Measurement of in-plane thermal conductivity of self-suspended thin films

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Abstract A method for in-plane thermal conductivity measurement of self-suspended thin films by steady-state infrared thermal thermography is introduced. Based on the one-dimensional heat conduction equation, a theoretical model of temperature distribution on the surface of thin film at steady state is established. The simulation results show that the error between in-plane thermal conductivity and theoretical value is less than 3% when the temperature rise of the film is less than 5K. By measuring the boundary temperature and thickness of the film, the in-plane thermal conductivity and emissivity can be obtained simultaneously without measuring the absorption of visible light by the film. Polyimide film with the thickness of 550 nm is experimentally investigated by this method. We find that the in-plane thermal conductivity is 2.15W/mK and emissivity is 0.93 by fitting temperature distribution curve. These results validate the method developed.

1. INTRODUCTION
Thin film materials have been widely used in microelectronics, information, aerospace technology and other high-tech fields. With the development of technology, more and more attention has been paid to the study of thermophysical properties of thin film materials. Because the thermophysical properties directly determine the research and application of thin films, it is of great significance to accurately measure the thermophysical parameters of thin films.

Transient 3ω method¹ is less restricted in terms of the type of film investigated, but sample preparation is very demanding. Time-resolved optical pump-and-probe measurements² depend on calibration and smooth film surfaces without diffuse reflection. Micro-bridge method³ is simple, but the influence of thermal radiation losses and contact thermal resistance is ignored. These methods cannot easily provide information of the thermophysical properties of thin film materials.

In this paper a method is introduced that in-plane thermal conductivity measurement of self-suspended thin films by steady-state infrared thermal thermography. The measurement is a non-contact methods, we cannot consider the contact thermal resistance and the sample preparation is simple. We will introduce the measurement principle and simulation and present the necessary experimental setup. We apply the method to the polyimide film.

2. MEASUREMENT PRINCIPLE AND SIMULATION

2.1 Theoretical model
When visible light illuminates the surface of the film, the film absorbs visible light energy and exchanges heat with the surrounding environment through conduction, convection, and thermal
Fig. 1 schematic diagram of the measurement

Fig. 1 shows the schematic diagram of the method. Z direction is the thickness direction of the film. The film surface is located in the X-Y plane. The model is divided into two parts. The left side is the illumination area, and the right middle position is the test area. Sample is placed over a Vacuum cavity, heat exchange caused by convection can be neglected, Owing to the thickness of the film is small enough, it can be considered that there is no temperature gradient in Z direction [4]. When visible light irradiates the film, Y direction is heated evenly. Thus the heat conduction equation of the film can be simplified into a one-dimensional heat conduction equation along the x-axis [5]:

\[ kd \frac{\partial^2 T(x)}{\partial x^2} - \sigma \varepsilon \left( T(x)^4 - T_\infty^4 \right) = C_p \rho \frac{\partial T(x)}{\partial t} \]  \tag{1}

With the in-plane thermal conductivity k, the ambient temperature \( T_\infty \), the thickness d, the density \( \rho \), the heat capacity \( C_p \), the emissivity \( \varepsilon \) and the Stephen Boltzmann constant \( \sigma \) and the temperature distribution \( T(x) \) at a distance \( x \) from the \( x=0 \) along the x-axis.

At steady-state conditions \( \frac{\partial T(x)}{\partial t} = 0 \), This leads to

\[ kd \frac{\partial^2 T(x)}{\partial x^2} - \sigma \varepsilon \left( T(x)^4 - T_\infty^4 \right) = 0 \]  \tag{2}

When the temperature difference between the thin film and the ambient temperature is small, approximate conditions \( \varepsilon \sigma \left( T(x)^4 - T_\infty^4 \right) \approx 4 \varepsilon \sigma T_\infty^3 \left( T(x) - T_\infty \right) \) can be adopted, and Eq. 2 can be simplified to:

\[ kd \frac{\partial^2 T(x)}{\partial x^2} - 4 \varepsilon \sigma T_\infty T(x) = 0 \]  \tag{3}

The energy of visible light is a fixed value, and the heat flux is given. It belongs to the Neumann boundary condition

\[ -k \frac{\partial T}{\partial x} \bigg|_{x=0} = q \]  \tag{4}

Merging Eq. 1 - Eq. 4, and applying the boundary condition \( T \big|_{x=\infty} = T_\infty = T_{\text{substrate}} \), leads to the temperature distribution

\[ T(x) = \frac{q}{k \sqrt{\alpha}} e^{-\sqrt{\alpha}x} + T_\infty \]  \tag{5}

Expected for the Theoretical model investigated here. With

In Eq. 5, the thermophysical information of the thin film is included, the in-plane thermal conductivity and emissivity can be obtained simultaneously by fitting thermal diffusion curve of film.
2.2 Simulation analysis

In the theoretical model, the linear approximation of the thermal radiation term is made by assuming that the temperature difference between the thin film and the ambient temperature is small. In order to study the error induced by the assumed conditions, the finite element method is used to establish the simulation model of the thin film.

In the simulation model, radius is set to 10mm and thickness is set to 1 micron. The illumination area is a rectangle with a size of 4×2mm located in the center. The ambient temperature, initial temperature and boundary temperature are set to 300K. Fig. 2 shows the temperature distribution of thin film at steady-state. In-plane thermal conductivities are set to 2 W/mK, 1.5W/mK, 1W/mK and emissivity is set to 0.9, Thermal diffusion curves of simulation are shown in Fig. 3.

With the thickness and emissivity of the thin film as known conditions, the in-plane thermal conductivity k can be obtained by fitting the temperature diffusion curve of the simulation model. By comparing with the thermal conductivity values set in the simulation model, we can obtain the error induced by the assumed conditions.

Fig. 4 shows the values of k obtained by fitting temperature diffusion curve. The range of maximum temperature increase is from 1K to 20K. With the rise of the maximum temperature increase of thin film, error of in-plane thermal conductivity obtained by fitting temperature diffusion curve increases. When maximum temperature increase is 5K, we obtain k=1.94W/mK, k1.5=1.46W/mK and k1=0.97W/mK. The errors induced by the thermal radiation approximation are 3%, 2.7% and 3%.
Simulation results show that when the maximum temperature increase of the film is less than 5 K, the error induced by the thermal radiation approximation is less than 3%.

3. EXPERIMENTAL STUDY

3.1 SETUP DETAILS
Integral parts of the setup are the IR camera for the spatially resolved temperature measurement and the vacuum cavity, shown in Fig. 5, for the reduction of the losses by air.

![Fig. 5 Schematic diagram of Setup](image)

In this paper, the polyimide self-suspension film samples with diameter of 3 inches and thickness of 550 nm were measured by this measuring system. Fig. 6 is the picture of the polyimide film sample.

![Fig. 6 Samples of polyimide films](image)

The sample is illuminated via an Projector, the illumination area is a rectangle with a size of 4×2mm located on the film. Temperature rise of thin films after absorption of visible light. At the steady-state conditions, temperature distribution of the thin films is captured via IR camera and the boundary temperature of thin films is measured by the thermocouple.

3.2 RESULTS AND DISCUSSION
In the experiment, the vacuum degree of the vacuum chamber was kept at 4×10⁻³ Pa, and the steady-state boundary temperature of the sample measured by the thermocouple was 307.89K.
Fig. 7 shows the film temperature distribution captured via IR camera. Take x=0 as the starting point of film diffusion curve, the maximum temperature increase is 1.86K, less than 5K, Within the range of simulation maximum temperature increase.

According to Stephen Boltzmann's Law\(^6\), the relationship between the equivalent blackbody temperature and the actual temperature of the film surface is as follows.

\[
E_{\text{radiation}} = \sigma T^4_r = \sigma \varepsilon T^4_{\text{film}}
\]  

(6)

Applying the Eq. 6, we get the radiation intensity distribution of thin film are shown in Fig. 8. Merging Eq.5 and Eq.6, we get

\[
E_r = \sigma \varepsilon \left( \frac{q}{k \sqrt{\varepsilon}} e^{-\sqrt{\varepsilon}} + T_e \right)^4
\]  

(7)

Fig. 8 Radiation intensity distribution

By measuring film thickness by Step profiler and the boundary temperature by thermocouple, we get \(d=550 \text{nm}\) and \(T_{\text{substrate}}=307.89 \text{K}\). Applying the Eq. 7, by fitting the curve of radiation intensity distribution of thin film, we obtain \(k=2.15 \text{W/mK}\), \(\varepsilon=0.93\) and heat flux \(q=1.75\times10^4 \text{W/m}^2\).

4. CONCLUSION

In this paper, we demonstrate a simple and quick method for the in-plane thermal conductivity measurement of the self-suspended thin films. The measurement method was validated by using the finite-element simulation results as the measurement results. The simulation results indicated that theoretical value of \(k\) is less than 3% when the temperature rise of the film is less than 5K. By
measuring the polyimide film with thickness of 550 nm, we obtain the in-plane thermal conductivity is 2.15 W/mK and emissivity is 0.93 at room temperature.

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