Electronic Supplementary Material

Thermal measurement techniques

Existing methods could be divided into the steady-state method and the transient method. The severe condition should be achieved in the traditional steady-state method (i.e. high vacuum degree, stable heating powder). Due to the limitations of technology, the steady-state method could not commonly be applied in the thermal transport measurement, especially in the measurement of composite materials. In this paper, the steady-state method, namely, the improved thermal bridge method, and the transient approaches including the hot-wire method [1] and the laser flash method [2–4] are introduced.

A.The improved thermal bridge method

The thermal bridge method is the most common approach of the steady-state method used for measuring in-plane thermal conductivity of both one-dimension and two-dimension micro-structures. The thermal bridge method is a direct approach of thermal conductivity measurement. The error bars induced by other parameters, such as thermal diffusivity, could be ignored. Compared with the transient method, the thermal conductivity measurement of the thermal bridge method is time-consuming and the sample preparation process is more complex.

In the thermal bridge method, the specimen is suspended by two sapphire backbones and fixed between the sapphire backbones and self-made resistors by using silver paste. The two self-made resistors (shown in Fig. S1), which are fabricated by electron beam lithography (EBL), covered the specimen and severed as thermometers. The whole device should be placed in a cryostat with a vacuum better than 1 mPa to reduce the thermal convection.

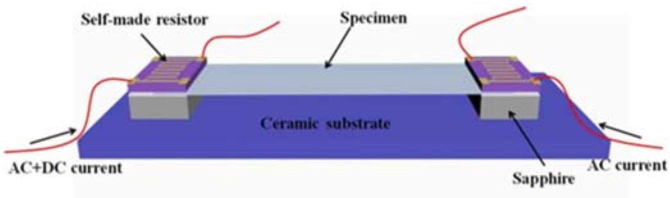

Fig. S1 Schematics of improved thermal bridge method

In the thermal conductivity measurements, a DC current of a slow change step combined with an AC current is added to one of the self-made resistor (heater R_h). The DC current is applied to provide joule heat across the specimen while the AC current is used to measure the change of resistance in the heater (ΔR_h). Meanwhile, an AC current of the same size is applied to another self-made resistor (sensor R_s), the ΔR_s represents the change of resistance in sensor. Thus, a temperature gradient generated at both ends of the specimen could be determined by monitoring the changes of resistances of the two resistors (ΔT_h and ΔT_s). The distribution of heat flux is depicted as

$$Q = Q_1 + Q_2,$$

$$Q_1 = G_s \times (\Delta T_h - \Delta T_s) = G_b \times \Delta T_s, \quad \text{(S1)}$$

$$Q_2 = G_b \times \Delta T_h;\ k = G_s \frac{\mathcal{L}}{S},$$

where Q is the total heat in the heater, which can be separated into Q_1 which represents the heat passing through the specimen and Q_2 which represents the heat flow arriving at Au substrate; G_s is the thermal conductance of the specimen; G_b is the thermal conductance of the sapphire backbones; k is the thermal conductivity of the specimen; and $\mathcal{L}$ and S represent the length and sectional area of the specimen, respectively.

B. The hot wire method

The hot wire method is based on measuring the temperature rise in a defined distance from a linear infinite hot wire. The hot wire serves as a heat source which is embedded in the specimens. Considering the ideal condition of the model, researchers should prepare an infinite specimen. Due to this huge difficulty in the sample preparation, the hot wire method is bound to introduce errors at the sample boundary.

The ideal mathematical model was presented by L. Vozrr in 1996 [5]. Assuming the heat source have a uniform output along the length of the sample, and the hot wire is an ideal, infinite thin and long line heat source, the surrounding specimen is an infinite homogeneous and isotropic material. Based on these assumptions, the thermal conductivity can be derived directly from Eq. (S2) [6].

$$\Delta T(r,t) = T(r,t) - T_0 = -\frac{q}{4\pi k} Ei\left\{-\frac{r^2}{4Dt}\right\}, \quad \text{(S2)}$$

where T_0 is the temperature when the time is equal to 0, q is the constant quantity of heat production per unit time and per unit length of the heating wire (W/m), k is the thermal conductivity of the specimen, D is the thermal diffusivity, and $Ei(x)$ is the exponential integral expressed as

$$-Ei(-x) = \int_x^\infty \frac{\mathrm{e}^{-u}}{u} \mathrm{d}u \quad \text{(S3)}$$

If the expression $r^2/4Dt<1$ is fulfilled, i.e. for a sufficiently long time t and a small distance r, the temperature rise could be simplified as

$$\Delta T(r,t) = \frac{q}{4\pi k} \ln \frac{4Dt}{r^2 C}, \quad \text{(S4)}$$

where C=exp(γ), γ is the Euler's constant. Thus the measurement of temperature rise $\Delta T(r,t)$ as a function of time may be employed to determine the thermal conductivity k by calculating the slope of the linear section of $\Delta T(r,t)$ vs. ln$t$.

C. The laser flash method

The laser flash method usually characterizes the thermal diffusivity of the specimens. The principle of the laser flash measurement is based on Eq. (S5) [7–9].

$$k = D\rho C_P \quad \text{(S5)}$$

where ρ is the bulk density and C_P is the specific heat at constant pressure. Many testing techniques were used to determine the thermal diffusivity [10,11]. Angstrom's method [12–14] is an example of this technique for the determination of the thermal diffusivity. Assuming the heat powder is periodically heated with sinusoidal signal at one end of the testing specimen, while the other end maintains surrounding temperature. The heat would be conducted between the two ends of the specimen with the sinusoidal form. After some time, the testing specimen could be heated within the sinusoidal signal, and at the same time, a phase difference was created between the two ends of the specimen. Utilizing the temperature curve vs. time measured by thermocouple at the two ends, the thermal diffusivity D could be obtained from Eq. (S6).

$$D = \frac{l^2}{2\,\Delta t\,\ln(\mathrm{M/N})}, \tag{S6}$$

where l is the length between two thermocouples, M is the temperature amplitude at the heat end, N is the temperature amplitude at the other end of the specimen, and Δt is the time interval induced by the heat conduct from one end to the other.

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