

# Annealing-Temperature Dependence of the Thermal Conductivity of LPCVD Silicon-Dioxide Layers

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**Abstract**—The reliability and performance of electronic circuits are influenced by heat conduction in low-pressure chemical-vapor-deposited (LPCVD) silicon dioxide layers. This work measures the effective thermal conductivity  $k_{\text{eff}}$  for conduction normal to films of LPCVD silicon dioxide layers as a function of annealing temperature, as well as for films of thermal and SIMOX oxides. The LPCVD oxide thermal conductivity increases by 23% due to annealing at 1150°C. The conductivities  $k_{\text{eff}}$  of LPCVD layers of thicknesses between 0.03 and 0.7  $\mu\text{m}$  are higher than those reported previously for CVD layers, and vary between 50% and 90% of the conductivities of bulk fused silicon dioxide. The values for SIMOX and thermal oxide layers are within the experimental error of the values for bulk fused silicon dioxide.

## I. INTRODUCTION

HEAT conduction normal to oxide layers is important in silicon integrated circuits because it determines the temperature of metal interconnect lines at “burn-in” and operation conditions. It also influences the interconnect and silicon film temperatures in emerging SOI applications. The parameter of interest is the effective thermal conductivity normal to the  $\text{SiO}_2$  layer,  $k_{\text{eff}}$ . Few data for  $k_{\text{eff}}$  of  $\text{SiO}_2$  are available in the literature. This work presents  $k_{\text{eff}}$  data obtained using an accurate method for undoped LPCVD, thermal, and SIMOX  $\text{SiO}_2$  films on silicon.

## II. MEASUREMENTS

Undoped silicon-dioxide layers of different thicknesses were grown using low-pressure chemical vapor deposition (LPCVD) at 400°C on silicon substrates by the reaction of  $\text{SiH}_4$  with  $\text{O}_2$ . Samples were also annealed at different temperatures for 30 min. Additional oxide layers were

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also obtained by thermal oxidation in pure  $\text{O}_2$ , and by stripping the surface silicon film of SIMOX wafers. All layer thicknesses were measured by ellipsometry near the thermal conductivity test structures.

The measurement technique was developed by Goodson *et al.* [1], [2] based on the method of Swartz and Pohl [3]. A cross section of the test structure is shown in Fig. 1. Three parallel Al lines (bridges) of 2 mm length are patterned on the oxide film to be measured. The central bridge half-width  $w$  is 2.5  $\mu\text{m}$ , and the bridge separations are  $x_C = 7.5 \mu\text{m}$  and  $x_D = 17.5 \mu\text{m}$ . The three bridges are all electrical-resistance thermometers. Bridge A measures  $T_A$  and carries a large current density, allowing it to serve also as a heater. It sets the substrate temperature  $T_B$ . Bridges C and D carry very small current densities, resulting in negligible self-heating, so that they measure  $T_C$  and  $T_D$  in the substrate, respectively. The temperature difference  $T_B - T_C$  is obtained by analyzing heat conduction in the substrate [1]. Comparison of the predicted and measured values of  $T_C - T_D$  yields an estimate of the uncertainty due to the approximations in the heat-conduction analysis. If  $P$  is the power and  $L$  the length of bridge A, the layer thermal resistance  $R_T$  of the oxide film is

$$R_T = \frac{d}{k_{\text{eff}}} = B \frac{T_A - T_B}{(P/2Lw)}. \quad (1)$$

Using  $B = 1$  assumes one-dimensional conduction in the sample layer. The present work uses an expression for  $B$  which accounts for two-dimensional conduction derived by Goodson and Flik [4]. The parameter  $B$  depends only on the ratio  $2w/d$ , and approaches unity as this ratio increases. The largest value of  $B$  for the present work is 1.084, for  $2w/d = 7$ .

An expression for the experimental uncertainty was given by Goodson *et al.* [1], [2]. The relative uncertainty in  $R_T$  is found to be very similar for measurements yielding the same value of  $R_T$ . For  $R_T \sim 5 \times 10^{-7}$ ,  $1.5 \times 10^{-7}$ , and  $0.5 \times 10^{-7} \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ , the relative uncertainty is approximately 8%, 11%, and 22%, respectively. The uncertainty is dominated by the uncertainty in the measured temperature derivative of the electrical resistance of bridge A. For the thinnest layers, where  $T_B - T_C$  can be comparable to  $T_A - T_B$ , the uncertainty due to the thermal analysis is also significant.

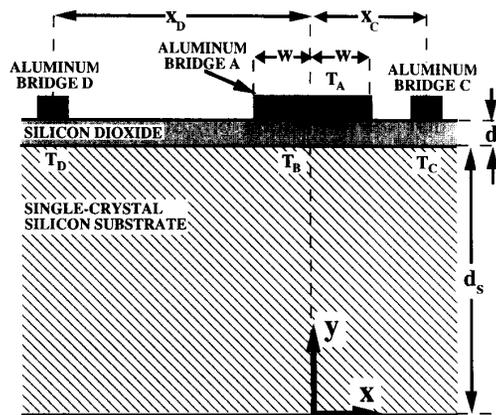


Fig. 1. Cross section of the thermal conductivity measurement test structure.

### III. THERMAL ANALYSIS

The experimentally measured effective conductivity  $k_{\text{eff}}$  is reduced by thermal resistances at the layer boundaries. A useful model assumes that the thermal boundary resistances are in series with a volume resistance internal to the layer,  $d/k_{\text{int}}$ . In this model, the total thermal resistance is

$$R_T = \frac{d}{k_{\text{eff}}} = \frac{d}{k_{\text{int}}} + R_B \quad (2)$$

where  $R_B$  is the sum of the thermal boundary resistances at both boundaries. Equation (2) is not valid for very thin layers or at low temperatures where phonons can have free paths that are comparable to the layer thickness. However, at room temperature, the short mean free paths of phonons in amorphous silicon dioxide make this a problem only when the layers are thinner than about 10 nm [1], [2].

The present work interprets the data in Fig. 2, discussed below, using (2) and the following assumption: the layer microstructure and interfacial properties that govern  $k_{\text{int}}$  and  $R_B$ , respectively, depend on the processing conditions, e.g., the annealing temperature, but *not* on the layer thickness. This assumes that the distance over which the boundaries influence the microstructure within the layer is small compared to the smallest layer thickness, which is near 40 nm. This allows  $k_{\text{int}}$  and  $R_B$  to be determined at a given annealing temperature using data for the thickness-dependent thermal resistance and (2). This assumption is consistent with the dependencies of  $R_T$  on  $d$  measured here. Section IV shows that on a plot of  $R_T$  as a function of  $d$ , all of the data for  $R_T$  of LPCVD  $\text{SiO}_2$  for a given annealing temperature can be linearly fitted within the experimental uncertainty.

### IV. RESULTS AND DISCUSSION

Fig. 2 shows the values of  $k_{\text{eff}}$  measured here for layers annealed at different temperatures. The highest process-

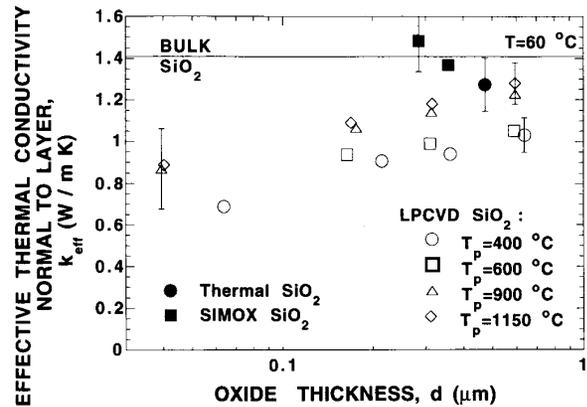


Fig. 2. Effective thermal conductivity of SIMOX, thermal, and LPCVD oxides.  $T_p$  refers to process temperature of the LPCVD oxides.  $T_p = 400^\circ\text{C}$  identifies as deposited films.

ing temperature is denoted by  $T_p$ , and the unannealed layers are denoted by  $T_p = 400^\circ\text{C}$ . Fig. 2 also shows  $k_{\text{eff}}$  data measured here for thermally grown oxide and SIMOX layers, which agree closely with the thermal conductivity of bulk  $\text{SiO}_2$ . The agreement of the SIMOX and thermal oxide data with the bulk conductivity is in stark contrast to all of the existing data for silicon dioxide layers fabricated using other techniques. This agreement for SIMOX layers is supported by the agreement of SOI MOSFET channel temperature data with predictions that use the bulk conductivity for the SIMOX layers.

The present data show that  $k_{\text{eff}}$  increases with thermal processing temperature  $T_p$  at a given layer thickness. The low experimental uncertainty allows the data to demonstrate this conclusively for  $T_p = 1150^\circ\text{C}$  and  $T_p = 400^\circ\text{C}$ . Fig. 3 shows the dependence of the layer thermal resistance on thickness and  $T_p$  for the LPCVD oxides. The lines in this figure are linear regressions of the data for a given value of  $T_p$ , and are used in (1) to determine  $k_{\text{int}}$  and  $R_B$ , which are given in the figure caption.

The local thermal conductivity within the layer may decrease near the layer-substrate interface. This is checked by estimating the local conductivity far from the substrate-layer interface, which is approximately the inverse of the slope of the line segment connecting the rightmost two data points for a given annealing temperature in Fig. 3. For each case, this yields a local conductivity which is slightly larger than  $k_{\text{int}}$ , by between 2% and 8%. This may be due to a porosity which decreases with increasing  $y$ , but the difference between the largest local conductivity estimated in this way and  $k_{\text{int}}$  is less than the experimental error in  $k_{\text{int}}$  for each case.

The  $k_{\text{eff}}$  data measured here are larger for a given thickness than those reported previously [5]–[7]. The differences between our data and those of Lambropoulos *et al.* [6] could be explained in terms of both the difference in deposition technique (ion and electron beam sputtering versus our LPCVD), as well as the large experimental uncertainty in their measurements. The experimental

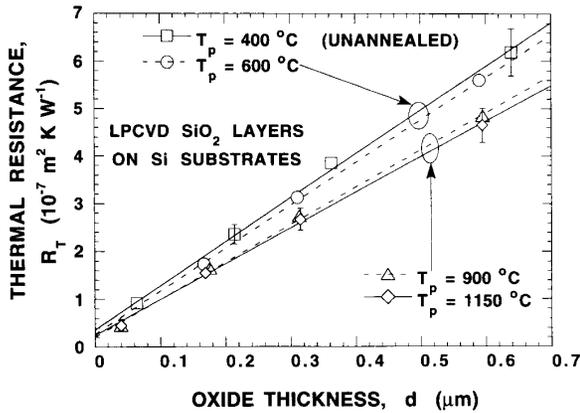


Fig. 3. Thermal resistance data for conduction normal to the oxide layers. The lines are linear regressions of the data for each value of  $T_p$ , which yield  $k_{\text{int}}$  and  $R_B$ . These values for  $T_p = 400, 600, 900,$  and  $1150^\circ\text{C}$  are:  $k_{\text{int}} = 1.08, 1.11, 1.28,$  and  $1.34 \text{ W/m} \cdot \text{K}$  with uncertainty of  $\pm 0.10 \text{ W/m} \cdot \text{K}$ ; and  $R_B = 0.36, 0.27, 0.21$  and  $0.25 \times 10^{-7} \text{ m}^2 \cdot \text{K/W}$  with uncertainty of  $\pm 0.12 \times 10^{-7} \text{ m}^2 \cdot \text{K/W}$ .

technique of Schafft *et al.* [7] and Brotzen *et al.* [8] is similar to that used here because they also employed a thin-layer bridge to heat the sample layer. But these authors determined  $T_B$  using heat-conduction analysis and the measured temperature at the *bottom* of the substrate. The temperature difference from the top to the bottom of the substrate is always much larger than  $T_B - T_C$ , so that the approximations in the heat-conduction analysis used by these techniques are much more important than those employed in our technique, particularly as the  $\text{SiO}_2$  layer thickness decreases. The influence of these approximations on the accuracy of the data of Brotzen *et al.* [8] needs to be assessed, particularly for very thin

layers, where the temperature drop in the substrate is significant compared to that in the silicon dioxide. But the large differences between the data of the present work and those of Brotzen *et al.* [8] for PECVD silicon dioxide indicate that the fabrication process has a strong influence on the conductivity of  $\text{SiO}_2$  layers. The 4 mass percent of dopant atoms in the LPCVD layers of Schafft *et al.* [7] may account for the lower values of the conductivities of these layers compared to the conductivities of the undoped layers of the present work.

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