

THERMAL CHARACTERIZATION OF IC PASSIVATION LAYERS USING JOULE HEATING AND OPTICAL THERMOMETRY

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The temperature rise in microdevices is in many cases strongly increased by the thermal resistance of dielectric passivation layers. This problem is especially important for integrated circuits (ICs) containing novel low-dielectric-constant passivation, such as polymers and porous oxides. We report progress on developing a technique for measuring the thermal properties of these passive layers, which uses harmonic Joule heating in a metal line and compares solutions to the heat equation with a photothermal signal. This approach makes measurements possible over a wide range of heating frequencies and allows the thermal conductivity to be determined without calibration or precise knowledge of the heat capacity of the layer. Data are reported for the thermal conductivity of thermally grown silicon dioxide and polymer thin films.

Accurate simulations of temperature rises in microdevices, which are crucial for the interpretation of results of failure studies and for the development of guidelines for thermal design, require the use of reliable thermal property data for constituent materials. This is of particular importance for modern integrated circuits incorporating multilevel interconnects. Upper-level interconnects are separated from the substrate by thick passivation layers, which strongly impede thermal conduction cooling. The problem is becoming more acute with the emergence of a large number of new passivation materials with low dielectric constants, such as polymers and porous silicon dioxide, which reduce electrical capacitance and

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NOMENCLATURE

C	heat capacity per unit volume, $J/m^3 K$	x	coordinate in the out-of-plane direction, m
d	film thickness, m	β	ratio of film thickness to complex thermal diffusion depth [$= d_f(i2\pi f_h C_f/k_f)^{1/2}$]
f_e	effective heat diffusion frequency, which is the frequency at which the in-phase and out-of-phase components of temperature oscillations have the same amplitude, Hz	ΔT	temperature rise, K
f_h	heating frequency, Hz	Superscripts and Subscripts	
h	heat transfer coefficient, $W/m^2 K$	f	quantities pertaining to dielectric film
k	thermal conductivity, $W/m K$	m	quantities pertaining to metal film
q	heat generation rate per unit volume, W/m^3	ox	quantities pertaining to silicon dioxide film
R_B	thermal boundary resistance between metal and dielectric films, $m^2 K/W$	p	quantities pertaining to polymer film
w	width of measurement structure, m	SUBS	quantities pertaining to substrate

improve circuit operation speed. The thermal conductivities of these materials in thin film form have not been well characterized and can vary with processing conditions. Recent experimental studies [1, 2] indicate that the thermal conductivity of some of these materials can be an order of magnitude smaller than that of silicon dioxide, which is a common passivation material.

Several different techniques have been developed for measurements of the thermal conductivity of dielectric films. For an extensive discussion of this subject, readers are referred to review articles (e.g., [3]). Steady-state techniques measure or calculate temperatures at two different locations in thin films as well as the heat flux between them (e.g., [4–6]). Steady-state techniques can have the advantage of a simple data extraction procedure and measurement setup, but they require accurate measurements of the magnitudes of temperature rises and heat flux. Furthermore, specially designed measurement structures are often needed to reduce uncertainties resulting from substrate heating. Thermal conductivity and diffusivity have also been measured using transient techniques. One type of technique monitors the time evolution of temperatures in metal films, which are deposited on dielectric films and are subjected to pulsed heating. In the laser flash technique [7], the thermal conductivity is extracted by monitoring the shape rather than the magnitude of the temperature *decay* after the termination of laser pulses using high-temporal-resolution optical thermometry. This technique does not require heat flux measurements or the calibration of a temperature sensor but does require a high-power heating laser with a short pulse duration. In the electrical pulse technique [8], in contrast, the magnitude of the temperature rise during an electrical heating pulse is measured to extract thermal properties. Electrical measurements of small temperature rises at time scales comparable to a few microseconds, however, are difficult and require special care. Another type of transient technique induces periodic surface heating by applying ac current to a metal layer and captures oscillations in its temperature by monitoring the electrical resistance [9, 10]. This technique has been applied to thin films with thermal conductivities smaller than that of the substrate and performed at frequencies of

around several kilohertz where the heat diffusion depth in the film is very large compared with the film thickness.

We report recent progress on developing a thermal characterization technique that takes advantage of both the simplicity of electrical heating and the high temporal resolution of optical thermometry techniques. The ability to conduct measurements over a large range of time scales can be advantageous, since it allows control of the heat diffusion depth and substrate heating. The present study proposes and applies a thermal conductivity extraction method suitable for uniform, thermally thick dielectric films, which are grown or deposited on substrates with much higher thermal conductivity. This method uses the relative magnitude of temperature rises at frequencies high enough to have negligible substrate heating and thereby eliminates the need for calibration of the temperature amplitude.

EXPERIMENTAL SETUP AND PROCEDURE

We induce harmonic Joule heating in a metal line deposited on a dielectric film using a waveform generator. Harmonic heating is chosen rather than pulsed heating because the signal-to-noise ratio can be greatly enhanced using the lock-in technique. The resulting oscillations in the metal temperature are measured using the thermoreflectance technique, which has high temporal resolution (e.g., [11]). This thermometry technique is based on the temperature dependence of the surface reflectance and has been applied for the laser flash technique [7] and also for the thermometry of interconnects with submicrosecond resolution [12]. Since the change in surface reflectance is, to a good approximation, linearly related to that in the surface temperature, the relative magnitude of temperature changes can be obtained without calibration.

Figure 1 shows a schematic diagram of the experimental setup. A probe laser beam is reflected from the heated metal line and is directed to a photodetector. The electrical output from the photodetector is fed into a lock-in amplifier, which captures the harmonic component of the signal at the heating frequency. Interrogation at frequencies as high as 100 kHz is demonstrated, with possible extension in future work to a few megahertz. The peak frequency is limited by problems associated with electrical heating, such as voltage reflection and capacitive coupling [8].

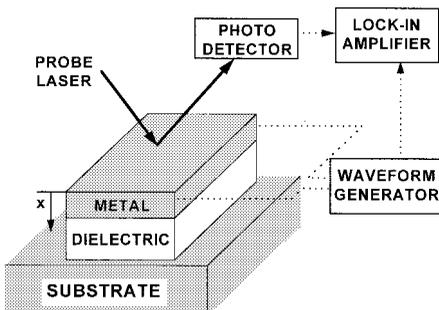


Figure 1. Experimental setup for the thermal conductivity measurement technique developed in this study. The quasi-one-dimensional measurement structure is designed to simplify the data analysis.

MEASUREMENT PRINCIPLE

Data analysis can be greatly simplified using a quasi-one-dimensional structure, such as the mesa structure depicted in Figure 1. The one-dimensional approximation is valid for the mesa structure when the Biot number for lateral conduction, which is defined as hw/k_f , is much smaller than unity. The thermal conductivity k_f of dielectric passivation layers of interest here is of the order of 0.1 W/m K, and the relevant heat transfer coefficient h is on the order of 10 W/m² K when natural convection or radiation is the dominant mechanism of heat loss to the ambient. The above condition therefore is well satisfied for mesa structures with width w less than 1 mm.

Under the one-dimensional approximation, the amplitude of temperature oscillations ΔT caused by harmonic Joule heating at the frequency f_h can be predicted by solving the heat conduction equation in the frequency domain:

$$i2\pi f_h \Delta T = \frac{k_i}{C_i} \frac{\partial^2(\Delta T)}{\partial x^2} \left(+ \frac{q}{C_m} \right) \quad (1)$$

The last term in parentheses is nonzero only in the metal, and the thermal properties of the metal and dielectric films are assumed to be constant. The real and imaginary parts of ΔT in the above equation correspond to the components of temperature oscillations in phase and out of phase with the harmonic heating, respectively.

The heating frequency is assumed to be sufficiently high that the temperature rise in the substrate can be neglected compared with that in the metal line. The lower bound of the heating frequency at which this assumption is valid depends on the thickness and thermal properties of the dielectric film. If we further assume that the metal line is isothermal at the temperature ΔT_m and direct heat loss to the ambient from the metal and dielectric films is negligible, a simple analytic expression for ΔT_m can be derived:

$$\frac{\Delta T_m}{q} = \frac{d_m \left[(d_f/k_f)(\tanh \beta/\beta) + R_B \right]}{1 + i\omega C_m d_m \left[(d_f/k_f)(\tanh \beta/\beta) + R_B \right]} \quad (2)$$

where β is a complex number representing the ratio of the film thickness to the thermal diffusion length, $d_f(i2\pi f_h C_f/k_f)^{1/2}$, and R_B is the thermal boundary resistance at the interface between the metal and dielectric films. The thermal boundary resistance at the interface between the dielectric film and the substrate is not included for the sake of simplicity. The thermal boundary resistances at the two interfaces would not alter the final results of thermal property extraction significantly unless they are comparable with or larger than the internal thermal resistance, d_f/k_f . Typical measured values of the thermal boundary resistance between a metal and a dielectric layer is of the order of 10^{-8} m² K/W at room temperature [13], while the internal resistance of a 1- μ m-thick silicon dioxide layer is of the order of 10^{-6} m² K/W. In some cases, thermal boundary resistance can

become much larger, due, for example, to incomplete contact between the layers. By enabling measurements over large frequency ranges, the present technique offers an opportunity to study the thermal boundary resistances at each interface, whose influences on the temperature rise differ depending on the interrogation frequency. Unless thermal boundary resistance accounts for a significant fraction of the total thermal resistance, however, simultaneous determination of the thermal properties of the film and the thermal boundary resistance can be difficult.

When the heat capacity C_f is known with sufficient accuracy and the effect of thermal boundary resistance is negligible, the thermal conductivity k_f can be extracted from the *relative* magnitude of temperature rises alone using Eq. (2) or its equivalent. The heat capacity, after being adjusted for porosity, is generally not strongly dependent on the microstructure of a given material, and a bulk value can be used as a good approximation for thin films [3]. Furthermore, increasing the thermal mass of the metal line diminishes the relative impact of uncertainty in the film heat capacity on the extracted thermal conductivity. This is because the amplitude of temperature oscillations is much more sensitive to k_f than to C_f when the thickness-to-thermal diffusion depth ratio β , which is a function of the heating frequency, is small compared to unity. For a dielectric film with thermal conductivity around 0.2 W/m K, 20% uncertainty in the heat capacity leads to less than 5% uncertainty in the extracted thermal conductivity when the thickness of the metal film is half as large as that of the dielectric film.

A particularly convenient way to extract the thermal conductivity of uniform, thermally thick layers is to monitor the frequency f_e , at which the amplitudes of the in-phase and out-of-phase components of harmonic temperature oscillations per unit heat generation rate coincide. The frequency f_e , which will hereafter be called an effective thermal diffusion frequency, depends on the thermal mass of the metal film, $C_m d_m$, as well as the thickness and thermal properties of the dielectric layer. Figure 2 plots the effective heat diffusion frequency as a function of dielectric film thickness and thermal conductivity. Values typically encountered in practice are used for the heat capacity and thickness of the dielectric and metal layers.

The present technique can also be used for the simultaneous determination of the thermal conductivity and heat capacity of a dielectric layer by employing a very thin metal layer. Data at high heating frequencies now become sensitive to both the heat capacity and the thermal conductivity of the dielectric layer. The calibration of the thermoreflectance thermometry is needed in this case, which can be performed using, for example, a two-step calibration procedure developed by the authors [12]. When the effect of thermal resistance is negligible, the thermal conductivity can be extracted independently using data at frequencies well below the heat diffusion frequency. At this low frequency, heat transport across the dielectric film contributes a nearly frequency-independent component to the temperature rise in the metal, a fact that forms the basis of the 3ω technique [9].

SAMPLE PREPARATION

The silicon dioxide sample is fabricated through wet thermal oxidation of a silicon wafer, which yields a 1.56- μm -thick oxide layer. A 0.25- μm -thick aluminum

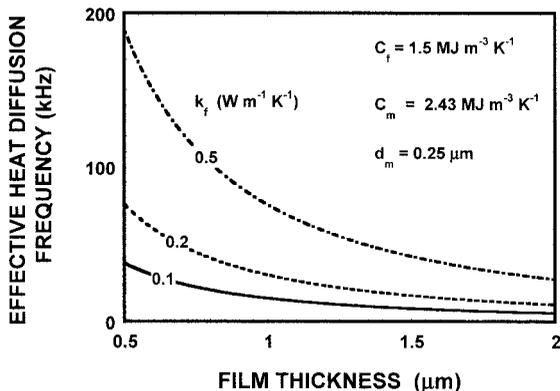


Figure 2. The frequency at which the in-phase and out-of-phase components of the temperature oscillations have the same amplitude as a function of film thickness. Relevant parameters are shown in the plot. The thermal boundary resistance is neglected.

layer is subsequently deposited using the sputtering process. The silicon dioxide and aluminum layers are patterned using anisotropic dry etching, resulting in a mesa structure as shown in Figure 1.

To fabricate the polymer samples, commercially available benzophenone tetracarboxylic acid dianhydride (BTDA-ODA-MPD) polyamic acid precursor (DuPont PI 2556) is first cast on adhesion promoter-coated silicon wafers and spin-coated to yield polyamic acid films. The thickness of the polymer films is varied from 0.5 to 2.5 μm by changing the rotational speed of the spinner. The polyamic films are cured in a nitrogen atmosphere by heating samples from room temperature to 375°C at a rate of 7°C/min, holding them at 375°C for 1 h, and letting them cool down to room temperature in air. A 150-nm-thick plasma-enhanced CVD (PECVD) silicon nitride layer is deposited on the sample surface to protect the polymer films from moisture absorption and to enhance adhesion of metallization used for the thermal conductivity measurement. The aspect ratio of the measurement structure is less than 0.02 for all the polymer samples studied. The thickness of the films is measured using a surface profilometer and also a laser interferometer for the case of dielectric films. The difference between the two measurements for the dielectric films is less than 2%.

MEASUREMENT EXAMPLES

The technique is first applied to the thermally grown silicon dioxide film, whose thermal properties are relatively well known (e.g., [5, 7, 8]) and are very close to the bulk values. Figure 3 shows the measured frequency dependence of the in-phase component of the temperature oscillation together with the predicted behavior. Each in-phase component is normalized by its value at 100 kHz. The

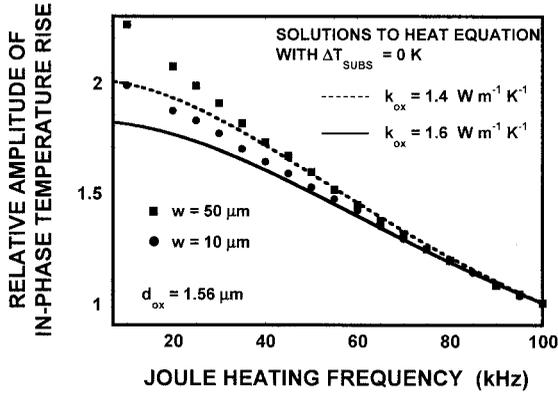


Figure 3. Frequency dependence of the amplitude of the in-phase component of temperature oscillations in a metal line deposited on a silicon dioxide layer. The metal line is subjected to periodic Joule heating.

heat-generation rate is maintained at a fixed value throughout the entire experiment. The predictions assume negligible substrate heating and use the bulk value for the heat capacity. Systematic deviation of the data from the predictions at low frequencies arises from the substrate heating. Less discrepancy is observed for the narrower structure because spreading of heat inside the silicon substrate is more efficient in suppressing the substrate heating. The impact of substrate heating is estimated to be less than 1% at frequencies higher than 50 kHz. Comparison of the data at these frequencies with the solutions to the heat equation given in Eq. (2) yield the thermal conductivity of 1.5 ± 0.15 W/m K. This is close to the bulk value of fused silica, which is consistent with previous studies.

Figure 4 shows a similar plot for the 0.5- μm -thick polymer sample. The impact of substrate heating is less pronounced due to the smaller thermal conductivity of the polymer layer. Assuming that the thermal boundary resistance is much smaller than the internal thermal resistance, the thermal conductivity is extracted to be 0.22 W/m K from the measured effective heat diffusion frequency. The extracted thermal conductivity does not vary by more than 5% when a thermal boundary resistance as large as 1×10^{-7} m² K/W is assumed to be associated with the nitride-polymer and polymer-substrate interfaces. The high-frequency data agree well with the solution of the heat equation using the value just obtained for the thermal conductivity. The heat capacity used for the polymer layer is that of bulk samples with the identical molecular composition [14], and the thermal properties of the PECVD nitride layer used are those of [10]. The impact of uncertainties in the heat capacity of the polymer layer and in the thermal properties of the nitride layer on the extracted thermal conductivity is found to be small. Varying the heat capacities of the two layers by as much as 20% results in less than 5% change in the deduced thermal conductivity.

For the thicker polymer layers, the temperature rise in the metal becomes more sensitive to the polymer heat capacity. Following a procedure similar to the

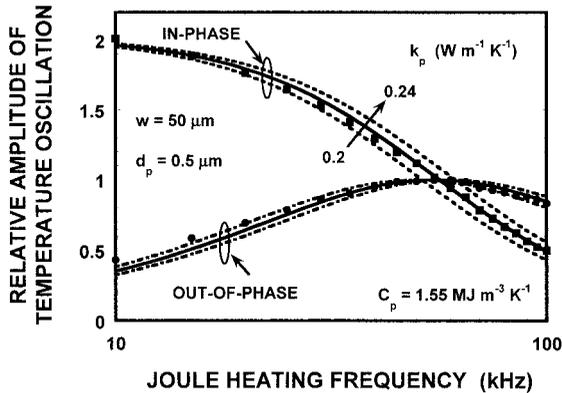


Figure 4. The amplitude of the in-phase and out-of-phase components of temperature oscillations in the metal line on the 0.5- μm -thick polymer sample.

one developed for the 3ω technique [9, 10], the thermal conductivity of the polymer layer is first extracted from the data at frequencies near 1 kHz neglecting the thermal boundary resistance. By comparing the data at much higher frequencies with solutions to the heat conduction equation, the heat capacity of the polymer layer is subsequently obtained and is shown to be close to the bulk value.

Figure 5 shows the measured thermal conductivities of the polymer films with different thicknesses. Also shown is a result from a steady-state thermal conductivity measurement, which shows reasonable agreement with the present data. The steady-state measurement employs a one-dimensional mesa structure in which a polymer layer is placed between two aluminum layers serving as a thermometer and/or a heater, an approach similar to that of [4, 6]. The thermal conductivity remains roughly constant within the uncertainty limit for the layers studied here. Due to the unique fabrication process involved and limitation on the available equipment, polymer layers with thickness less than 0.5 μm were not investigated in the present study.

This study also examines the impact of nitride capping layers, which are intended to prevent moisture absorption by the polymer film. The thermal conductivity is observed to increase slightly when the nitride layer is removed, which is consistent with the observation that moisture uptake by relatively thick polymer layers raises their thermal conductivity [15].

In summary, a new thermal characterization method employing an optical thermometry technique with high temporal resolution is developed and applied to polymer passivation layers with submicrometer thickness. The measured thermal conductivity remains nearly constant with thickness and is somewhat larger than the typical bulk value [14]. Protective nitride layers are found to influence the polymer thermal conductivity, presumably by a mechanism related to the moisture content of the polymer layer.

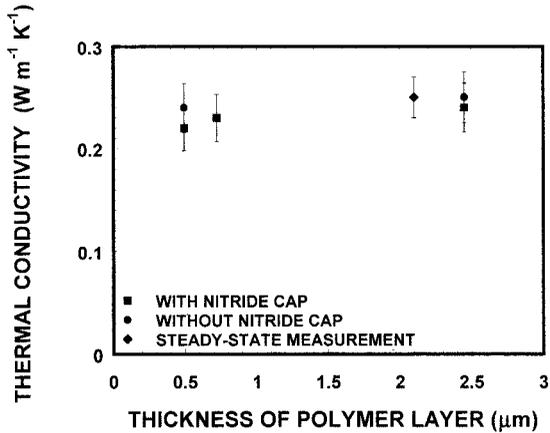


Figure 5. The thermal conductivities of the polymer thin films as a function of thickness. The result from a steady-state thermal conductivity measurement is also shown for comparison. For some of the samples, the silicon nitride capping layer, which serves to protect the polymer layer from moisture absorption, is removed except for the portion beneath the metal line.

Various extensions of the present technique can be suggested. Two-dimensional effects can be utilized to investigate anisotropy in thermal conductivity using metal heating lines of varying widths or multiple heating lines. The capability of the optical thermometry to capture local temperature rises also offers opportunities to study spatial variations and anisotropy in thermal properties. The technique can be applied to thermally thin films, for which substrate heating is significant even at relatively high frequencies, as an extension of the 3ω technique [9]. Measurements at high frequencies in this case would be helpful by providing additional leverage on the volume of the heat-affected region and thus reducing the uncertainty resulting from substrate effects.

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