Silicon-carbide-enhanced thermomigration

Masoud Abbasi
Department of Mechanical Engineering, The University of Utah, Salt Lake City, Utah 84112

Torbjorn Johansson
Department of Electrical Engineering, The University of Utah, Salt Lake City, Utah 84112

Richard A. Normann[a)]
Department of Bioengineering, 2480 Merrill Engineering Building, University of Utah, Salt Lake City, Utah 84112

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The widespread acceptance of thermomigration technology to produce through-chip interconnects has been impaired by (i) a random walk of the Si-Al liquid eutectic inclusion as it traverses the wafer, and (ii) a "surface barrier" which allows thermomigration of only relatively large inclusions. In this paper it is shown that these problems can be mitigated by thermomigrating at high wafer temperatures and with large temperature gradients through the wafer. It has been possible to achieve these high wafer temperatures and large gradients using a bank of infrared lamps and a bilaminar structure of silicon carbide powder compressed onto the top of a silicon wafer. This increases the delivery of energy to the wafer and reduces the random walk of the liquid inclusion. Further, the high wafer temperatures and enhanced temperature gradients created with this bilaminar silicon carbide structure allow relatively small, square aluminum pads (35 μm on a side) to thermomigrate through a 16-mil-thick silicon wafer.

I. INTRODUCTION

As the semiconductor industry and the technology of high-performance parallel processing continue to mature, methods for producing functional 3D circuit architectures have become increasingly important. The complexity of the parallel processing circuitries produced today suggests that more efficient methods for building 3D structures should be investigated in this area. Conventional two-dimensional very large-scale integrated (VLSI) circuitry can be used to achieve relatively simple parallel processing architectures. However, as the computing complexity is augmented by additional parallel channels, the interconnects between the channels quickly become unwieldy and the benefits that accrue from the use of a "true" 3D architecture warrant its development.

One example where a true 3D architecture could be profitably used is in the emerging field of analog neural networks. As the complexity of the analog neural networks is enhanced, more interconnects between cells are needed. For simple neural networks in the planar silicon processing technology, the multimetal and polycrystalline layers can serve as interconnects. An integrated circuit realization of a 64 input, 64 output recursive neural network containing at least one hidden layer would have to devote a large fraction of its total silicon area simply to interconnect traces between the nodes. However, as the neural networks are made more complex the multilayers may not be sufficient enough for all the needed interconnects in a specific design. A 3D architecture with a laminar structure of silicon wafers with interconnects through and between wafers will provide more interconnects enabling the design of more complex neural networks.

Another application where a 3D architecture could prove valuable is in data acquisition and signal processing from 2D sensor arrays. 3D architectures have been investigated in the area of chemical and neurophysiological sensing where the sensors need to be both electrically and chemically isolated from the signal processing circuitry.[1,2] A true 3D architecture could also provide large dividends in "intelligent" sensing, the application which provided the impetus for this study. Photodetector arrays that not only transduce incident stimuli, but also preprocess transduced signals before they are sent to other systems have already been described.[3,4] These first-generation "silicon retinas" provide automatic gain control for each photodetector and also achieve a high-pass spatial filtering operation over all the photodetectors. These signal preprocessing features release the computational demands placed on subsequent systems, but they "consume" large amounts of "real estate" on the silicon retina. The biological counterpart of the silicon retina achieves its signal processing using a 3D lamellar architecture. A sheet of photoreceptors is placed on top of additional sheets of neurons that operate on the output signals of the photodetectors. A 3D silicon version of this architecture would place various signal processing functions on separate layers beneath a layer of photodetectors.

While there are abundant reasons to develop a true 3D parallel processing architecture, few attempts to achieve this goal have been made.[5,6] One approach, developed in the late 1970s by Cline and Anthony,[7-10] uses the "thermomigration" technique to produce a set of through-chip interconnects that allow signals and power to pass through a silicon wafer from one surface to the other. A 3D computer has been successfully developed using the thermomigration technique as interconnects through a stack of silicon wafers.[11]

[a)]Author to whom correspondence should be addressed.

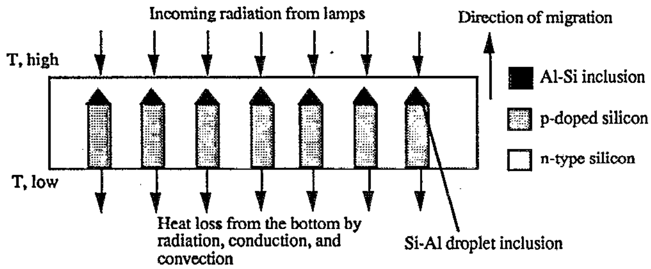


FIG. 1. A block of silicon during the thermomigration process.

In this technique, a large number of Al-doped p-type columns can be selectively created through an n-type silicon wafer. These columns are formed from aluminum pads deposited on one side of a wafer. The wafer is heated to a high temperature (1100 °C typically via infrared radiation from "heat lamps") from the opposite side and a liquid zone (Al+Si) migrates through the wafer in the direction of the imposed temperature gradient (Fig. 1).

While thermomigration can produce through-chip interconnects, several problems exist with this method that have limited its widespread use. Thermomigration columns (p-type) form diodic isolation in the n-type substrate and, therefore, they are subject to current leakage to the substrate when a potential difference is imposed across the p-n junction. A relatively high resistivity and high junctional capacitance of the thermomigration columns are additional disadvantages associated with this method.[12] Further, previously published results suggest that thermomigration of aluminum square pads smaller than 175 μm may be difficult to achieve.[9] This places a severe constraint on the use of this process since interconnects of this size have very few applications in VLSI circuit designs.

Yet another difficulty with the thermomigration process is a "random walk" of the liquid zones which takes place in various directions as the aluminum droplets pass through the silicon wafer.[13] In this paper we shall show that the degree of random walk can be decreased by increasing the rate at which the aluminum migrates through the wafer. During the thermomigration process, the liquid zone has two velocity components, one along the temperature gradient axis and the other orthogonal to this direction. Thus, if the velocity component along the temperature gradient axis can be increased, the velocity component normal to the temperature gradient will participate less and produce a smaller degree of random walk.

The expression below shows the rate of thermomigration as a function of the major parameters of the process:[7,9]

$$V=\frac{D_0 e^{-Q/RT}}{(1-X)}\left(\frac{\partial X}{\partial T}\right)\nabla T, \tag{1}$$

where V is the velocity of the droplet in silicon (cm/s), D_0 the diffusion coefficient (8×10^{-4} cm^2/s), Q the heat of fusion of Si (46.92 kJ/g mol), R the gas constant (0.008 314 kJ/g mol K), T the temperature (K), X the atomic fraction of silicon in liquid, $\partial X/\partial T$ the atomic fraction change with respect to temperature (1/K), and ∇T the temperature gradient through the wafer (K/cm). Equation (1) shows that the velocity of the liquid zone is strongly temperature and temperature gradient dependent. One can increase the velocity of the liquid zone in the thermomigration process by increasing the average temperature of the wafer, by increasing the temperature gradient through it, or by increasing both. This paper describes an enhancement of the thermomigration process using a method that increases the absorption of radiant energy and, therefore, mean wafer temperature during the thermomigration process.

Since silicon is virtually transparent to long-wavelength infrared radiation,[14] a significant portion of the energy from the radiation source (tungsten halogen lamps), is transmitted through the wafer without being absorbed. That which is absorbed is absorbed more or less uniformly through the wafer and contributes only slightly to the temperature gradient. In order to increase the energy absorption, silicon carbide powder (1000 mesh grit) was compressed onto the upper surface of the wafer. Due to the high absorptivity[15] and thermal conductivity[16] of silicon carbide, a higher mean wafer temperature as well as an increased temperature gradient is produced through the wafer.

By increasing the average temperature of, and the temperature gradient through, a silicon wafer during the thermomigration process, we have reduced the extent of random walk of the thermomigrated aluminum pads by a factor of 3. Further, the high wafer temperatures and steep temperature gradients produced have allowed us to thermomigrate 35 μm square pads through a 16-mil-thick silicon wafer.

II. METHODS, MATERIALS, AND INSTRUMENTATION

One-side-polished, n-type silicon wafers, ⟨100⟩ crystallographically oriented, 10 Ω cm (Virginia Semiconductors, Fredericksburg, VA), with diameters and thicknesses of 2 in. and 16 mils, respectively, were cleaned by a hydrogen-peroxide-based wafer cleaning method.[17] A 3-μm-thick layer of aluminum was evaporated onto the polished surface of the wafer. Photolithographic techniques were then applied to create arrays of square aluminum pads with dimensions of 20, 35, 50, 75, 100, 140, and 170 μm on the polished side of the wafers.

Silicon carbide powder (approximately 0.7 g of 1000 mesh grit), was distributed over and uniformly covered the rough surface of the wafer. 25 kg of mass was applied to a 1-in.-thick, 3-in.-diam steel disk to compress the powder against the surface of the silicon wafer in order to enhance the contact between the powder and the wafer producing an approximately 27-mil-thick layer of silicon carbide powder on the silicon wafer.

The coated wafer was then heated for 1.5 h in a custom-made oven. The oven has two compartments, a 7.2 kW infrared source and the oven chamber. The lamp housing (model no. 5208-05, Research Inc., Minneapolis, MN) consists of six, 6-in.-long, 145 V tungsten halogen lamps. The housing is cooled by water and the lamps by forced air. The wafer sits on three quartz pins (1 mm high) at the center of the oven chamber approximately 1.5 cm below the lamps. Therefore, the wafer is heated on its top surface by means of infrared radiation while it is simultaneously cooled from the other surface by emission (reradiation), conduction, and convection (Fig. 1).

To visualize the results of the thermomigration process, the thermomigrated patterns were stained with a p^+-stain solution (99% HF and 1% HNO_3) which was applied to the rough surface of the wafer. This caused the thermomigrated areas to appear darker than the substrate (Fig. 2).

III. RESULTS

In order to investigate the extent of "random walk" and its dependency on the velocity of the liquid droplet, the mean temperature of, and the temperature gradient through, the wafer was determined by measuring the wafer's top and bottom temperatures during the thermomigration process. Surface temperatures were determined from silicon dioxide growth rate. These determinations were then confirmed with a special wafer that contained a thermocouple.

A. Wafer surface temperatures

The thickness of the silicon dioxide layer formed when a wafer is heated in an oxidizing atmosphere is a function of wafer temperature and the duration of the heating cycle. Deal and Grove[18] have quantified the silicon dioxide thickness with the following equation:

$$x_0^2=B_0\, te^{-E_a/kT}, \tag{2}$$

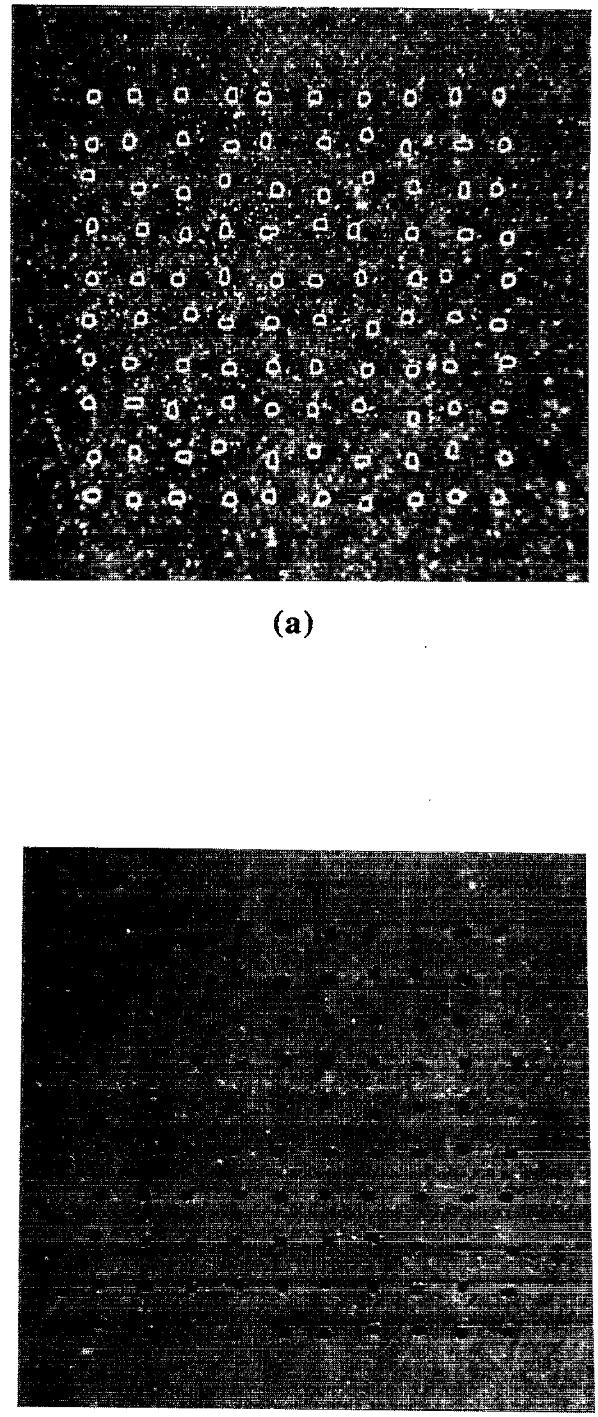
where x_0 is the thickness of the oxide layer (μm), B_0 the preexponential rate constant (μm^2/h), t the time of process (h), E_a the activated energy (1.24 eV), k the Boltzmann constant (8.62×10^{-5} eV/K), and T the temperature (K).

A 16-mil-thick, 2-in.-diam, ⟨100⟩ crystallographically oriented, double-side-polished silicon wafer was heated for 1.5 h in the thermomigration oven at the lamp voltage used for most of our thermomigration procedures (155 V). The average thicknesses of the oxide layers on both surfaces of the wafer were determined by ellipsometry. This process was performed on two wafers.

A double-side-polished wafer was used to measure the film thicknesses. While there is a difference between the emissivity of a polished and a rough surface, it was assumed that at high temperatures (above 1000 °C) the emissivity of both surface textures is very similar.

Equation (2) was solved for upper and lower surface temperatures, and the average temperatures were calculated at various loci on both surfaces. The oxide layer measurements and the corresponding calculated surface temperatures of the two wafers are presented in Table I.

These same measurements (lamp voltage setting and the duration of the heating cycle) were performed on another two silicon wafers that had identical specifications but that had a layer of silicon carbide powder compressed onto their upper surfaces. In order to make the measurements in the presence of the silicon carbide powder, a 1.5-mm-wide swath of the powder was removed from the center to the edge of the wafer. This allowed exposure of the silicon surface to air for oxidation. The results with these wafers are also presented in Table I, which illustrates that the silicon carbide coating produces a pronounced increase



(a)

(b)

FIG. 2. Random walk at average wafer temperatures of (a) 950 °C and (b) 1200 °C, for an array of 100, 100 μm aluminum pads with an edge-to-edge spacing of 300 μm.

TABLE I. The effect of silicon carbide on wafer temperatures during the thermomigration process. A comparison among four silicon wafers of top and bottom surface temperatures estimated from oxide layer growth. Also shown are average wafer temperatures, and temperature gradient through wafers, with and without SiC powder. All wafers were heated at a lamp voltage of 155 V for 1.5 h. SiC powder produces a higher average wafer temperature as well as a larger temperature gradient through the wafers.

	Without SiC				With SiC			
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
SiO_2 (Å)	1368	1290	1411	1321	2466	1937	2421	1892
Temperature (°C)	1089	1074	1097	1080	1260	1185	1254	1178
Average temperature (°C)	1082		1088		1222		1216	
Temperature gradient (°C/mil)	0.94		1.06		4.69		4.75	

in the average wafer temperature as well as the temperature gradient through the wafer.

To validate these measurements, an instrumented wafer (SensArray Co., Santa Clara, CA) was used to determine the average temperature of the wafer during the process. The instrumented wafer (16 mils thick and 2 in. in diameter) was a one-side-polished silicon wafer containing an R-type (platinum versus platinum-13% rhodium) thermocouple mounted halfway through its center. The temperature reading obtained from the instrumented wafer was 1084 °C, which is in excellent agreement with the average temperature estimate based on the oxide layer thickness formed on wafers without silicon carbide powder.

B. Random walk at average wafer temperatures of 950 and 1200 °C

In order to examine the effect of temperature on the extent of random walk of the thermomigrated trails which occurs during the thermomigration process, two sets of thermomigration experiments were performed at average wafer temperatures of 950 and 1200 °C. The degree of random walk was determined by measuring the average displacement of each thermomigrated pad on the exit side of the wafer with respect to its neighboring pads. These measurements were performed on a total of 1800 trails. The trails resulted from the thermomigration of 100 μm square pads. These results, presented in Table II, show that the degree of random walk at an average wafer temperature of 950 °C has been decreased by a factor of 3 if the average wafer temperature is raised to 1200 °C during the thermomigration process. It should be noted that silicon carbide coating was used in both cases.

C. Thermomigration yield

1. Without silicon carbide powder

Another major problem with the thermomigration process is that not all sizes of aluminum pads successfully migrated through the silicon wafer. In other words the process yield was a function of the size of the pads we were attempting to migrate through the wafer.

We attempted to thermomigrate arrays of square pads (50–140 μm in dimensions) through 16-mil-thick wafers. In the array of 100, 140 μm pads, only approximately 50% of the pads emerged from the back surface of the wafer in a period of 2 h. Those that successfully migrated manifested a particularly high random walk. 170 μm pads were the smallest pads that were successfully thermomigrated (100% yield) through a 16-mil-thick silicon wafer without silicon carbide powder.

This dependence of thermomigration yield on pad size has been noted by Cline and Anthony,[9] and has been ascribed by them to the presence of a "surface barrier" which makes it progressively more difficult for smaller pads to enter into the silicon wafer. These authors found it difficult to thermomigrate pads smaller than 175 μm through a silicon wafer. We have found that the silicon carbide enhancement of wafer temperature and temperature gradient also reduces this "surface barrier."

TABLE II. The average (avg.) extent of random walk and the standard deviation of three patterns of 100 μm square aluminum pads on six silicon wafers at temperatures of 950 and 1200 °C. Each pattern contained 100 aluminum pads. Less random walk was observed at higher average wafer temperatures (by a factor of 3).

			Average random walk (mils)	Standard deviation (mils)
950 °C	Pattern 1		1.29	0.52
	Pattern 2		1.40	0.47
	Pattern 3		1.48	0.62
		avg.	1.39	
950 °C	Pattern 1		1.72	0.47
	Pattern 2		1.59	0.47
	Pattern 3		1.62	0.52
		avg.	1.64	
950 °C	Pattern 1		1.31	0.62
	Pattern 2		1.51	0.70
	Pattern 3		1.28	0.65
		avg.	1.37	
	Average		1.47	
1200 °C	Pattern 1		0.47	0.33
	Pattern 2		0.52	0.37
	Pattern 3		0.54	0.32
		avg.	0.51	
1200 °C	Pattern 1		0.41	0.36
	Pattern 2		0.49	0.42
	Pattern 3		0.59	0.40
		avg.	0.50	
1200 °C	Pattern 1		0.43	0.33
	Pattern 2		0.43	0.40
	Pattern 3		0.48	0.31
		avg.	0.45	
	Average		0.49	

TABLE III. Percentage yield of thermomigration of various pad sizes with silicon carbide powder (1000 mesh grit) compressed onto and covering the silicon wafers during the process. Percentage yield is the ratio of the number of thermomigrated pads on the exit side to the number of pads on the entry side times 100.

	% yield			
	Wafer I	Wafer II	Wafer III	Wafer IV
170 μm	100	100	100	100
140 μm	100	100	100	100
100 μm	100	100	100	100
75 μm	100	100	100	100
50 μm	100	95	100	100
35 μm	95	87	100	100
20 μm	20	15	30	60

2. With silicon carbide powder

When attempting to thermomigrate small aluminum pads, the yield in silicon-carbide-covered wafers was higher than that observed with uncoated wafers. The results are presented in Table III for four coated wafers. Table III shows that aluminum pads as small as 50 μm can be thermomigrated through a 16-mil-thick silicon wafer with the use of silicon carbide. The thermomigration yield progressively decreased with size for pads smaller than 50 μm.

We have also investigated two other methods of applying SiC to the wafers. SiC (0.5 μm thick) was sputtered onto a silicon wafer. We also made a SiC-Si bilayer structure using a 2-in.-diam, 20-mil-thick silicon carbide wafer. The thermomigration oven parameters were identical for these two experiments. In the first case, only pads with dimensions of 75 μm and larger thermomigrated through the wafer. Percentage yields of 80, 90, and 100 for 75-, 100-, and 140-μm-size pads, respectively, were observed. In the second case no pads thermomigrated through the wafer possibly because of poor mechanical contact between the two wafers.

D. Electrical characterization of thermomigration columns

The mean resistivity of a set of 10, 170 μm trails, thermomigrated through a 20-mil-thick wafer, was measured to be 0.3 Ω cm by placing the probes from a digital multimeter across the ends of a thermomigration column and directly measuring the resistance of the column. The dopant concentration of these *p*-type columns was estimated to be 9×10^{17} atoms/cm^3.

E. Problems associated with silicon carbide

Although thermomigration of small aluminum pads through a block of silicon is enhanced by the use of silicon carbide, we also encountered extensive warping in wafers which had undergone the thermomigration process using SiC powder. The edges of the wafer tended to bend downward resulting in a deviation from flatness that varied from about 2.0 to 4.0 mm in four wafers. To determine these deviations, a digital caliper was used to measure the maximum effective thickness of the wafer. This value, less the unwarped wafer thickness, provided an estimate of the extent of warping. It was observed that the deviation was greater for wafers with higher thermomigration yield.

IV. DISCUSSION

A. Migration rate

During the thermomigration process, the velocity of the liquid zone depends upon both the average wafer temperature and the temperature gradient through the wafer [Eq. (1)]. Because these two factors can be increased by increasing the energy input into and the flux of heat through the silicon wafer during the process, the thermomigration velocity could be substantially increased.

Due to the 1.1 eV band gap of silicon, silicon wafers are transparent to infrared radiation for wavelengths longer than 1.1 μm at room temperature.[14] Thus, heating silicon wafers with infrared heat lamps is an inefficient process since most of the infrared radiation incident upon a wafer is transmitted through it without being absorbed (even though at higher temperatures a lowering of the band-edge energy of silicon is observed[14]). In order to increase the absorption during the thermomigration process, a bilaminar structure was used; the material in the top layer was selected to absorb most of the infrared radiation incident upon it and to conduct that energy through the silicon wafer beneath it. Therefore, the top layer must have high absorptivity, high thermal conductivity, and be capable of withstanding high temperatures without mechanically deforming. Silicon carbide powder with an absorptivity of 0.9 (Ref. 15) and thermal conductivity of 30 W/m K (Ref. 16) met these requirements. For a given output power from the infrared lamps, it was able to increase the average temperature of the wafer by 10% and the temperature gradient through the wafer by almost a factor of 5.

B. Random walk

It was clear from these experiments that the degree of random walk of the liquid zones during thermomigration is a time-dependent process. By increasing the velocity of the liquid zone during thermomigration, the degree of random walk could be reduced (Fig. 2 and Table II).

Anthony and Cline claimed that the random walk of an aluminum-rich droplet migrating in a temperature gradient along the ⟨100⟩ axis in silicon is a result of dislocations in the crystallographic structure of silicon.[13] They suggest that a droplet migrating up a temperature gradient will encounter dislocations in its path. Such intersecting dislocations will affect localized droplet dissolution or deposition rates. These localized dissolution rates will cause the droplet to be randomly displaced in various directions.

The experiments we have performed indicate that the extent of random walk can be controlled. The random walk phenomenon can be thought of as reflecting two processes. One process is driven by the imposed temperature gradient and produces a Si-Al inclusion velocity component that is parallel to the temperature gradient. The other process can be characterized as having a velocity component orthogonal to the temperature gradient. By increasing the average wafer temperature and augmenting the temperature gradient through the wafer during thermomigration, the velocity component of the migrating droplet in the direction of the temperature gradient is increased. The resultant velocity vector shifts towards the temperature gradient axis reducing the extent of the random walk of liquid zone.

It should be noted that the consequences of random walk are application dependent. If a thermomigration column is to contact a moderately large area on the back side of a wafer, a moderate amount of random walk will not cause significant complications.[19] On the other hand, if the purpose of thermomigration is to produce precise contacts with target pads on the opposite side of a wafer, then random walk, even if it occurred to a moderate extent, could cause major problems.

C. Problems associated with SiC-enhanced thermomigration

Three methods of applying silicon carbide to the silicon wafer were examined: compression of silicon carbide powder onto the top surface of the silicon wafer, positioning a silicon carbide wafer on top of the silicon wafer, and sputtering silicon carbide onto the top surface of the silicon wafer. The compressed silicon carbide powder was found to be the most successful technique and was used for most experiments.

The use of the silicon carbide wafer was not successful. Due to the rough surface of the silicon carbide wafer, a uniform mechanical contact between the surfaces of the silicon and the silicon carbide wafers could not be achieved. This resulted in a nonuniform temperature distribution through the wafer.

The use of sputtered silicon carbide also had a major difficulty. The sputtered silicon carbide had a porous nature and was oxidized by the oxidizing atmosphere inside the thermomigration oven. As a result of this oxidation silicon dioxide was formed which did not enhance the wafer's temperature significantly.

The issue of wafer warping, which was only briefly considered in this study, is another challenging problem caused by silicon carbide powder. The high temperatures achievable using this technique could produce dislocations. The yield stress of silicon decreases with temperature which makes the silicon wafer vulnerable to any imposed stresses.[20] Further it was observed that at the end of the thermomigration process, silicon carbide powder had diffused into and bonded with the silicon wafer. Since the coefficient of thermal expansion of SiC is higher than that of Si, more expansion of silicon carbide could exert tensile forces on the top surface of the wafer during the process resulting in warping. The large temperature gradient produced through the wafer by silicon carbide could also cause more expansion of the top surface of the wafer compared to the bottom surface.

V. CONCLUSION

The extent of random walk produced by the thermomigration process is dependent on the average wafer temperature and the temperature gradient. Further, by increasing temperature and temperature gradient, smaller-sized aluminum pads can be thermomigrated through a silicon wafer. Because a large fraction of the radiant energy striking the silicon wafer passes through it without being absorbed, increases in wafer temperature and in the temperature gradient across the wafer have been difficult to achieve.

To affect these temperature increases, we have found that silicon carbide powder (1000 mesh grit) deposited on the top surface of the wafer enhances radiant energy absorption and conducts the absorbed energy through the wafer. With a high absorptivity and thermal conductivity, silicon carbide increased the average wafer temperature by 10% as well as the temperature gradient through the wafer by almost a factor of 5 over the case when no SiC powder was used.

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