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Heat Conduction of Air in Nano Spacing

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Abstract The scale effect of heat conduction of air in nano spacing (NS) is very important for nanodevices to improve their life and efficiency. By constructing a special technique, the changes of heat conduction of air were studied by means of measuring the heat conduction with heat conduction instrument in NS between the hot plate and the cooling plate. Carbon nanotubes were used to produce the nano spacing. The results show that when the spacing is small down to nanometer scale, heat conduction plays a prominent role in NS. It was found that the thickness of air is a non-linear parameter for demarcating the heat conduction of air in NS and the rate of heat conduction in unit area could be regard as a typical parameter for the heat conduction characterization at nanometer scale.

Keywords Heat conduction · Air · Nano spacing · Thickness · Rate

Introduction

Heat transfer is the transition of thermal energy or simply heat from a hotter object to a cooler object. When an object is at a different temperature than its surroundings or another object, heat transfer occurs in such a way that the body and the surroundings reach thermal equilibrium. Heat transfer always occurs from a higher-temperature object to a cooler-temperature one, a result of the second law of thermodynamics. Where there is a temperature difference between objects in proximity, heat transfer between them can never be stopped.

Heat conduction is the transfer of heat by direct contact of particles of matter. The transfer of energy could be primarily by free electron diffusion as predominant in metals or phonon vibration as predominant in insulators. In other words, heat is transferred by conduction when adjacent atoms vibrate against one another, or as electrons move from atom to atom.

The mechanisms of heat conduction are different in solid [1], liquid [2], and gas [3] conditions. The mechanisms of heat conduction in gas can be divided into two parts, macro mechanisms and micro ones. In macro mechanisms, heat conduction is produced by the collision of a large number of molecules and randomly heat movement [4]. In micro mechanisms, when the distance between gas molecules is less than that of mean free path of gas molecules, the way of heat conduction is changed [5].

Heat conduction is widely used in many industrial fields. On account of the development of the nanotechnology, nanodevices have attracted much attention in recent years [6]. However, with the decreasing size of nanodevices [7], there are many problems about thermotics and electrics in nano spacing (NS), which cannot be solved by macro theories. So it is important to study and develop micro theories at nanometer scale.

Many efforts have been made toward investigating heat conduction of thin film [8, 9]. However, research on heat conduction of gas, especially in NS, is rarely reported.

Air is a common mixing gas in nature. However, it has a complicated composition and exists in everywhere. So many theories must be firstly taken into account in ambient air and then extended to other gaseous surroundings.

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This present work will focus on heat conduction of air in NS. The change of heat conduction of air in NS will be measured with heat conduction instrument. It is very important for the nanodevices to improve their life and efficiency, which may lead to a new research direction.

Experimental

Figure 1 shows schematic diagram of heat conduction instrument. The hot plate and cooling one were made of copper, a diameter of 13 cm and a thickness of 0.8 cm. The two plates were polished by the polishing machine to make sure surface roughness less than 0.3 nm. At first the sample was put on the cooling plate in order to ensure the bottom of the sample to closely touch the top of the cooling plate. The hot plate was simultaneously set on the sample to make sure the top of the sample to tightly contact with the bottom of the hot plate. Finally the hot plate was heated. After a short time, the temperature of the hot plate (T_1) and cooling plate (T_2) obtained by measuring the voltage were hold under an equilibrium condition. The hot plate was further heated in order to make the temperature of cooling plate increase 10 °C. Then the hot plate was moved away and the cooling plate was cooled in air automatically. The changes of the temperature of the cooling plate were recorded by measuring the voltage in 30s interval until the temperature of the cooling plate was cooled to less than 5 °C below T_1. Finally, the cooling rate and the heat conduction coefficient of the sample were calculated.

The key point in the experiment was to obtain the different thickness of air in NS, so the suitable spacers needed to be found. Carbon nanotubes (CNTs) were put into the spacing between the hot plate and the cooling plate and utilized to produce 2 and 15 nm thicknesses of air in NS using the 2-nm-diameter single-walled carbon nanotubes and 15-nm-diameter multi-walled carbon nanotubes, respectively. In order to make parallel to two plates, CNTs were settled at three different points which size was less than 100 µm on the cooling plate. The papers were used to make the spacing at micron scale. The thickness of 100 pieces of papers was firstly measured to calculate the thickness of one piece of paper. According to the thickness of spacing, an appropriate numbers of papers were also set at three different points which size is less than 1 mm on the cooling plate.

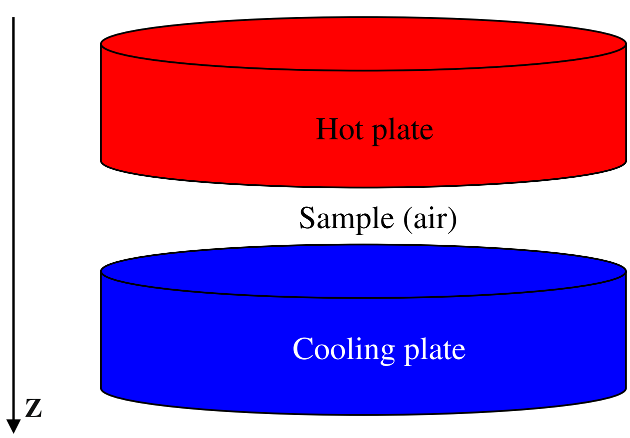

Fig. 1 Schematic diagram of heat conduction instrument

Results and Discussion

Heat transfer has three kinds of forms, including conduction, convection, and radiation. In this experiment, convection can be ignored on the NS condition.

The equation of radiation is $M = \varepsilon \cdot \sigma \cdot T^4$, where M is the spectral radiance factor, ε is emissivity (for copper, $\varepsilon = 0.03$), σ is Stefan–Boltzmann constant (5.67×10^{-8} W K^{-4} m^{-2}), and T is the absolute temperature. So the quantity of heat through radiation in NS is 0.5 W $\sim$ 2 W. However, the quantity of heat through heat conduction in NS is 70 W $\sim$ 500 W. So the quantity of heat through radiation in NS can be ignored.

Now the experiment only considers the heat conduction.

The diameter of the plate is 13 cm while the size of the CNTs and papers are less than 1 mm. The interface between plates and spacer is too much smaller relative to the area of plates so that the effect of materials properties of the samples on heat conduction of air can be ignored.

The spacing of air between plates is too much smaller than the diameter of the cooling plate, so the thermal diffusion effect at the side of the air layer can be ignored [10, 11].

The plate is 0.8-cm-thick and enough hard to ensure that the two plates are parallel each other when the sample is settled between them.

This experiment is supposed that the direction of temperature-change is along the direction Z. So the heat conduction equation can be written as follows:

$$Q = K \times \frac{\Delta T}{\Delta Z} \times A \quad (1)$$

In Eq. 1, Q is the quantity of heat, K is heat conduction coefficient (refers to the conducting heat ability of material), A is the area of heat conduction, and ΔT is the difference in temperature of the material. Take into consideration of the time,

$$\mathrm{d}Q = -K \times \frac{\mathrm{d}T}{\mathrm{d}Z} \times \mathrm{d}A \times \mathrm{d}t \quad (2)$$

Eq. 2 contains the temperature grads $\left(\frac{dT}{dZ}\right)$ [12] and unit time (dt). Minus symbol represents the direction of heat conduction along the direction of the decreasing temperature.

The quantity of heat conduction through the air during Δt is:

$$\Delta Q = -K \times \frac{\Delta T}{h} \times A \times \Delta t \quad (3)$$

where A is the area of the hot plate in present study (namely, the area of heat conduction) and h is the thickness of spacer.Change Eq. 3:

$$\frac{\Delta Q}{\Delta t} = -K \times \frac{\Delta T}{h} \times A \quad (4)$$

In Eq. 4, $\frac{\Delta Q}{\Delta t}$ is the quantity of heat conduction in unit time, which can be regarded as the heat conduction rate of air (v). These parameters, including ΔT, h, and A can be got by the experiment. The heat conduction coefficient can be calculated if only the heat conduction rate of air is known.

In this experiment, it can be supposed that temperature do not change with surroundings so that $\Delta T = T_1 - T_2$ keeps stable ($T_1 > T_2$) [13]. It is obvious that the rate of heat conduction is equal to the rate of heat diffusion.

Supposing R and D are the semi-diameter and the thickness of the plates, respectively, the total diffusive heat area (A_1) can be calculated:

$$A_1 = \pi R^2 + 2\pi R \times D = A + 2\pi R \times D \quad (5)$$

According to Eq. 4, when heat is conducted from the cooling plate to air, v_1 is proportional to A_1.

If the cooling plate can diffuse heat by itself, the total diffusive heat area is equal to the surface area of the plate (A_2).

$$A_2 = 2\pi R^2 + 2\pi R \times D = 2A + 2\pi R \times D \quad (6)$$

v_2 is the corresponding heat conduction rate of the cooling plate. v_2 is proportional to A_2. Combine v_1, A_1, v_2, and A_2 into a new equation:

$$\frac{v_1}{v_2} = \frac{A_1}{A_2} \quad (7)$$

Next specific heat of the cooling plate will be discussed [14].

$$c = \frac{1}{m} \times \frac{dQ}{dT} = \frac{1}{m} \times \frac{\Delta Q}{\Delta T_1} \quad (8)$$

In Eq. 8, m is the weight of the cooling plate, ΔT_1 is the difference in temperature between T_2 and the instantaneous temperature.Change Eq. 8:

$$\frac{\Delta Q}{\Delta t} = c \times m \times \frac{\Delta T_1}{\Delta t} \quad (9)$$

Substituting Eqs. 5 and 6 into Eq. 9:

$$v_1 = \frac{R + 2D}{2R + 2D} \times c \times m \times \frac{\Delta T_1}{\Delta t} \quad (10)$$

Substituting Eq. 10 into Eq. 4:

$$K = -\frac{R + 2D}{2R + 2D} \times c \times m \times \frac{\Delta T_1}{\Delta t} \times \frac{h}{A \times \Delta T} \quad (11)$$

Eq. 11 shows the heat conduction coefficient. All the parameters can be measured from the experiment, so the heat conduction coefficient can be calculated.

In this experiment, the temperature is obtained by measuring the voltage on the heat conduction instrument. There are linear correlation between voltage and temperature. The relationship can be written as an equation $T = x \times V$. T is temperature, x is constant, and V is voltage. Substituting it into Eq. 11, replace T by V, and then get a new equation about the heat conduction coefficient as follows,

$$K = -\frac{R + 2D}{2R + 2D} \times c \times m \times \frac{\Delta V_1}{\Delta t} \times \frac{h}{A \times \Delta V} \quad (12)$$

Figure 2 is the relationship between the heat conduction coefficient and the thickness of air. As shown, when the thickness of air is small down to nanometer scale, the heat conduction coefficient increases with the increasing of thickness of air. When the thickness of air is big up to millimeter, the heat conduction coefficient tends to a stable value, 0.026 W K^{-1} cm^{-1}. The resulting heat conduction coefficient is within macro range.

When the thickness of air is small down to nanometer scale, the change of heat conduction coefficient is unstable with the thickness resulting in a complex non-linear relationship, so it is not a good parameter for evaluating the change of heat conduction coefficient in NS.Change Eq. 4:

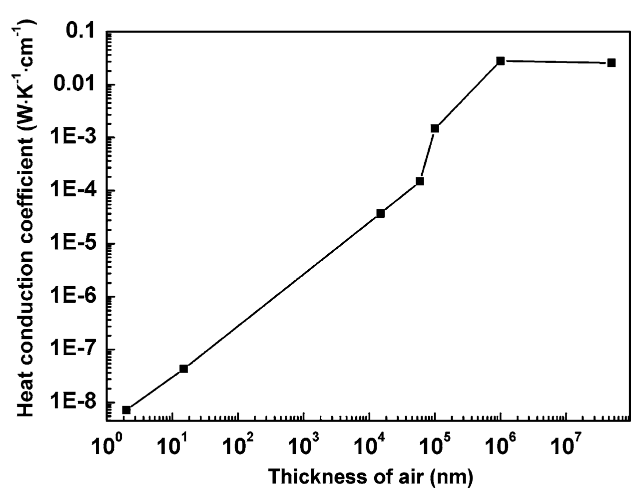

Fig. 2 The relationship between heat conduction coefficient and the thickness of air

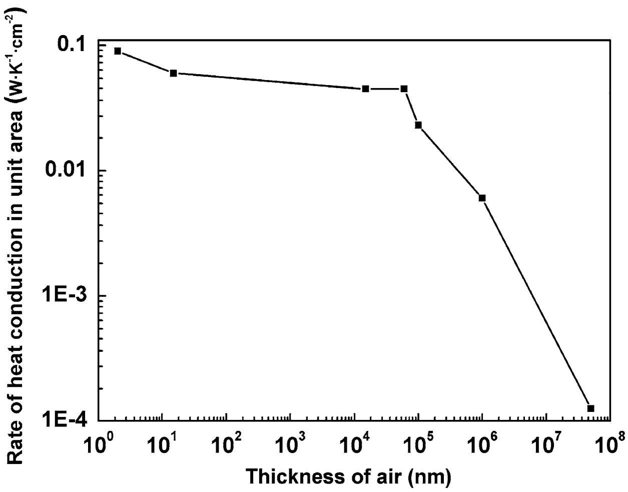

Fig. 3 Effects of the rate of heat conduction in unit area on the thickness of air

$$\frac{\Delta Q}{\Delta t} \times \frac{1}{A} \times \frac{1}{\Delta T} = -\frac{K}{h} \quad (13)$$

The left side of Eq. 13 represents the rate of heat conduction in unit area (v_3). Figure 3 is the relationship between the rate of heat conduction in unit area and the thickness of air. The results show v_3 is stable in nano spacing (h is at nanometer scale). So v_3 is more suitable as a parameter in NS.

In present work, the thickness of air ranging from 100 nm to 1000 nm is difficult to construct. Due to the systematic errors of the instrument by itself, the exactly demarcate point in $1.0 \times 10^5 \sim 1.0 \times 10^6$ nm (thickness of air) has not been found. Further research is still required.

Conclusions

The changes of heat conduction of air in NS produced by CNTs were studied by means of measuring the heat conduction with heat conduction instrument. The results show when the thickness of air is small down to nanometer scale, the thickness of air present a complex non-linear relationship with heat conduction coefficient and is unsuitable for evaluating the change of heat conduction in NS. It was found that the rate of heat conduction in unit area could be more suitable as a typical parameter. The present study will draw lots of interests on heat conduction at nanometer scale.

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