2460 K at about 40 GPa, the resistance jump across melting was 21.7%. After temperature quenching, the sample resistance showed the same value as that before heating, and no additional XRD peaks other than those of Fe and sapphire were detected. Importantly, we did not observe any changes in the sample geometry under a microscope after melting. These facts guarantee that
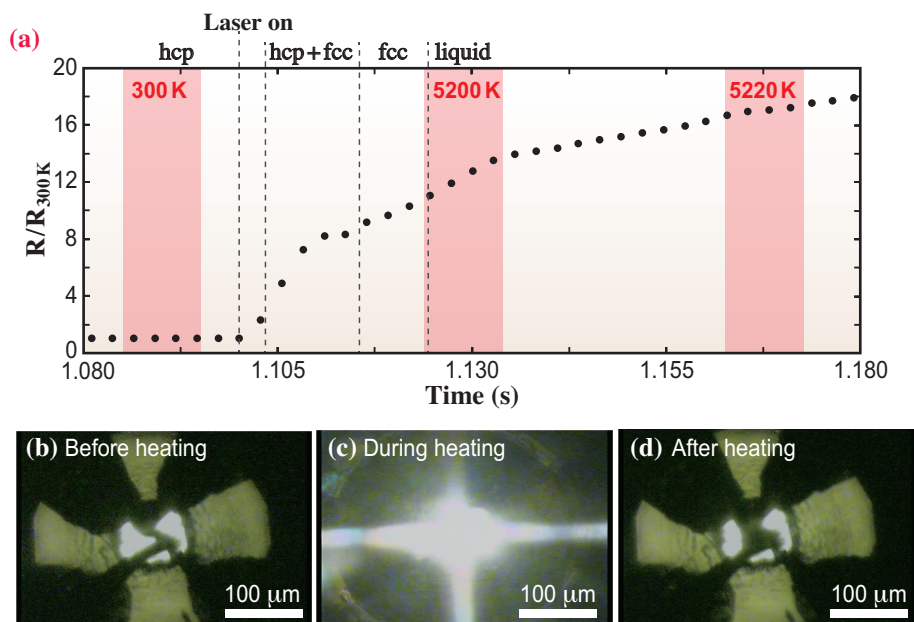

Fig. 1. Instantaneous resistance detection method: **(a)** Representative time (t) series of temperature and normalized resistance data obtained in a run, in which the maximum $P-T$ condition was 107 GPa and 5200 K. The Fe phase(s) is/are identified from XRD measurements every 1 ms. Red rectangles indicate time windows for temperature measurements with 10 ms of exposure time. **(b)-(d)** Photos of a sample chamber viewed through a diamond anvil before, during, and after laser heating.

there was no change in the sample geometry during melting and no chemical contamination from the surroundings during the heating experiment.

An instantaneous resistance detection method was used to perform six separate runs at 135 GPa. The core of this method is high-speed simultaneous measurements of XRD in 1 ms, sample resistance in 2.25 ms, and temperature in 10 ms. Double-sided laser heating was used to melt the Fe sample during the synchronized data acquisition. Figure 1 shows the representative experimental data for which we started heating at 61 GPa. High-power laser shot heating began approximately 1.102 s after the start of synchronized data acquisition, resulting in $P–T$ conditions of 105 GPa and 5200 K at $t = 1.125$ s, which are much higher than the melting point of Fe (Fig. 1(a)). The measured resistance responded to temperature changes by turning the laser beam on: a jump in the resistance at the beginning of heating ($t > 1.102$ s) and a gradual increase during melting ($t > 1.125$ s). We confirmed Fe melting by the disappearance of the XRD peaks of Fe at $t = 1.125$ s and simultaneously obtained its resistance at the same time. We considered these resistance data as the resistance of liquid Fe at 105 GPa and 5200 K, considering that the sample deformation and chemical reaction had not yet occurred at this time. The sample geometry changed after laser heating for approximately 3 s (Figs. 1(b-d)). Similar to the aforementioned run, we obtained the electrical resistance of liquid Fe within 1 ms of melting at 42, 49, 65, 79, and 135 GPa.

The obtained liquid Fe resistance data are converted to its high $P–T$ resistivity, which provides the experimentally constrained resistivity of liquid Fe to more than two times higher pressures than in previous experiments (Fig. 2). For Mars and smaller terrestrial bodies in our solar system, the resistivity of liquid Fe at their core conditions is about 120 $\mu\Omega\cdot$cm, which is the lower limit of the core resistivity (note that the cores should contain some impurity elements that increase the resistivity). On the other hand, for the Earth and probably Venus, the lower limit of their liquid core resistivity is less than 80 $\mu\Omega\cdot$cm. Such a nonlinear pressure dependence on the resistivity of liquid Fe must be considered when estimating the conductivity of planetary metallic cores.
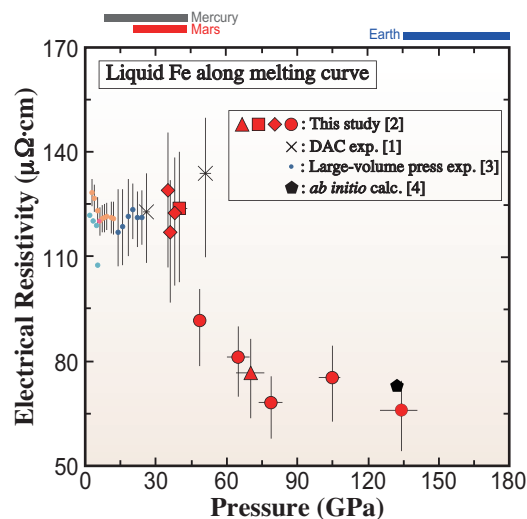

Fig. 2. The resistivity of liquid Fe along the melting curve. Red symbols represent values from this study [2], smaller circles depict the experimentally determined resistivities of liquid Fe in a large volume press [3], crosses indicate data from our previous study [1], pentagon indicate data from an *ab initio* calculation [4]. Color bars at the top of the figure show the pressure ranges of the cores of the Earth, Mars, and Mercury.

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