Experimental determination of the electrical resistivity of iron under Earth's core conditions

Earth continuously generates a dipole magnetic field in its convecting liquid outer core by a self-sustained dynamo action. Metallic iron (Fe) is the dominant component of the outer core, so its electrical and thermal conductivity control the dynamics and thermal evolution of Earth's core. Since free electrons are the primary carrier of both electric current and heat, the electron scattering mechanism in Fe under high pressures and temperatures holds the key to understanding the transport properties of planetary cores. Extensive efforts have been made to measure the electrical resistivity of Fe at high pressures since the earliest high-pressure mineral physics experiments, but its direct measurement under the conditions of Earth's core is still challenging. Recent density functional theory calculations predicted the core resistivity to be 20–50% of these conventional estimates [1,2]. Static high-pressure, low-temperature experiments also suggested a low core resistivity because the resistivity saturates at high temperatures [3]. These values suggest that Earth's core has been cooling rapidly, which implies a young inner core and high initial core and mantle temperatures. However, the saturation of resistivity and the resulting low electrical resistivity of Earth's core have not been verified by experiments under the relevant high-pressure, high-temperature conditions.

In this study [4], we measured the electrical resistivity (the reciprocal of electrical conductivity) of Fe at high temperatures (up to 4500 K) and pressures (megabars) corresponding to those of Earth's core in a laser-heated diamond anvil cell. We made use of advanced experimental techniques, including the shaping of the sample-and-electrode composites, to measure the electrical resistivity of Fe at ultrahigh pressures and temperatures (Fig. 1(a)). The Fe foil was shaped into a single member with four probes by using focused ion beam apparatus. This shaping technique enables us to prepare samples with uniform geometry corresponding to each anvil culet size. Concurrently with all high-pressure, high-temperature resistivity measurements, we performed synchrotron X-ray diffraction (XRD) measurements at SPring-8 **BL10XU** (Fig. 1(b)).

We carried out the electrical resistivity measurements at pressures between 75 and 212 GPa, in which only the ε phase was found (Fig. 2). From the high-pressure, low-temperature (up to 450 K) data, we obtained the slope of the temperature–resistivity relation in a wide pressure range (Fig. 2(a)). These measurements indicated that the resistivity increased linearly with increasing temperature. However, the present experiments, performed up to 4500 K in the range 80–157 GPa (Figs. 2(b)-(f)), demonstrate that the measured resistivity is clearly lower than the value predicted from the lower-temperature experiments shown in Fig. 2(a). The low resistivity of ε Fe observed in this study may be attributed to the well-known effect of resistivity saturation at high temperatures (in which the increase in resistivity is suppressed at high temperatures). The electrical resistivity of metal asymptotically approaches the Ioffe-Regel value (that is, saturation resistivity, ρ_{sat}) when the mean free path of free electrons becomes comparable to the interatomic distance. An empirical description of the resistivity saturation in a simple shunt resistor model can be applied to a variety of metals [5]. The present temperature-resistivity data at each pressure is well explained by the shunt resistor model with a reasonable value of ρ_{sat} (black lines in Figs. 2(b)–(f)). Thus, the present results up to 4500 K demonstrate the effect of resistivity saturation, which defines the upper bound for the resistivity and leads to the low electrical resistivity (high thermal conductivity) of Earth's core.

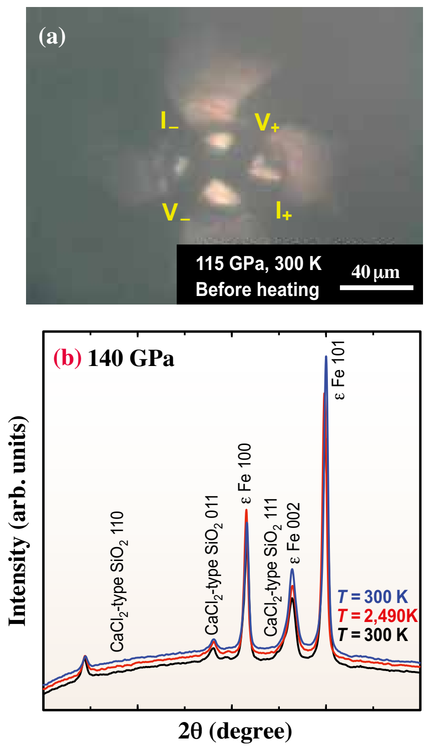

Fig. 1. (a) Photomicrographs of a sample chamber viewed through a diamond anvil cell at 115 GPa and 300 K. The four-probe method was used for electrical resistance measurements. (b) XRD patterns of ε Fe samples at 140 GPa.

The present data demonstrate the electrical resistivity of Fe to be 40.4 (+9.7/–6.5) μΩcm at 140 GPa and 3750 K (Fig. 2(e)), close to the core-mantle boundary conditions. This corresponds to the electronic thermal conductivity $\kappa_{el} = 226\,(+71/-31)$ W/m/K when the Wiedemann–Franz relation ($\kappa_{el} = L_0 T/\rho$, for the ideal Lorenz number $L_0 = 2.445 \times 10^{-8}$ WΩ/K^2) is applied. Since Earth's core contains some nickel and light elements in addition to Fe, we consider the effect of such impurity elements. The resistivity of solid $Fe_{67.5}Ni_{10}Si_{22.5}$, a possible outer core composition inferred from its density, is calculated to be 86.9 (+15.4/–21.6) μΩcm at 140 GPa and 3750 K, considering the saturation effect. When the 20% resistivity increase upon melting is taken into account, we obtain 104 (+18/–26) μΩcm, giving a thermal conductivity of 88 (+29/–13) W/m/K for liquid $Fe_{67.5}Ni_{10}Si_{22.5}$. As a consequence, the present study supports the high thermal conductivity of Earth's core, suggesting rapid core cooling and a young inner core less than 0.7 billion years old [1-3].

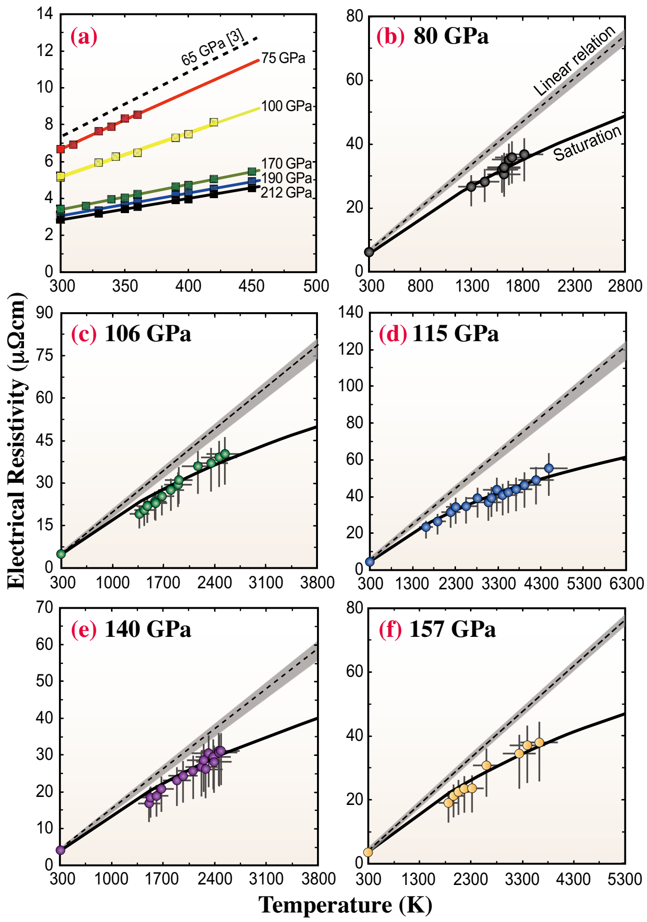

Fig. 2. Change in the resistivity of ε Fe with increasing temperature. **(a)** Temperature dependence of the resistivity up to 450 K at 65–212 GPa fitted by a linear function (colored lines). Similar results at 65 GPa from [3] are also shown. **(b)**–**(f)** Electrical resistivity measured at 80 GPa up to 1820 K (b), at 106 GPa up to 2540 K (c), at 115 GPa up to 4490 K (d), at 140 GPa up to 2490 K (e), and at 157 GPa up to 3630 K (f). The resistivity measured at high pressures and high temperatures in this study is lower than that predicted by the linear relation (dashed lines with grey uncertainty band) with parameters obtained from the high-pressure, low-temperature measurements in (a). Such a low resistivity can be accounted for by the effect of resistivity saturation at high temperature (solid curves).

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