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Differential 3ω method for measuring thermal conductivity of AlN and Si_3N_4 thin films

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ABSTRACT

The thermal conductivity λ of plasma enhanced chemical vapor deposited Si_3N_4 and sputtered AlN thin films deposited on silicon substrates were obtained utilizing the differential 3ω method. A thin electrically conductive strip was deposited onto the investigated thin film of interest, and used as both a heater and a temperature sensor. To study the thickness dependent thermal conductivity of AlN and Si_3N_4 films their thickness was varied from 300 to 1000 nm. Measurements were performed at room temperature at a chamber pressure of 3.1 Pa. The measured thermal conductivity values of AlN and Si_3N_4 thin films were between 5.4 and 17.6 $Wm^{-1} K^{-1}$ and 0.8 up to 1.7 $Wm^{-1} K^{-1}$, respectively. The data were significantly smaller than that of the bulk materials found in literature (i.e., $\lambda_{AlN} = 250–285\ Wm^{-1} K^{-1}$, $\lambda_{Si_3N_4} = 30\ Wm^{-1} K^{-1}$), due to the scaling effects, and also strongly dependent on film thickness, but were comparable with literature for the corresponding thin films.

1. Introduction

Thin film technology has been developing rapidly in the past decades due to the advances in thin film deposition and characterization techniques, leading to increased and simultaneously decreased structure dimensions of microelectronic devices. As a result, alternate approaches for thermal management of thin films are frequently required in order to achieve a high efficiency and to ensure the reliability of fabricated devices. Thermal conductivity of thin films is an important fundamental material property since the ability to dissipate heat is often the limiting factor to determine the device performance. Therefore, materials with a high thermal conductivity are needed. Aluminum nitride (AlN) is one of the most promising candidates for effective heat conductors in microelectronic devices due to its high bulk thermal conductivity and thermal expansion coefficient which are close to silicon [1]. The bulk thermal conductivity of AlN is 200 times higher than those of silicon dioxide (SiO_2) and silicon nitride (Si_3N_4) [2,3]. However, thermal conductivity of thin films can be substantially different from that of bulk materials due to the scaling effects [1,4–6]. Therefore, precise determination of thermal conductivity for thin films is crucial for designing or analyzing microelectronic devices. Furthermore, the limited thermal conductivity data of AlN available in literature vary significantly from each other, which is mainly attributed to the differences in film preparation processes [1]. Currently, thermal conductivity of AlN films has been determined using a variety of measurement methods, such as laser ablation, AC calorimetric method and photothermal reflectance method [1,3, 7–9]. Results using these methods indicate that the thermal conductivity of polycrystalline AlN films is strongly dependent on film thickness, defect density and oxygen content. Clearly, an appropriate method to determine the thermal conductivity of AlN and other dielectric thin films is required. This work reports an approach to measure the thermal conductivity λ of insulating thin film material AlN in the sub-micrometer range, in order to characterize the thickness dependency of the film thermal conductivity. The thermal conductivity of AlN thin films was measured using an improved differential 3ω method. In contrast to commonly used thermal conductivity measurement methods, such as laser flash [5], AC calorimetric method or photothermal reflectance, the differential 3ω method is insensitive to errors from black-body radiation because the effective thickness of the sample is extremely small [10]. Therefore, higher accuracy and better reproducibility of the film thermal conductivity data can be obtained.

2. Experimental details

In this work the thermal conductivity of AlN and Si_3N_4 thin films was determined by applying the differential 3ω method, which was originally developed by Cahill [10]. The 3ω measurement technique was evolved from conventional hot-wire techniques and is currently used to measure the thermal conductivity of dielectric thin films [1,5, 11]. A thin metal strip, with a width of $2b$ and a resistance R_h, as

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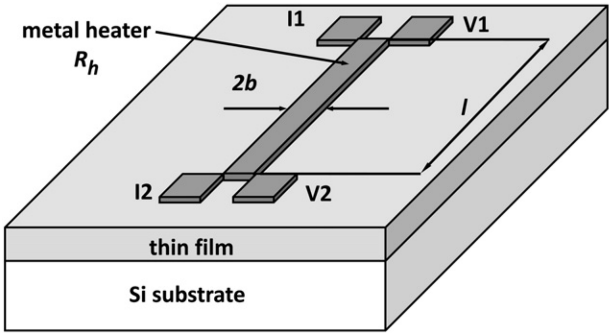

Fig. 1. Schematic layout of the four-pad test structure used to determine the thermal conductivity of a thin film by the differential 3ω method. A metal strip serves as both the heater and the thermometer. The four pads are the connections for current leads (I1, I2) and voltage leads (V1, V2). *l* is the distance between the current leads and *2b* is the strip width.

shown in Fig. 1, is deposited on top of the thin film sample for simultaneous operation as a heater and thermometer. An alternating current with an angular modulation frequency ω is driven through the metal strip causing Joule heating and induces a temperature oscillation $\Delta T(\omega)$ at a frequency of 2ω. This results in a voltage oscillation $\Delta V(\omega)$ along the heating resistor with a third harmonic which depends on the temperature oscillation of the heater. The temperature and voltage oscillations are the key parameters of the differential 3ω method. Thermal conductivity of a thin film can be obtained by comparing the temperature oscillation in a film-on-substrate structure with the corresponding value of the substrate. The temperature variation of the film-on-substrate structure is experimentally measured by detecting the voltage oscillation across the metal heater, which is proportional to the oscillating resistance value. The substrate temperature oscillation can be determined by [12]:

$$\Delta T = \frac{P}{\pi l \lambda_s}\left(\frac{1}{2}\ln\frac{4D}{b^2} + In2 - 0.5772 - \frac{1}{2}\ln(2\omega) - \frac{i\pi}{4}\right) \tag{1}$$

where λ_s is t D the thermal diffusivity of the substrate, P the power supplied to the metal strip, l the length of the metal strip and i the imaginary unit, respectively [12].

If the thin film thermal conductivity λ_f is much smaller than that of the substrate material and also the width $2b$ of the metal strip is much larger than the thickness d_f of the investigated film, the temperature shift induced by the thin film ΔT_f is given by [11]:

$$\Delta T_f = \frac{p\, d_f}{l \lambda_f 2b}. \tag{2}$$

The AlN and Si_3N_4 thin films were prepared on a p-doped Si-substrate of about 640 μm in thickness. The AlN thin films were deposited using a magnetron sputtering process, whereas Si_3N_4 films were deposited using plasma enhanced chemical vapor deposition. The AlN thin film was deposited on a single crystal Si (001) wafer by a radio frequency (rf) reactive magnetron sputtering process with an rf power of 5 kW and a dc power of 100 W. The ambient pressure and temperature in the deposition chamber were adjusted to be 133.3 Pa and 20 °C, respectively. An aluminum target

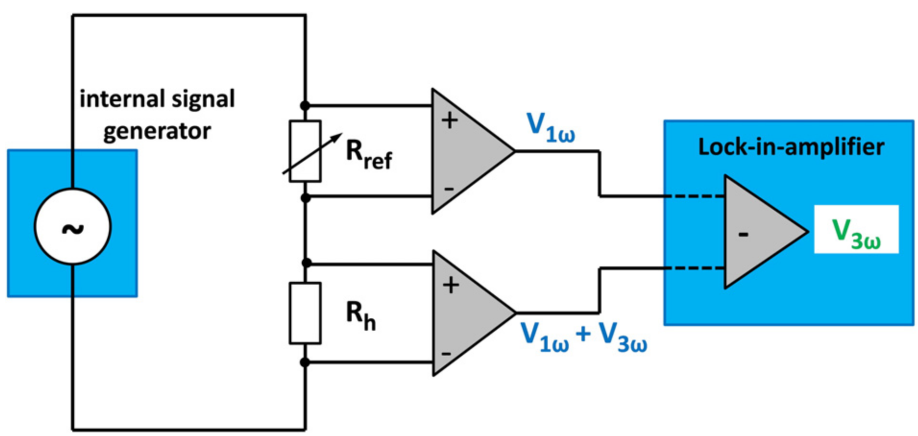

Fig. 2. Schematic circuit diagram used to extract the 3ω voltage component from the voltage signal across the metal strip deposited on the sample.

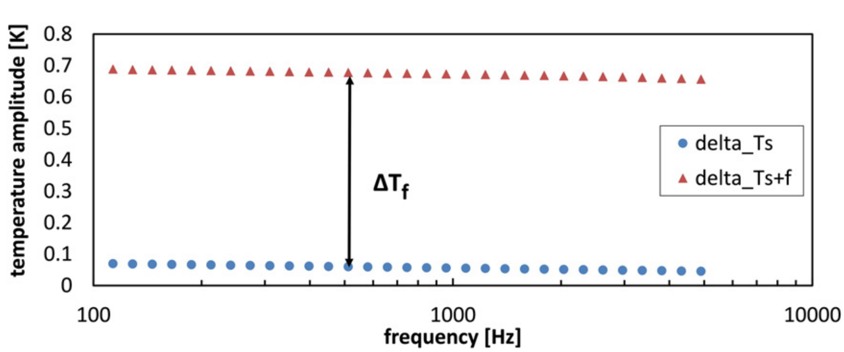

Fig. 3. The temperature amplitudes for the substrate and for the film-on-substrate structure for the 1001 nm Si_3N_4 thin film. The triangles represent the temperature amplitude of the film-on-substrate structure, which is experimentally measured by detecting the 3ω voltage across the 5.5 μm wide Au-heater. The thermal conductivity of the Si_3N_4 is determined by comparing the temperature amplitude of the film-on-substrate structure with the corresponding value in the Si substrate. The circles represent the corresponding temperature amplitude of the Si-substrate, obtained by Eq. (1).