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Characterisation of high thermal conductivity thin-film substrate systems and their interface thermal resistance

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ABSTRACT

This paper characterises the high thermal conductivity thin-film substrate systems and the interface thermal resistances between the films. First, three-omega (3ω) method was proposed and verified, obtaining a reliable thermal conductivity measurement at shallow thermal-penetration depths. The method was then applied to a thin-film/substrate system to identify the individual thermal conductivities. The interface thermal resistance between the thin films was then successfully characterised with the aid of theoretical modelling and experimental measurements. As an example of the method application in the IC industry, the AlN/Si systems were investigated. The study identified that the thermal conductivity of the 2 μm-thick AlN film in an AlN/Si system is 172.1 W/mK and the AlN/Si interface thermal resistance is 1.796×10^{-9} m^2 K/W.

1. Introduction

Semiconductor thin films on electrical-insulator substrates have been considered a new technology to extend the Moore's law [1]. However, conventional dielectric-insulation layers such as silicon dioxide (SiO_2) or alumina (Al_2O_3) have relatively low thermal conductivity. Hence, while they function as dielectric insulators, they also shield the heat induced by the self-heating of electronic devices, which greatly deteriorates their performance reliability. In theory, three primary factors can affect the temperature rise of the thin film/substrate in electronic devices. First, the thermal resistance of the film and substrate materials themselves (i.e. due to thermal diffusivity) cause some temperature increase. Secondly, the interface thermal resistance (ITR) may significantly shield the heat conduction from the film into the substrate. Further, any crystallographic defects such as dislocations, grain boundaries or twins may affect the thermal properties of the material and consequently reduce the thermal conductivity. However, existing theoretical models are not capable of introducing all three effects due to the complexity of the thin-film/substrate system; and the actual temperature rise in electronic devices such as in high-performance chips is significantly higher than theoretical predictions [2–5]. Thus, the actual thermal conductivity of thin film and the ITR must be experimentally measured for optimisation and thermal management.

Relevant studies have demonstrated that different methods of thermal-conductivity characterisation for thin-film/substrate systems have been utilised, including the time-domain thermoreflectance (TDTR) [6–8], scanning thermal microscopy [9–11], coherent optical thermometry [12–14] and the 3ω method [15,16]. Each method has its own advantages and drawbacks. For instance, a very shallow heat-penetration depth is the primary advantage of the TDTR method. Therefore, it enables the thermal-conductivity characterisation of extremely thin materials. However, the initial setup for TDTR is expensive and the noise from the laser may affect the accuracy of the results. Moreover, the heat capacity of the specimen can significantly alter the measurement and induce error, particularly at high frequencies [17]. In the scanning thermal microscopy method, a localised heat source enables the specimen to be probed at very small surface volumes. Hence, this method is promising for studying microstructures and nanostructures. However, the heat transfer between the tip and specimen is very complex, requiring a deep understanding of heat conduction and sophisticated modelling of the system. In addition, there is no local thermal equilibrium available below the scale of heat carriers' mean-free path. This means that for certain materials with higher mean-free paths, the tip radius may not be suitable which can induce significant error in the measurement results [11]. The coherent optical thermometry has noise and calibration complications. In addition, the method is not suitable for materials with relatively low transmittance.

The 3ω method has several unique advantages over the others

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mentioned above. First, it is non-destructive in that the specimen material property does not change after the measurements. Secondly, low temperature causes lower undesirable heat loss from the sample and increases the accuracy of the measurements, because the metal-strip element is merely a fraction of a degree Celsius hotter than the surrounding temperature. Thirdly, the 3ω method is non-invasive, meaning that it can be utilised to perform an in-situ characterisation of the specimen. In addition, the facilities required for applying the 3ω method are relatively inexpensive.

Researchers have attempted to implement the 3ω method in various thin-film/substrate systems [15,16,18–23]. Cahill and Pohl [16] characterised the thermal conductivities of some dielectric solids such as polymethylmethacrylate (PMMA), amorphous As_2S_3, Ca-K nitrate glass, three SiO_2-based glasses and glycerol in the temperature range of 30–300 K. They deposited 5–35 μm and 90 μm wide metal strips on the surfaces of the specimens by photolithography and evaporation through mask techniques, respectively. They argued that the thermal-conductivity characterisation of thin films as thin as 100 μm thickness is feasible by the 3ω method. It is noted that the dielectric materials characterised by Cahill and Pohl [15,16] have very low thermal conductivities—ranging between 0.1 and 12 W/mK. Yamane et al. [22] investigated a series of different thickness SiO_2 thin films prepared using various deposition techniques. Utilising the conventional 3ω method, they observed that by decreasing the thin-film thickness, the characterised thermal conductivity was significantly reduced. In addition, different deposition procedures result in differences between the microstructure of the SiO_2 thin-film specimens. Consequently, the thermal conductivity of the thin-film material is different for each deposition method. Dechaumphai et al. [19] characterised the thermal properties of ultralow thermal conductivity multilayers using the conventional 3ω method; where, the theoretical heat-conduction equations within both substrate and the insulating thin-film layers were analytically modelled and compared with the experimental measurement of the 3ω method. Overall, the application of the 3ω method on low thermal conductivity dielectric materials is favourable.

In spite of the importance of knowing the thin-film thermal conductivity, an accurate measurement is challenging, especially when the thermal conductivity is extremely high. In the case of a high thermal-conductivity crystalline material, heat can rapidly penetrate into the material, making the control of the heat-penetration depth difficult. This then aggravates measurement errors. Bulk crystalline silicon (Si) and aluminium nitride (AlN), for instance, have a high thermal conductivity of about 140 and 285 W/mK respectively at room temperature [24–28]. Significant attempts have been made to implement the 3ω method in various thin-film/substrate systems [15,16,19,22,29–34]. However, its applicability to high thermal conductivity ultrathin systems is questionable. Moreover, the conventional 3ω method cannot separate the thermal conductivity of the thin film and the substrate; which means that it characterises only the thermal conductivity of the underneath material as a whole.

Assuming that the heat loss to the atmosphere is negligible in the 3ω method, all the generated heat penetrates into the specimen material underneath the metal-strip. Therefore, there will be a temperature gradient along the vertical thickness of the specimen. This temperature-gradient under the metal-strip element can be divided into three regions of planar, transient and linear [35]. There are no precise boundaries between these regions; but their limits are placed by convention according to the experimental and theoretical results available in the literature [35]. In the planar region, the thermal-penetration depth is in the vicinity of the metal-strip element and the temperature oscillation is negligible. This region could be from the top specimen surface to one-fifth of the metal-strip element half width [35]. The planar region is not suitable for the thermal-conductivity calculations using the theory of the 3ω method. The linear region is usually from five times the metal-strip element half width to one-fifth of specimen thickness [35]. In the linear region, the temperature oscillation has reached a steady-state and is therefore a suitable characterisation region for thermal-conductivity approximation. The frequency applied on the metal-strip element can influence the depth of heat penetration into the specimen. Hence, depending on the thickness of the specimen, there are low- and high-frequency limits for the linear region.

The conventional 3ω method is with the metal-strip element of micrometers in width, e.g., 50 μm to 60 μm [3], 8 μm [4–5], 25 μm [6–7], 10 μm [8], 5 μm [9], and 2 and 50 μm [10]. However, according to the temperature-gradient regions aforementioned, if the metal strip is large, the measurement error will be exacerbated at high frequencies. Therefore, in the majority of previous studies, the specimen materials have relatively low thermal conductivities, usually below 100 W/mK (e.g. Refs. [19,22,29–34].). Furthermore, due to the large width of the metal strip element and lower frequency of the applied voltage, previous studies assumed that the heat penetrates through the film and substrate [15,22,36,37]. Moreover, because the film thickness is significantly thinner than that of the substrate, those studies assumed that the film effect on the overall thermal resistance was negligible. In so doing, the thermal resistance is only attributed to the thick substrate and the ITRs. However, such kind of treatment becomes questionable when the effect of the ITR on the overall thermal resistance is not significantly larger than the film itself.

This study will show that the width of the metal-strip element and the heating frequency are the primary parameters that affect the thermal-penetration depths. Hence, a sufficiently narrow metal strip and high frequency range is essential in characterising high thermal conductivity thin-film substrate systems. The method will be applied and tested on bulk and ultrathin Si freestanding wafers as well as on AlN/Si thin-film/substrate systems. Based on the theory of the 3ω method and the total heat penetration depth, an analytical method will be developed for thin-film/substrate systems enabling the separation of the effects of the thin film and substrate thermal resistances in the 3ω method.

2. Methods

2.1. Theoretical analysis

2.1.1. Metal-strip width effect

To apply the 3ω method, a long and narrow metal-strip element is deposited on the top surface of the specimen (Fig. 1). This metal-strip element functions as a heater and a temperature sensor. The heat is generated by the applied voltage (V_0) and the temperature is sensed by the 3ω voltage ($V_{3\omega}$) measurement. The two ends of the metal-strip element are attached to the contact pads. The contact pads do not affect the results, but their dimensions are much larger than the width of metal-strip element, which makes the connection of the metal strip to a suitable measurement circuit easier.

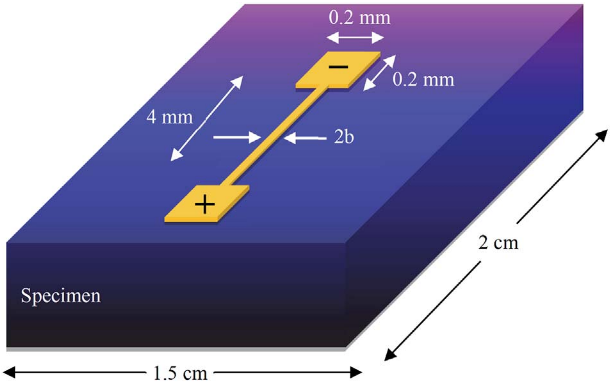

Fig. 1. Typical schematic of metal-strip element for the 3ω method (the dimensions are typical and the schematic is not to scale).