International Journal of Heat and Mass Transfer 95 (2016) 727–734

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Measurement of in-plane thermal and electrical conductivities of thin film using a micro-beam sensor: A feasibility study using gold film

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ARTICLE INFO

Article history:
Received 24 July 2015
Accepted 20 December 2015
Available online 7 January 2016

Keywords:
Thermal conductivity
Measurement technique
Steady-state measurement
MEMS sensor
Thin film

ABSTRACT

A new method is proposed for measuring the in-plane thermal conductivity of thin films using a free-standing micro-beam metallic sensor. The sensor is heated in a vacuum by DC to induce a temperature rise, which is determined from the electrical resistance of the sensor. The method consists of two protocols: measurement of a bare sensor before and after deposition of a sample film on its top surface. The thermal conductivity of the sample film is determined by comparing the measured temperature rise with that obtained through numerical analysis. This is based on the principle that the temperature rises of the sensor with and without a deposited film are different because of a difference in in-plane thermal conductance. In this study, measurement of a 20-nm-thick gold film was demonstrated by fabricating two platinum sensors of different widths. The measured thermal conductivities of the platinum sensors and gold film were significantly smaller than those of bulk materials. The relationship between the thermal and electrical conductivities was also discussed.

1. Introduction

Thermal management is essential for the design and operation of electronic devices and recording media because of the concentrated heat generation resulting from significantly miniaturized and integrated elements [1–4]. It is therefore important to precisely analyze heat generation and heat dissipation in devices that consist of multilayered patterns of thin films. However, the electrical and thermal transport properties of thin films are different from those of bulk materials due to the effects of electron scattering at the surfaces and grain boundaries, which are not significant in bulk materials. These properties also depend on the film thickness, grain size, and fabrication process. For example, the electrical resistances of single-crystal gold films that are fabricated by different processes or have different thicknesses are different from one another [5]. The electrical and thermal transport properties of platinum and gold films depend on the grain size and film thickness [6,7]. The anisotropic nature of thin films has also been demonstrated. For example, the in-plane thermal conductivity of deposited TbFeCoZr film is an order of magnitude smaller than the cross-plane thermal conductivity [8].

Various methods have been proposed for measuring the thermal conductivity in each direction. The 3ω and thermoreflectance methods are commonly used for measuring the cross-plane thermal conductivity and interfacial thermal resistance [9–11]. A common feature of these methods is that the signals associated with the temperature change after heating the surface of a film on a substrate are detected. Materials with higher thermal conductivities than the film are used as substrates when preparing a system where the heat flow across the film in a vertical direction is dominant. With the 3ω method, the metallic line heater/sensor that is fabricated on the film is electrically heated at an angular frequency ω followed by the detection of a voltage oscillation at frequency 3ω [12]. With the thermoreflectance method, the change in reflectivity is optically detected using a probe laser after heating the surface with a different laser beam [13].

The in-plane thermal conductivity can be measured using these methods, but the principles are quite complicated [14–16]. Other methods for measuring the in-plane thermal conductivity and/or thermal diffusivity use a thin film in a membrane structure [17,18]. A typical method is to use temperature detectors and heaters that are fabricated on the free-standing membrane [19,20]. The thermal conductivity is then determined by comparing the measured temperature with the numerical solution to the 3D heat conduction model. Hence, the configuration of the system, i.e., sizes and locations of the sensors and heaters, must be precisely measured because it is critically important for the accuracy of the measurement. Another method is to use the sample film both as a heater and a temperature detector [21–25]. With this method, the sample is prepared in a bridge-like structure

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.047
0017-9310/

Nomenclature

D	thickness (m)
H_t	depth of trench (m)
L	length (m)
L_o	Lorentz number ($\mathrm{W\,\Omega\,K^{-2}}$)
L_r	length of overhang (m)
q_v	rate of heat generation per unit volume ($\mathrm{W/m^3}$)
Q	heating power (W)
R	electrical resistance (Ω)
T	temperature (°C)
W	width (m)
Greek symbols	
α	voltage drop at the electrode pad relative to that at the whole region (–)
β	temperature coefficient ($\mathrm{K^{-1}}$)
ε_R	rate of electrical resistance per heating power ($\mathrm{\Omega\,W^{-1}}$)
Φ	nondimensional electric potential (–)
λ	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
Θ	nondimensional temperature rise (–)
σ	electrical conductivity ($\mathrm{W^{-1}\,m^{-1}}$)
Subscripts	
0	zero degrees
1D	one-dimensional
A	middle of sensor
ap	apparent
B	end of sensor
C	electrode
f	film
i	initial condition
s	sensor
sf	sensor with film

suspended from the substrate. Although the in-plane thermal conductivity of thin films is successfully measured using these methods, it would not be feasible for a variety of samples because all of these methods need special fabrication procedures after preparation of the thin film. Fabrication of heaters and sensors or a bridge-like structure is needed as well as preparation of a free-standing structure. Therefore, these methods are not easy to use for the on-site measurement of thin films, although the properties significantly depend on the film size as well as fabrication conditions.

In this paper, we propose a new method for measuring the in-plane thermal conductivity of deposited thin films using a micro-beam sensor. The sensor, which was originally developed for measuring the thermal conductivity of small samples of gases and liquids [26], is made of a beam-type thin metallic film suspended across a trench on the silicon substrate, which is used as a self-heating thermometer. The protocol consisted of measuring the temperature of the sensor, which was heated in a vacuum, and repeating the same procedure after the deposition of a sample film on the sensor. A numerical analysis of the heat conduction was also performed to obtain the relationship between the thermal conductance and temperature rise. This method has several advantages over the others. One is that the measurement principle is simple and robust with adequate accuracy for the measurement of thin film samples. Another advantage is that electrical conductivity is measured at the same time. However, the greatest advantage is that thermal conductivity can be measured after deposition of a sample film on the sensor with no additional fabrication procedures. Assessing the effects of post-deposition processes such as annealing is also possible with the same specimen.

The objective of the present study is to demonstrate the feasibility of the method using prototype micro-beam sensors. We measured gold film samples of the same thickness deposited on two platinum micro-beam sensors of different widths. The measurement uncertainty was carefully checked and analyzed in detail.

2. Principles of measurement

The sensor is made of an approximately 10-μm-long freestanding metallic film suspended from a silicon substrate across a trench on the substrate (Fig. 1). It is a self-heating resistance thermometer that is heated by DC in a vacuum. Although the temperature increases by uniform heat generation in the sensor, the temperature at both ends does not change from the constant substrate temperature owing to the large heat capacity of the substrate. By heating at a constant power, the sensor eventually reaches a steady state with a parabolic temperature distribution along the sensor, as shown in Fig. 2(a). The temperature distribution, which depends on the thermal conductance of the sensor, is estimated by solving the heat conduction equation. After a sample film is deposited on the surface of the sensor, the temperature rise is less than the original because of the increased thermal conductance due to the deposited layer (Fig. 2(b)). The thermal conductivity of the sample film is thus calculated from the difference in the measured average temperature rises before and after deposition of the sample film.

When a sensor of uniform cross section is uniformly heated while keeping both ends at the initial temperature T_i, the average temperature rise of the sensor is calculated from the analytical solution to the one-dimensional heat conduction equation and expressed by a unique value in the nondimensional form

$$\Theta \equiv \frac{T - T_i}{(q_v L^2/\lambda)} = \Theta_{1\mathrm{D}} = \frac{1}{12} = 0.0833 \tag{1}$$

where Θ is the nondimensional temperature rise, T is the average temperature of the sensor, q_v is the rate of heat generation per unit volume, L is the length of the sensor, and λ is the thermal conductivity of the sensor. We can therefore determine the thermal conductivity by measuring the average temperature rise of the sensor at a given heating power Q using the relationship

$$q_v = \frac{Q}{LWD}, \tag{2}$$

where W and D are the width and thickness of the sensor, respectively.

In the experiment, we measured the electrical resistance of the sensor at several given current intensities while keeping the chip at controlled temperatures in a vacuum chamber. The results indicated that the electrical resistance R increased linearly with the heating power Q:

$$R = R_i + \varepsilon_R Q, \tag{3}$$

where R_i is the electrical resistance at a given chip temperature T_i. By repeating the experiment at different chip temperatures, we determined the electrical resistance R_i as a function of temperature and obtained the relationship

$$R = R_0\{1 + \beta(T - T_0)\}, \tag{4}$$