

# Thermal Conductivity Measurement of Thin Dielectric Films Using the $3\omega$ Technique

A. Delan, M. Rennau, S.E. Schulz

The measurement of thermal conductivity is the prerequisite for simulation of thermal behaviour of interconnection systems using low k dielectrics and Cu. Especially for low density and porous low k dielectric materials, the low thermal conductivity may cause heat dissipation problems. The so-called  $3\omega$  measurement technique (transient hot wire method) was established to determine the thermal conductivity of thin films. Measurements of standard substrates and films show validation of the achieved thermal conductivity values and agreement with published, commonly accepted values. The method was successfully applied to determine the thermal conductivity of porous low k dielectric materials using special test structures. The thermal conductivity of the porous low k dielectrics measured in that way is only 7 and 16% of the thermal conductivity of thermally grown silicon dioxide.

The name  $3\omega$  measurement technique derives from the method of detection; a current at angular frequency  $\omega$  is caused to flow through the wire resulting in heating at frequency  $2\omega$  (dc heating is negligible). The voltage signal at  $3\omega$ , measured with a lock-in amplifier, is proportional to the ac temperature in the specimen. By proper calibration, the thermal conductivity is obtained from the frequency dependence of the signal. The measured values are thermal coefficient of resistivity, heater resistance, temperature and the  $\omega$  and  $3\omega$  signals. Heating power, the geometry (width, length, thickness of the heater and film) and material properties affect the measurement.

The  $3\omega$  method has been used extensively for measuring the thermal conductivity of thin films and bulk materials [1-4]. We applied it to determine the thermal behavior of porous ultra low k dielectric materials.

The geometry (cross-section, layout) of the 4-pad test structure for the  $3\omega$  method is shown below (Fig. 1). A substrate is covered with the film to be measured. On top the test structure is fabricated.

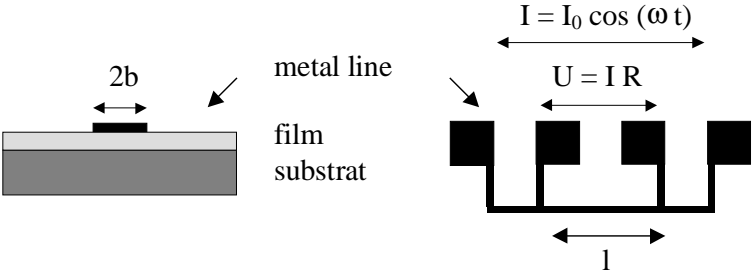


Fig. 1: Geometry of the 4 pad test structure for the  $3\omega$  method

Fig. 2 shows the schematic diagram of the measurement system of thermal conductivity. The control was realised using a PC with IEC-bus.

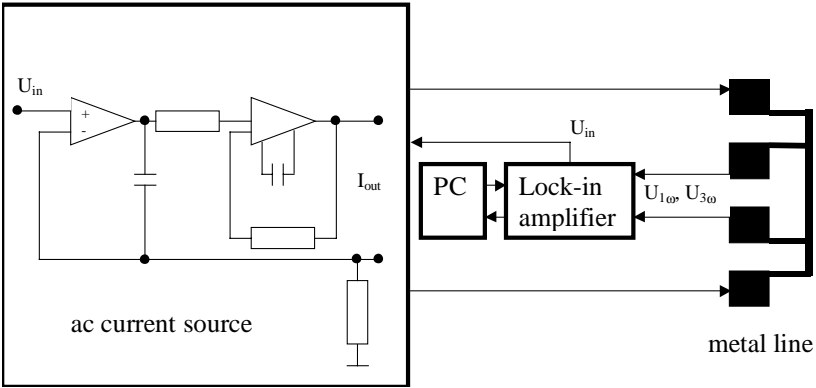


Fig. 2: Schematic diagram of the measurement system

The experimental technique was tested with glass substrate. The calibration was made by thermal estimation as given by Cahill. This equation  $\Delta T = P_1 / \pi \lambda [-0.5 \ln(2\omega) + 0.5 \ln(\lambda / \rho c_p b^2) + \eta]$ ,  $\eta = \text{const.}$  [5] is valid for the

substrate. In this simplest case, there is only the substrate. With the constant  $\eta$  the estimation can be fitted to the measurement.

With the equation  $\lambda = [V_{1\omega}^3 \ln(f_2/f_1)] \alpha / [4 \pi l R (V_{3\omega,1} - V_{3\omega,2})]$  [1] the thermal conductivity of the glass wafer  $\lambda = (1.18 \pm 0.07)$  W/mK (condition: 10 Hz / 3 Hz) is investigated. The accuracy of the measurement is good comparing the measured value with the one provided by the manufacturer (Corning 7740 Pyrex<sup>®</sup>)  $\lambda_{\text{pyrex}} = 1.13$  W/mK.

For a film-on-substrate sample, the total temperature rise at the heater is composed of two parts: one is the temperature rise in the substrate and the other one is the temperature drop across the film. If the metal line is wide compared to the thickness of the film, the heat flow in the film will be mainly in the cross-plane direction, and the film simply adds a frequency independent thermal resistance: ( $\Delta T_{\text{film}} = P_l d_{\text{film}} / (2b \lambda_{\text{film}})$ ) [5]. This approach requires that the thermal conductivity of the film must be much smaller than that of the substrate.

The temperature rise of silicon wafer covered with thermal oxide ( $\Delta T = 4 V_{3\omega} / (\alpha V_{1\omega})$ ) [1] was calculated depending on the frequency (fig. 3). The estimation corresponds with the measurement if it is calculated with a thermal conductivity  $\lambda_{\text{oxide}} = 1.4$  W/mK between 3 and 300 Hz. The thermal conductivity of the thermal oxide  $\lambda_{\text{oxide}} = (1.4 \pm 0.3)$  W/mK is in good agreement with the literature value of 1.4 W/mK [6].

Fig. 4 shows the thermal conductivity of thermal oxide thin films at a frequency of 3 Hz as a function of thickness. Similar results have been reported by some researchers (see [7], [8]). The thermal conductivity of the thermal oxide films above approximately 500 nm thickness agrees with the literature value of 1.4 W/mK of silicon dioxide [6]. For thermal oxide films below approximately 250 nm thickness, the observed thermal conductivity decreases as a function of film thickness, because the influence of the interface layer-substrate increases.

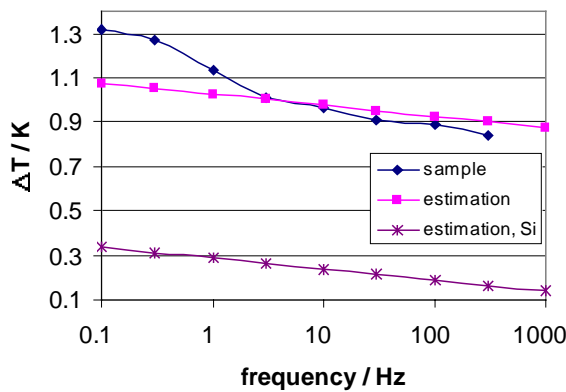


Fig. 3: Temperature rise of 1023 nm thermal oxide vs. frequency

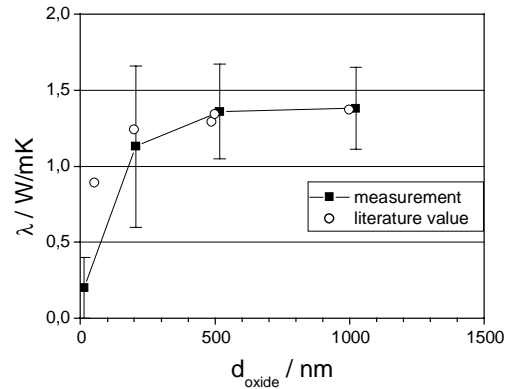


Fig. 4: Thermal conductivity of thermal oxide vs. oxide thickness

For a film-on substrate sample with cap layer, the total temperature rise at the heater is composed of three parts: the first is the temperature rise in the substrate, the second is the temperature rise in the cap layer and the third is the temperature drop across the film. First the cap layer is measured only on Si and then low k material with cap layer on Si. The temperature rise ( $\Delta T = 4 V_{3\omega} / (\alpha V_{1\omega})$ ) [1] was calculated depending on the frequency. The thermal conductivity of the low-k material was calculated from the difference between these measurements ( $\Delta T_{\text{film}} = P_l d_{\text{film}} / (2b \lambda_{\text{film}})$ ) [5]).

An example of low k material is porous silica aerogel (551 nm aerogel with 50 nm PECVD oxide) made with a R&D process at the Center of Microtechnologies ( $k \approx 2.1$ ,  $\rho \approx 0.8$  g/cm<sup>3</sup>,  $\approx 55\%$  porosity (EP = ellipsometric porosimetry)). The thermal conductivity of the aerogel was determined  $\lambda_{\text{aerogel}} = (0.13 \pm 0.03)$  W/mK. That means, the thermal conductivity of aerogel is by a factor of  $\approx 10$  smaller than thermal oxide.

## References

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