Experimental Studies on Thermal and Electrical Properties of Platinum Nanofilms

ZHANG Xing(张兴)[1,2*], ZHANG Qing-Guang(张清光)[1], CAO Bing-Yang(曹炳阳)[1], FUJII Motoo[2], TAKAHASHI Koji[3], IKUTA Tatsuya[3]

[1]*Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Tsinghua University, Beijing 100084*

[2]*Institute for Materials Chemistry and Engineering, Kyushu University, Kasuga 816-8580, Japan*

[3]*Graduate School of Engineering, Kyushu University, Fukuoka 812-8581, Japan*

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We experimentally studied the in-plane thermal and electrical properties of a suspended platinum nanofilm in thickness of 15 nm. The measured results show that the in-plane thermal conductivity, the electrical conductivity and the resistance-temperature coefficient of the studied nanofilm are much less than those of the bulk material, while the Lorenz number is greater than the bulk value. Comparing with the results reported previously for the platinum nanofilm in thickness of 28 nm, we further find that the in-plane thermal conductivity, the electrical conductivity and the resistance-temperature coefficient decrease with the decreasing thickness of the nanofilm, while the Lorenz number increases with the decreasing thickness of the nanofilm. These results indicate that strong size effects exist on the in-plane thermal and electrical properties of platinum nanofilms.

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There have been increasing studies on the thermal and electrical properties of nano-sized thin films because of their wide applications in the modern microelectronic industry and MEMS technology.[1] A variety of methods have been developed to study these properties, including the theoretical calculations,[2,3] the molecular dynamics (MD) simulations[4−6] and the experiments.[7] Most results show that the thermal conductivity and the electrical conductivity of the thin films are less than those of the corresponding bulk materials, even down to one or two magnitudes, and tend to decrease with the decreasing thickness of the films. However, these studies were mainly focused on dielectric thin films, in which the phonon scatterings on the surface boundary and/or the grain boundaries, as well as the interactions between phonons themselves, were considered. There exist greater difficulties in obtaining the thermal and electrical properties of metallic thin films in the theoretical calculations and the MD simulations, since the electron scatterings on the surface boundary and/or the grain boundaries, as well as the interactions with lattice vibrations, should be considered. Also, there are much fewer experimental results about the thermal and electrical properties of metallic thin films, compared with those of dielectric thin films. Recently, we provided an experimental method called the one-dimensional steady-state electrical heating method (1-D SSEH) to measure the in-plane thermal and electrical conductivity of metallic thin films simultaneously.[8] In this Letter we use this method to measure the in-plane thermal conductivity, the electrical conductivity and the resistance-temperature coefficient of a suspended platinum nanofilm in thickness of 15 nm, which is the thinnest one among the suspended platinum nanofilms. The results show that these properties of the studied nanofilm are much less than those of the corresponding bulk material, and tend to decrease with the decreased thickness of the nanofilm. The Lorenz number, however, is much greater than that of the bulk value predicted by the Wiedemann–Franz law,[9] and tends to increase with the decreasing thickness of the film. These results demonstrate that there are strong size effects on the in-plane thermal and electrical properties for the platinum nanofilm.

The platinum nanofilm involved in the experiment, with 8.9 μm in length, 496 nm in width, and 15 nm in thickness, was fabricated by the electron beam-physical vapour deposition (EB-PVD), as shown in Figs. 1(a) and 1(b), which are the views taken by scanning electron microscopy (SEM) from the top and side, respectively. We can easily see from the side view that the nanofilm has been suspended from its silicon substrate, which eliminates the effects of the substrate on the measured properties of the nanofilm. The corresponding fabrication processes in detail can be found in Ref. [8]. In the experiments, the silicon chip having the suspended nanofilm is mounted on the sample holder of a liquid nitrogen cryostat, where the sample chamber is continuously evacuated to be about 10^{-6} Torr by a vacuum pump and a molecular pump, and the temperature of the sample holder can be controlled from 77 K to 500 K. The tested nanofilms were annealed at 413 K for two hours before experiment. In the 1-D SSEH method, the nanofilm serves both as a heating unit with homogeneous heat generation and

* To whom correspondence should be addressed. Email: x-zhang@tsinghua.edu.cn

as an electrical thermometer. When a heating direct current flows through the nanofilm, the temperature of the nanofilm will rise rapidly by the Joule heating. Since the heat sinks at both the ends of the nanofilm are kept at the constant temperature T_0, the generated heat will be conducted away along the nanofilm length direction, without the heat losses caused by convective heat transfer for its vacuum circumstances or by radiative heat transfer for the present temperature range. Therefore, the heat transfer of the nanofilm is dominated by one-dimensional steady-state heat conduction along the length direction, and the relationship among the thermal conductivity λ_0 at T_0, the volume average temperature rise ΔT_V and the heat power IV can be drawn from the analytical solution[10] by

$$\lambda_0 = \frac{IV}{\Delta T_V}\frac{l}{12wd}, \tag{1}$$

where l, w and d represent the length, width, and thickness of the nanofilm, respectively. The current I and voltage V of the nanofilm can be measured by two digital multimeters (Keithley 2002). When the heat power IV increases, the resistance R of the nanofilm that is measured by a four-wire method also increases, caused by the temperature rise of the nanofilm. The experimental results show that there exists a linear relationship between the heat power and the nanofilm resistance, which can be expressed in terms of $R = aIV + R_0$. The interception with the R axis, which corresponds to the zero heat power, is the resistance R_0 of the nanofilm at the set temperature T_0. The electrical conductivity σ_0 and the resistance-temperature coefficient β_0 at T_0 can be readily obtained by

$$\sigma_0 = \frac{1}{R_0}\frac{l}{wd}, \tag{2}$$

$$\beta_0 = \frac{R_0 - R^*}{R^*(T_0 - T^*)}. \tag{3}$$

In Eq. (3), R^* is the base resistance at T^* for the calculation of the resistance-temperature coefficient, which is often assumed to be the value at 293.15 K. The volume average temperature rise ΔT_V can be related to $\Delta R = R - R_0$ through $\Delta T_V = \Delta R/\beta_0 R_0$, and then the relationship between ΔT_V and IV can be obtained from $\Delta T_V = aIV/\beta_0 R_0$, since $\Delta R = aIV$. Thus the thermal conductivity of the nanofilm λ_0 can be written in experimental parameters as

$$\lambda_0 = \frac{\beta_0 R_0}{a}\frac{l}{12wd}. \tag{4}$$

For the metallic materials, the relationship between the thermal conductivity λ_0 and the electrical conductivity σ_0 is usually related by the Wiedemann–Franz Law,[9] which shows that the ratio between λ_0 and σ_0 is proportional to the absolute temperature T_0 and the Lorenz number $L_0 = \lambda_0/\sigma_0 T_0$ is a constant. Since the thermal conductivity λ_0 and the electrical conductivity σ_0 of the nanofilm can be obtained simultaneously in this method, the Lorenz number L_0 can also be calculated by

$$L_0 = \frac{\lambda_0}{\sigma_0 T_0} = \frac{\beta_0 R_0^2}{12a}. \tag{5}$$

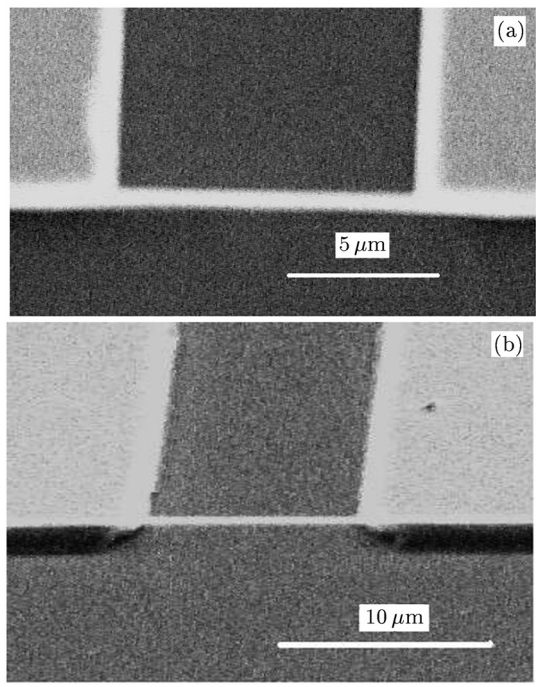

Fig. 1. Scanning electron micrographs of the suspended platinum nanofilm: (a) view from top, (b) view from side.

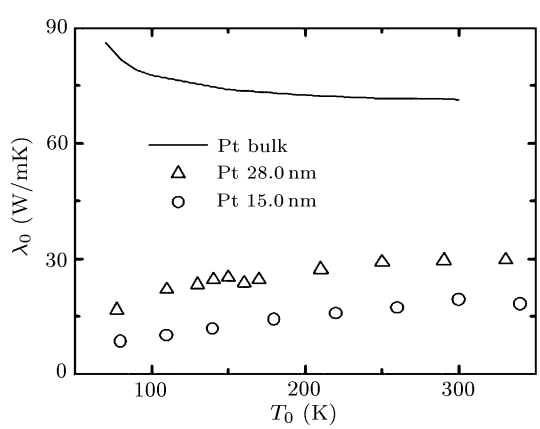

Fig. 2. Dependence of the thermal conductivity on temperature.

From Eqs. (2)–(5), the electrical conductivity σ_0, resistance-temperature coefficient β_0, thermal conductivity λ_0 and the Lorenz number L_0 at the set temperature T_0 can be readily obtained. The measured results are shown in Figs. 2–5, compared with those of the nanofilm in thickness of 28 nm reported in Ref. [8] and those of the bulk material. From the comparisons, some conclusions can be drawn:

(1) The thermal conductivity λ_0, electrical conductivity σ_0 and resistance-temperature coefficient β_0 of the nanofilm in thickness of 15 nm are much less than those of the bulk material along the whole range of the experimental temperature from 80 K to 340 K. They are 27%, 10%, and 16% of the corresponding bulk values at 300 K, respectively. While the Lorenz number L_0 is much greater than that of the bulk material, with even 2.6 times of the bulk value at 300 K.

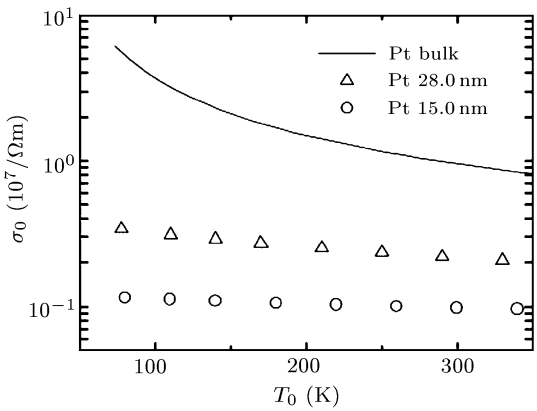

Fig. 3. Dependence of the electrical conductivity on temperature.

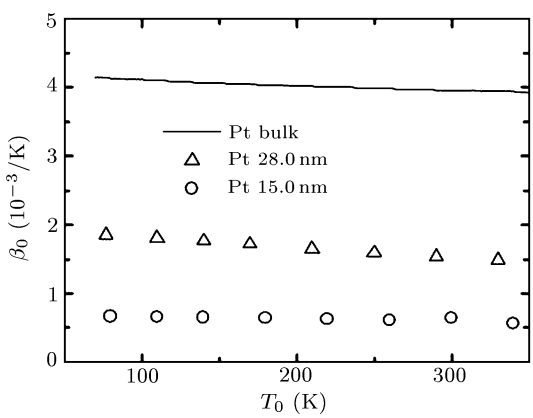

Fig. 4. Dependence of the resistance-temperature coefficient on temperature.

(2) The above three properties of the nanofilm in thickness of 15 nm, λ_0, σ_0 and β_0 are less than those of the nanofilm in thickness of 28 nm at the temperature ranging from 80 K to 340 K, while the Lorenz number increases with the decreasing thickness of the nanofilm from 28 nm to 15 nm.

(3) The thermal conductivity λ_0 of the nanofilm in thickness of 15 nm increases with the increasing temperature from 80 K to 340 K, and becomes flat around 300 K, which is very different from the tendency occurred in the bulk material. While the electrical conductivity σ_0 and the resistance-temperature coefficient β_0 decrease with the increasing temperature, just as the cases occurred in the bulk material.

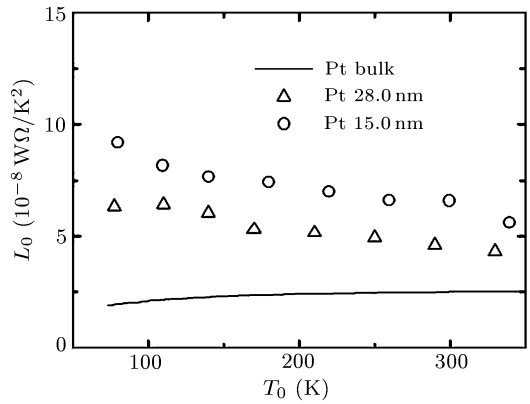

Fig. 5. Dependence of the Lorenz number on temperature.

In summary, the thermal and electrical properties are experimentally measured by the 1-D SSEH method. The results show that the thermal conductivity, electrical conductivity and resistance-temperature coefficient of the nanofilm in thickness of 15 nm are much less than those of the bulk material, and tend to decrease with the decreasing thickness of the nanofilm. However, the Lorenz number of the nanofilm is greater than the bulk value, and tends to increase with the decreasing thickness of the nanofilm. The thermal conductivity of the nanofilm increases with the increasing temperature from 80 K to 340 K, which is different from the tendency occurred in the bulk value, while the electrical properties, including the electrical conductivity and the resistance-temperature coefficient, decrease with the increasing temperature from 80 K to 340 K, which shows the similar tendency as that of the bulk material.

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