

# Direct Silicon–Silicon Bonding by Electromagnetic Induction Heating

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**Abstract**—A novel heating technique, electromagnetic induction heating (EMIH), uses electromagnetic radiation, ranging in frequency from a few megahertz to tens of gigahertz, to volumetrically heat silicon above 1000 °C in only a few seconds. Typical power requirements fall between 900 to 1300 W for silicon wafers 75 to 100 mm in diameter. This technique has successfully produced direct silicon wafer-to-wafer bonds without the use of an intermediate glue layer. Infrared images indicate void free bonds that could not be delaminated with knife-edge tests. In addition, four pairs of stacked wafers were bonded simultaneously in 5 min, demonstrating the potential for multiwafer bonds and high-throughput batch processing. [690]

**Index Terms**—Bonding, electromagnetic, radiation, silicon.

## I. INTRODUCTION

IN THE PAST decade, silicon–silicon (Si–Si) bonding has received increased use in the fabrication of micromechanical structures and power electronics. It is also a candidate technology for manufacturing silicon-on-insulator (SOI) wafers. Because MOS transistors fabricated on SOI wafers have minimal source and drain parasitic capacitance, SOI wafers are attractive for high-speed digital microelectronics.

In the bonding process, the polished surfaces of silicon wafers are pressed together at moderate temperatures to form an initial prebond. To complete the bond and achieve full strength, the wafers require baking at temperatures greater than 900 °C [1], [2]. Conventionally, this is done in large furnaces, which require long ramp times, consume large amounts of power, and have significant manufacturing footprints. The resultant high thermal budget limits process flexibility, making integration difficult. In addition, furnaces lack the flexibility to adapt to unconventional bonding requirements.

Silicon bonding through electromagnetic induction heating (EMIH) overcomes many conventional limitations [3]. Initially intended as a means to control dopant diffusion during the formation of ultra shallow junctions [4], [5], EMIH has now been applied to heating wafers for low thermal budget wafer

bonding [6]. This not only increases the throughput of the bonding process, it also increases the process flexibility during the manufacture of certain sensors and actuators, such as piezoresistors, that are limited by high thermal budget steps, for example to limit the diffusion of dopants.

Although the use of electromagnetic radiation for wafer bonding has been reported in the past, intermediate glue layers, such as gold or copper, were used to absorb the radiation [7]. Past work was influenced by the premise that silicon was transparent to electromagnetic radiation because of its small imaginary dielectric relaxation response to fields whose frequencies were below 100 GHz [7], [8]. As a consequence, an intermediate metal layer was used to absorb the incident radiation. The bond was performed by either melting the eutectic glue layer, thereby sealing the two wafers together, or by diffusive heat transfer from the glue layer to the silicon at a rate that would elevate the temperature of the silicon above 900 °C. A third possibility is to place the silicon wafer pair on top of a metal susceptor, such as copper, and to use this susceptor to couple the electromagnetic energy to the wafers. The drawback to this technique is that the bonding temperature is limited by the melting point of the metal susceptor, which can also be a source of impurities. EMIH does not require any eutectic glue layers to bond the silicon wafers. Instead, by taking advantage of the ohmic response of silicon to an oscillating electromagnetic field, EMIH directly heats the silicon to temperatures at which the bond can form [4], [5].

This paper describes the direct bonding of silicon wafers by electromagnetic radiation without the use of any intermediate metal layers<sup>1</sup>. Section II details the fundamental electromagnetic theory behind the heating phenomenon. Section III describes the experimental apparatus. Sections IV and V discuss heating and bonding results respectively. Finally, Section VI concludes with details on future experiments and potential applications.

## II. THEORY

Electromagnetic induction heating is a fundamental extension of Maxwell's equations. A magnetic field oscillating transverse to a surface induces electric currents along that surface. The energetic electrons, upon collisions with the lattice, ohmically transfer their energy to the material, thereby heating it. EMIH differs from previous attempts to heat silicon with microwave radiation [8] in that it focuses on maximizing the magnetic field transverse to the wafer surface. Exactly why this technique efficiently heats silicon to temperatures in

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<sup>1</sup>Portions of this paper have appeared in conference abstract form in [6].

excess of 1000 °C whereas other techniques do not requires a more in-depth study of how electromagnetic fields interact with materials.

Power absorption from the electric field component of a wave incident upon a semi-infinite magnetic material can be described by [9]:

$$P_{abs} = \left[ \frac{1}{2} \omega_0 \epsilon_0 \epsilon' \tan \delta \right] |E|^2 \text{ Watts/m}^3 \quad (1)$$

where  $\epsilon_0$  is the permittivity of free space,  $\epsilon'$  is the real component of the dielectric response,  $\omega_0$  is the frequency of operation,  $|E|$  is the magnitude of the electric field, and  $\tan \delta$  is the loss tangent of the material. This loss tangent can be separated into dipole relaxation and conduction current (ohmic) components:

$$\tan \delta = \tan \delta_a + \tan \delta_s = \frac{\epsilon''}{\epsilon' \epsilon_0} + \frac{\sigma}{\omega_0 \epsilon' \epsilon_0} \quad (2)$$

where  $\sigma$  represents the material conductivity and  $\epsilon''$  the imaginary part of the dielectric permittivity associated with polarization relaxation. Equation (2) in combination with (1) indicates that the dissipation mechanism depends on the four parameters:  $\sigma$ ,  $\epsilon'$ ,  $\epsilon''$ , and  $\omega_0$ . For conventional conductors with large  $\sigma$  and  $\epsilon' \sim 1$ , ohmic dissipation dominates. For conventional insulators with small  $\sigma$ , dipole relaxation characterized by  $\epsilon''$  dominates. For semiconductors the dissipation mechanism varies between dipole relaxation and ohmic conduction losses, depending on the frequency and conductivity. At low conductivity (e.g., low temperature and low impurity doping) and high frequency (e.g., 100 GHz), dipole relaxation, i.e., dielectric losses, dominate. At moderate or high conductivity (high temperature or high doping) or lower frequency ( $< 100$  GHz), ohmic conduction losses will usually dominate. It is well known that ohmic heating of silicon can be effective through induction of AC currents at low frequencies, e.g., less than 1 MHz [10]. However, this heating mechanism provides slow heating rates, on the order of those achieved in a conventional furnace. In fact, it had been previously concluded that at higher microwave frequencies direct induction heating and ohmic losses in silicon are too weak for rapid high temperature bonding [8]. Hence, it was felt necessary to add a highly conductive eutectic glue layer (e.g., gold) at the interface to enhance the ohmic response. Finally, for a medium in which ohmic losses dominate dielectric losses,  $\tan \delta$  can be replaced by  $\sigma / \omega_0 \epsilon_0 \epsilon'$  in (1) to obtain the more familiar expression for ohmic power absorption:

$$P_{abs} = \frac{1}{2} \sigma E^2. \quad (3)$$

In addition to having a large  $\tan \delta$ , efficient electromagnetic heating also requires coupling the electromagnetic fields into the medium being heated. From this perspective, efficient coupling occurs when the load (the silicon wafer to be heated) is “well matched” to the electromagnetic fields. Because the properties of the load are fixed when the heating begins, the fields must be tailored to closely match the load. If not, significant wave reflection at the wafer surface results in poor coupling to the

wafer. The impedance of electromagnetic waves in a nonmagnetic medium can be described by [9]:

$$\eta = \frac{E}{H} = \sqrt{\frac{\mu_0}{\epsilon (1 + \frac{j\sigma}{\omega\epsilon})}} \quad (4)$$

where  $\eta$  is the wave impedance in the medium,  $\mu_0$  is the permeability of free space, and the other variables are as previously defined. From this equation the proper electric field to magnetic field ratio, at the surface of the material to be heated, can be extracted. A dielectric, for example, has a conductivity that approaches zero, so  $\eta \sim 377 \Omega$  (for  $\epsilon' = 1$ ), indicating an  $E/H$  ratio that should be quite large for effective field coupling. For conductors, however, the impedance reduces to:

$$\eta = \frac{E}{H} = \sqrt{\frac{\mu_0 \omega}{\sigma}}. \quad (5)$$

From this relation it is apparent that for the range of conductivity observed in silicon, penetration and thus absorption of plane wave radiation (for which  $E/H \sim 377 \Omega$ ), or what is more commonly known as “direct wave absorption”, can only be accomplished at rather high frequencies, i.e., millimeter waves. At microwave (and lower) frequencies, the impedance is significantly less than unity, indicating that efficient coupling requires the magnetic field amplitude be significantly larger than the electric field amplitude at the wafer surface.

Two separate techniques for accomplishing this small electric to magnetic field ratio, for efficient EMIH, are outlined in this paper. The first, a resonant cavity, involves placing the wafer at the bottom of the cavity where the electric field is forced to be small (almost but not quite zero) and the magnetic field is at a maximum. The second involves placing the wafer in the extreme near field of a spiral antenna where the field configuration is known to give large magnetic and small electric fields. More is said about this in the experimental apparatus section.

With EMIH, the induced current flow is directly dependent on the free carrier density. For rapid high temperature heating, this implies that the free electron density should either increase, or at least not decrease appreciably, with temperature. If the electron density were to decrease with temperature, the current would decrease as well, self-limiting the maximum temperature. On the other hand, if the carrier density were to increase with temperature the heating could be accelerated, especially if the mobility of the charged species does not change appreciably with temperature. The latter situation is optimal as it results in a very rapid heating of the material.

The material properties of silicon make it a suitable candidate for rapid EMIH heating. The conductivity is large enough for significant levels of current to flow. Most importantly, the free carrier density is extremely sensitive to temperature. As the thermal energy of silicon increases, the number of electrons elevated to the conduction band grows exponentially, increasing the number of carriers available to couple to the electromagnetic fields. The electron collision frequency, on the other hand, does not change as rapidly with increasing temperature as compared to the growth of free carrier electrons. As a consequence,

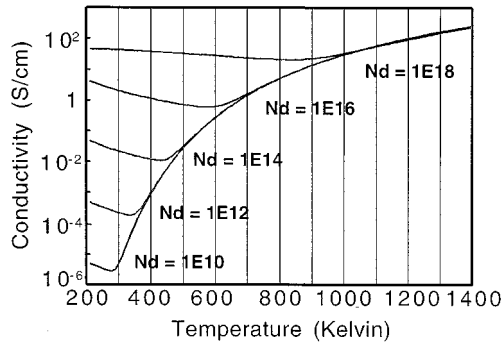


Fig. 1. Conductivity as a function of temperature for silicon. The drop in mobility initially causes conductivity to decrease with temperature. The increase in free carriers soon overcomes this loss, causing conductivity to increase quite rapidly with temperature.

the overall conductivity of silicon generally rises with temperature as shown in Fig. 1. This figure illustrates conductivity as a function of temperature for several doped levels of silicon. Initially a loss in mobility, due to increasing collision frequency, causes conductivity to drop until the elevation of electrons to the conduction band overcomes this loss. Eventually the intrinsic carrier concentration rises to such a level that it dominates the doped levels, and the lines merge together. The only potential problem is that the initial decrease may create a coupling valley that inhibits heating past a rather low temperature,  $\sim 150$  °C. Once past this valley, however, rapid heating occurs as the electron density and conductivity increase. The temperature of the wafer will continue to increase until the electromagnetic power absorbed is balanced by the radiation losses.

A first order solution for the power absorption efficiency of a silicon wafer can be analytically obtained through a self-consistent solution of both Ampere's and Faraday's laws. The result [11]:

$$P_{abs} = \frac{\frac{\pi a^2 t_w^3}{\delta_{EM}^4 \sigma}}{1 + \left(\frac{t_w}{\delta_{EM}}\right)^4} H_0^2 \text{ Watts} \quad (6)$$

$$\delta_{EM} = \sqrt{\frac{2}{\omega_0 \mu_{n,p} \sigma}} \text{ m} \quad (7)$$

includes the effectiveness of electromagnetic field penetration and depends on a parameter referred to as the skin depth parameter  $\delta_{EM}$ . In (6), " $a$ " represents the wafer radius ( $\pi a^2 =$  surface area),  $t_w$  the wafer thickness,  $\sigma$  the conductivity,  $\mu$  the carrier mobility, and  $H_0$  is the magnitude of the magnetic field. This equation simultaneously includes the heating rate physics of (1) and the field penetration physics of (4). It also accommodates the finite thickness of the wafer stack.

Equation (6) is plotted in Fig. 2 at both 13.56 MHz and 2.45 GHz. For low conductivity materials (i.e., quartz) the skin depth approaches infinity, indicating complete penetration of the fields through the wafer with very little absorption. As conductivity increases, skin depth decreases and more of the wave is ohmically absorbed in the material. Eventually the conductivity increases to such a level that the skin depth becomes very small, indicating that most of the electromagnetic field is reflected (i.e., copper) and heating can only occur in the very thin skin depth layer.

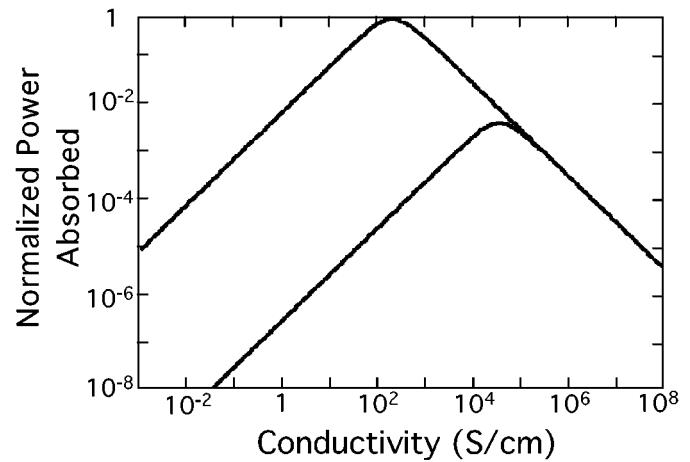


Fig. 2. Power absorbed as a function of conductivity for both 13.56 MHz and 2.45 GHz, which is higher [see (6)].

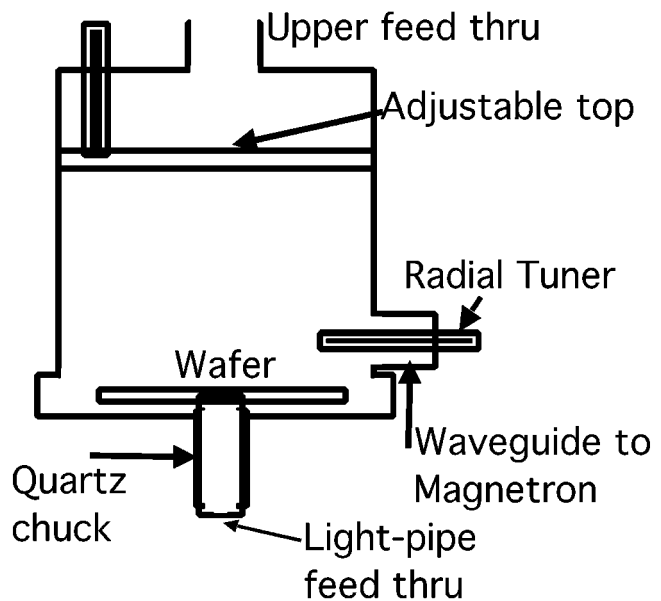


Fig. 3. Schematic of the cylindrical resonant cavity used for microwave heating. The cavity is azimuthally symmetric.

### III. EXPERIMENTAL APPARATUS

In the microwave regime, EMIH was performed in a resonant cavity of radius 17 cm (Fig. 3). The height of the cavity was left adjustable to tune in specific modes, and a radial tuning stub helped to minimize reflected power. Although several modes were found that resonated at 2.45 GHz, the dominant TM111 and TM011 modes were primarily used. All experiments were strictly single mode, but with additional power sources multi-mode cavities could be constructed. Up to 3000 W at a frequency of 2.45 GHz was available from a magnetron source, but to date no more than 1500 W has been necessary. The wafer was supported by a hollow quartz cylinder positioned 1 mm above the cavity bottom to ensure that it was in a magnetic field maximum. Fig. 4 illustrates the fields present during heating for both TM111 and TM011 modes. Since the electromagnetic energy absorbed by the silicon is directly proportional to the magnetic

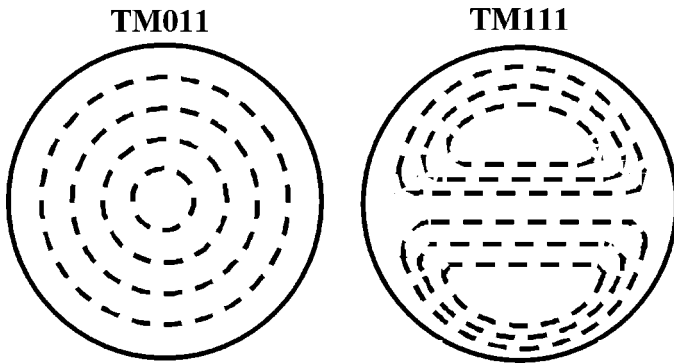


Fig. 4. Magnetic field patterns in the microwave cavity for TM011 and TM111 modes in the plane of the wafer.

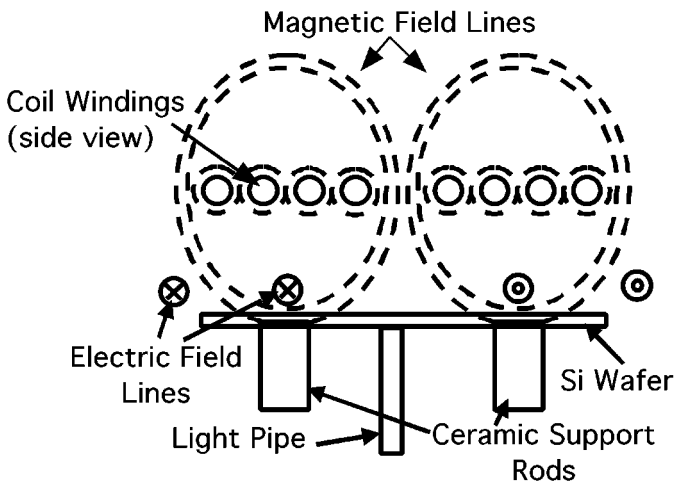


Fig. 5. Schematic of RF system showing the induced magnetic and electric field lines.

field intensity, the uniformity of these modes can have a strong influence on the uniformity of the heating.

Since EMIH in the RF regime is not practical in a resonant cavity, an alternate approach, illustrated in Fig. 5, uses a spiral copper antenna to excite RF magnetic flux. Up to 1000 W from a fixed frequency, 13.56 MHz power supply was provided through an L-type matching network. The wafer was positioned 2.5 cm below the coil, in the extreme near field of the antenna, on a ceramic chuck that could be optionally heated to 150 °C by a resistive heating element.

Examination of the fields in Fig. 5 reveals a drawback to this source design. The center of the wafer experiences some reduction of the local magnetic flux density due to the presence of induced current. Near the edges, however, boundary conditions significantly reduce this effect. The induced currents are ultimately determined by the net magnetic flux density, which is the field imposed by the antenna currents minus the field arising from the induced wafer currents. Since less field reduction occurs at the edge of the wafer, the current density at the edge of the wafer will be more intense than at the center of the wafer. This results in a somewhat nonuniform heating pattern in the radial dimension. A semi-analytical solution for the heating profile was obtained by assuming quasistatic fields (which is permissible when radiation wavelength is long compared to wafer

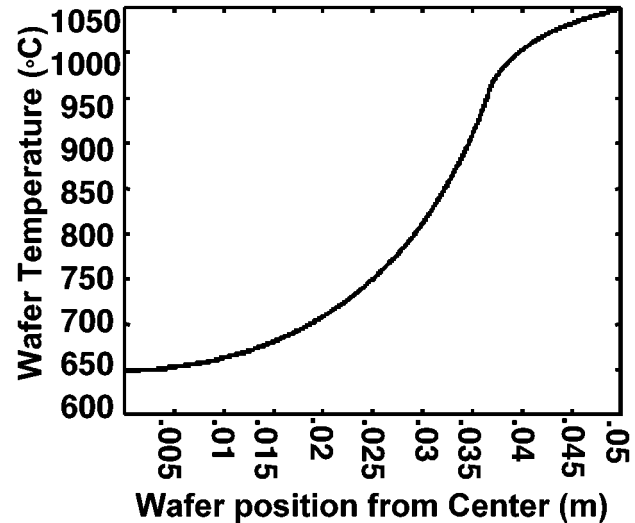


Fig. 6. Semi-analytical solution to the temperature distribution on a 100-mm-diameter wafer during RF heating with a spiral coil antenna. Eliminating the boundary condition by placing a larger diameter wafer under the wafers to be bonded significantly improves the uniformity.

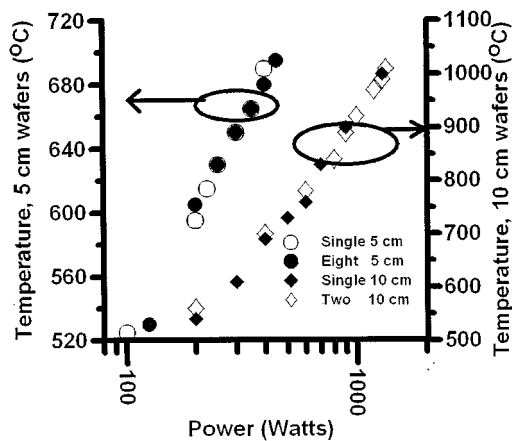
thickness) using mixed boundary value conditions [12] to define the electric flux density inside and outside the radius of the wafer; fitting empirical temperature measurements from the center and edge of the wafer (Fig. 6). The preferential heating at the outer radii of the wafer with this antenna is evident.

The radial temperature variation can be substantially reduced by placing a wafer of larger diameter below the pair of wafers to be bonded, which effectively removes the radial boundary effect from the bonded wafer pair. However, this also increases the power dissipation, necessitating more power to achieve the same heating rate or process temperature. Additional details concerning the uniformity of the heating process are presented in [4], [5].

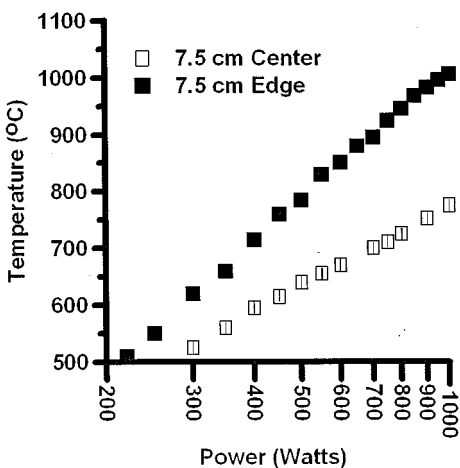
Temperature measurement in the presence of intense electromagnetic fields requires careful techniques [4]. An optical pyrometer or light-pipe—calibrated to the specific emissivity of silicon in the temperature range of interest (800–1100 °C)—accurately measured the temperature without perturbation of the field patterns [4], [5]. The light-pipe could be fed through the bottom of the chamber to obtain localized spatial measurements or the pyrometer could remotely view the wafer from outside the chamber to obtain an areal temperature average.

#### IV. HEATING MEASUREMENTS

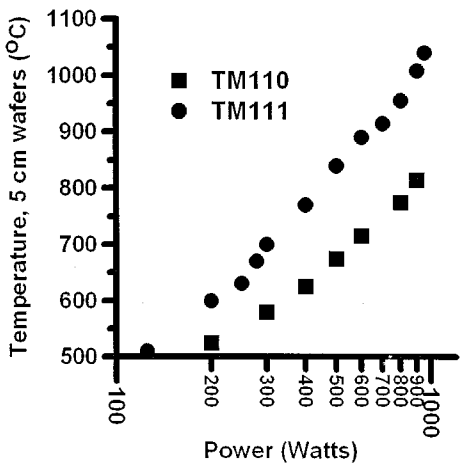
Both intrinsic and heavily doped wafers were successfully heated to temperatures in excess of 1000 °C in both the RF and the microwave systems. Since RF fields do not couple efficiently to lightly doped silicon at room temperature, wafers in the RF system were pre-heated to 150 °C to elevate enough electrons into the conduction band to initiate coupling. The thermal loss mechanism, in this temperature regime, should be dominated by radiation. The linear relationship between measured steady state temperatures and the fourth root of power absorbed verifies that radiation is the dominant heat loss mechanism (Fig. 7).



(a)



(b)



(c)

Fig. 7. (a) Steady-state temperature for a single and a pair of 50 mm and 100 mm wafers. The 50-mm wafers were heated in the TM011 mode while the 100-mm wafers were heated in the TM111 mode. (b) Center and edge temperatures of a 75-mm wafer heated in the RF system. (c) A 75-mm wafer heated in the microwave system in the TM110 and TM111 mode.

EMIH heating in the microwave regime illustrates the potential to perform multistack wafer bonds. At a given power level, the same temperature can be achieved for simultaneously heating several wafers or a single wafer [see Fig. 7(a)]. The radial temperature gradient present during RF heating, discussed

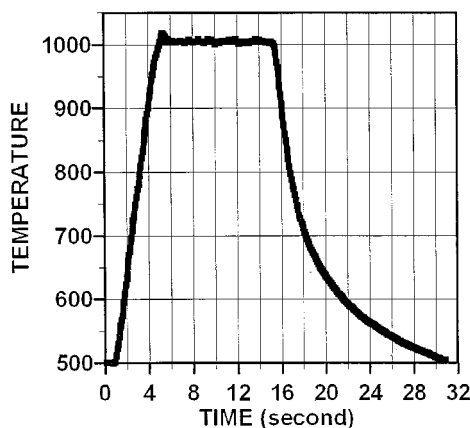


Fig. 8. Typical heating and cooling transient for EMIH. Volumetric heating rates of 125 °C/s are possible with our experimental apparatus.

earlier, is shown more quantitatively in Fig. 7(b). Alternative source designs that provide potentially greater uniformity are being investigated. To illustrate the difference in heating efficiency between the two modes for our experimental setup, the temperature measured in the center of a 75-mm microwave heated wafer using both TM011 and TM111 modes is shown in Fig. 7(c). Finally, a typical heating and cooling transient is displayed in Fig. 8. This figure indicates a maximum heating rate of 125 °C/s for the given load at an input power of 1000 W.

V. BONDING RESULTS

Several <100> silicon wafers were bonded in the microwave and RF systems. Bond uniformity and strength were evaluated by infrared imaging and knife-edge delamination tests. Excellent bonds were obtained in only 5 min at 1000 °C in both systems. While the time necessary to obtain a full strength silicon-silicon bond is known to be within these time frames [1], conventional furnace processing cannot function on these time scales.

In a typical bonding sequence, the wafers were cleaned first in a NaOH:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O (5:1:1) solution at 80 °C, followed by H<sub>2</sub>SO<sub>4</sub>:H<sub>2</sub>O (5:1) at 80 °C, and finally dipped in dilute (100:1) HF to remove any residual oxide layer. The wafers were then rinsed in DI water and spun completely dry to minimize the amount of residual moisture on the silicon surface. Once dry, the wafers were immediately pressed together. To create the bond, the wafers were ramped to 1000 °C at a rate of 125 °C/s, soaked at 1000 °C for 5 min, and cooled to room temperature in ≈ 5 s. Infrared images of the resulting EMIH bonds were void free. Fig. 9 shows both microwave and RF bonded wafers of 75 mm diameter and ≈ 375 μm thickness.

The strength of the microwave-heated bonds attained was tested using conventional knife-edge delamination tests. At a bonding temperature of 1000 °C (measured at the center) the wafers shattered before debonding, with the shatter point emanating from the center of the wafer and not at the point of blade insertion. The new surface area created, obtained by summing the perimeter of the shattered pieces (41 cm) minus the original perimeter (23.6 cm) and multiplying by the thickness of the bonded pair (1 mm), was 1.74 cm<sup>2</sup>. When a

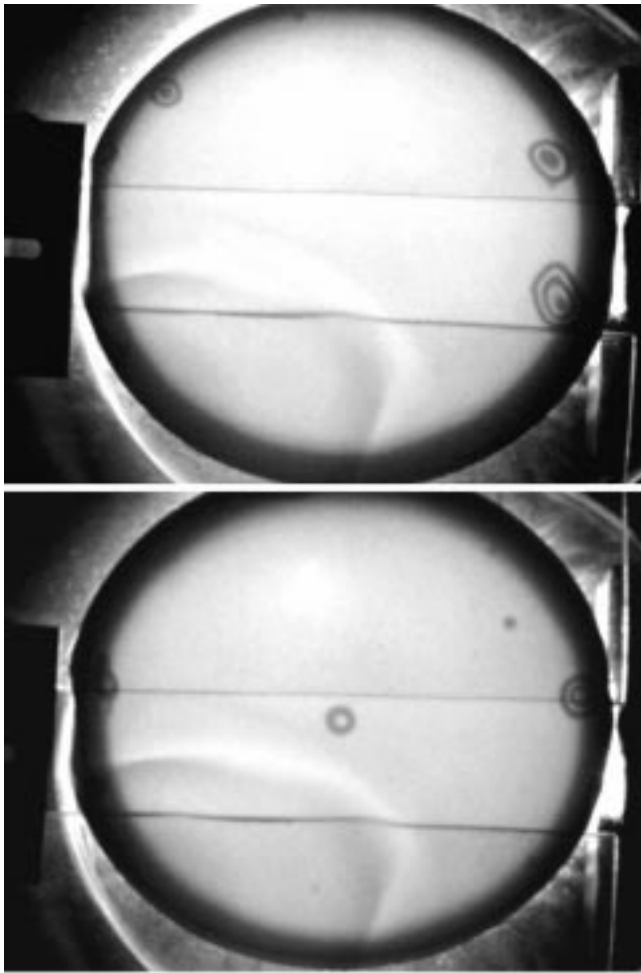


Fig. 9. IR images of EMIH bonded wafers heated for 5 min at 1000 °C. Top: microwave (2.45 GHz) Bottom: RF (13.56 MHz).

bonded pair (both wafers of the same material) shatters instead of delaminating, studies by Cook and Gordon [13] state that the minimum bond strength can be set at 20% of the strength of the material being bonded. While the bond strength may be higher than this value, they showed that fracture tests can not discern a more precise value. Nevertheless, this minimum bond strength along with the void free IR images indicate a bond of excellent quality.

Assessment of bond uniformity by IR imaging is limited by the available viewing resolution; defects smaller than this limit go undetected. A more accurate assessment of the largest flaw size involves a calculation of the fracture stress present when the wafer shatters. Taking the fracture area ( $1.74 \text{ cm}^2$ ) and multiplying by the surface energy of silicon ( $2.62 \text{ J/m}^2$ ), the dissipated energy can be calculated. Because energy was most likely dissipated in areas other than just the shattering process (i.e., kinetic energy), this calculation represents a minimum energy value. Dividing this energy by the volume of the wafer pair gives the energy/unit volume, and this energy/unit volume can be equated to the fracture stress by the following formula:

$$\text{ENERGY/m}^3 = \frac{\frac{1}{2}\sigma_F^2}{E} \quad (8)$$

where  $E$  is the Young's modulus and  $\sigma_F$  is the fracture stress to be calculated. The stress for this case is found to be 176 MPa, and with this value the largest defect size is deduced from:

$$\text{TOUGHNESS} = 0.9 \text{ MPa} = \sigma_F \sqrt{c} \quad (9)$$

where  $c$  is the defect radius measured in micrometers. Using this calculation, a maximum for the defect radius is found to be  $26 \mu\text{m}$ , much lower than the resolution available through the IR imaging system used.

The strength of bonds performed at temperatures less than 1000 °C was measured to investigate whether microwave annealing offered the possibility of strong bond formation at temperatures lower than those required by conventional heating. Using the formula [2]:

$$\gamma = \frac{3Et_w^3 t_b^2}{32 L^4} \quad (10)$$

it was found that at 900 °C the surface energy was  $\sim 2100 \text{ mJoules/m}^2$ , and at 800 °C  $\sim 700 \text{ mJoules/m}^2$ . Bond strengths below 800 °C were not tested. These bond strengths are comparable to those obtained during conventional furnace annealing [2].

The significant temperature gradient in the radial direction during RF bonding presents an opportunity to study the effects of electromagnetic radiation on materials interactions. During the bonding of the 75-mm wafers, the edge of the wafer was maintained at 1000 °C, but the center was only at 780 °C. Despite this lower temperature, delamination tests of the silicon bonds at the center of the wafer pair indicate bond strengths typically seen from anneals at temperatures greater than 900 °C [2]. The reason these bond strengths were attained at lower temperatures is unclear; however, unique phenomena involved with electromagnetic materials processing have been shown to enhance reaction kinetics (as compared to conventional thermal techniques) in several other areas [5], [14], [15]. The absence of evidence of enhanced kinetics during bonding with microwave radiation is believed to be due to the smaller skin depth penetration of the electric field. At 1000 °C, the skin depths of the electric field at 2.45 GHz and at 13.56 MHz are  $100 \mu\text{m}$  and  $1.4 \text{ mm}$  respectively [4]. As a consequence, the microwave frequency electric field is unable to penetrate the  $500 \mu\text{m}$  thick wafer, but the radio frequency electric field is able to penetrate completely through to the bond interface. Because it is the electric field that enhances the reaction kinetics, it is plausible that the microwave frequency radiation would not play a significant role in enhancing the bonding process. On the other hand, the RF electric fields present at the interface may play a significant role in the bonding reaction. The potential for an enhanced bonding mechanism due to the presence of these specific RF fields is an area worthy of continued research.

Surface preparation is an important part of conventional wafer bonding [1], [2]. This is true for EMIH bonding as well, in which poor surface preparation can result in voids, particularly when rapid temperature ramps are used. During the heating process, adsorbed water trapped between the wafer surfaces quickly vaporizes and expands, increasing local pressures along the bond interface [1], [2]. This pressure can force the surfaces apart,

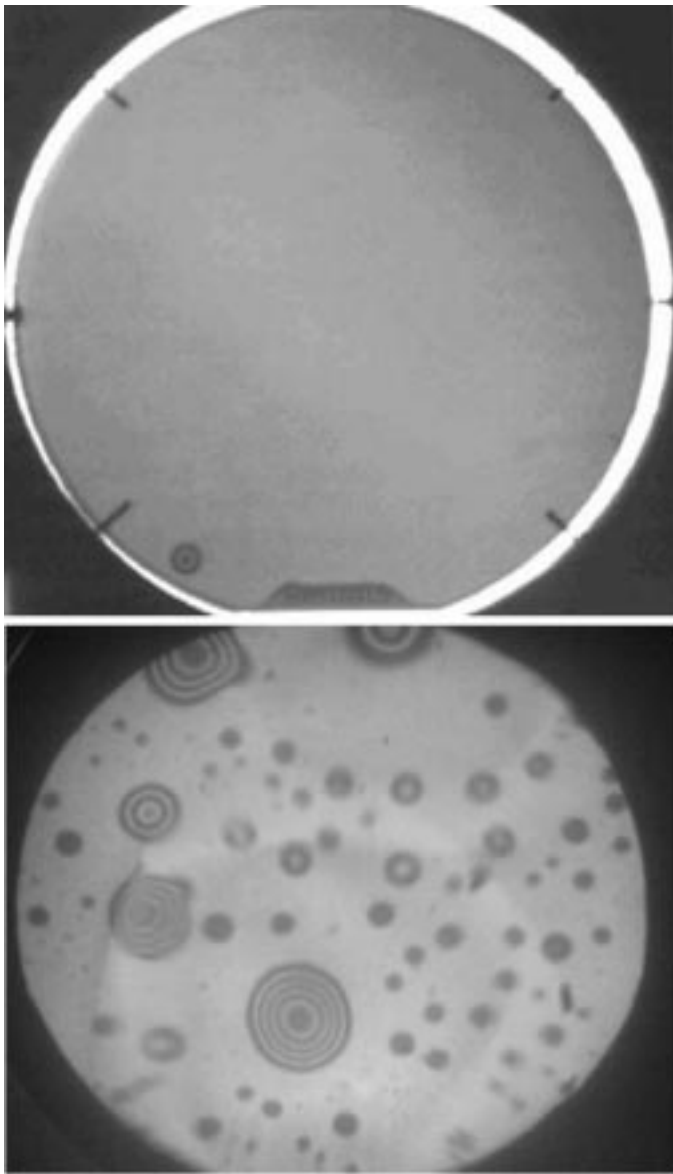


Fig. 10. Infrared (IR) images of a wafer pair before (top) and after (bottom) anneal for 5 min at 1000 °C. Voids are created from residual water when very high ramp rates are used with either RF or microwave heating.

creating voids in an otherwise uniform bond. Furthermore, the oxygen released from the water vapor may react locally with the silicon surface to form silicon dioxide, causing the local nonuniformities that contribute to void formation.

An increase in the formation of voids from surface moisture was observed when very rapid temperature ramps were used to bond a pairs of 500  $\mu\text{m}$  thick, 100 mm diameter wafers in the microwave system. Prior to bonding, the wafers were cleaned and spun dry, but no HF dips were used to remove residual oxide and no special effort was made to minimize moisture adsorption on the wafer surface. After pressing together, the wafers were ramped to 1000 °C at a rate of  $\approx 125$  °C/s, soaked at 1000 °C for 5 min and cooled to room temperature in  $\approx 5$  s. Infrared images taken before and after the EMIH cycle clearly show the creation of voids as residual moisture forced the two wafers apart before the bond could completely set, Fig. 10. Voids were not observed

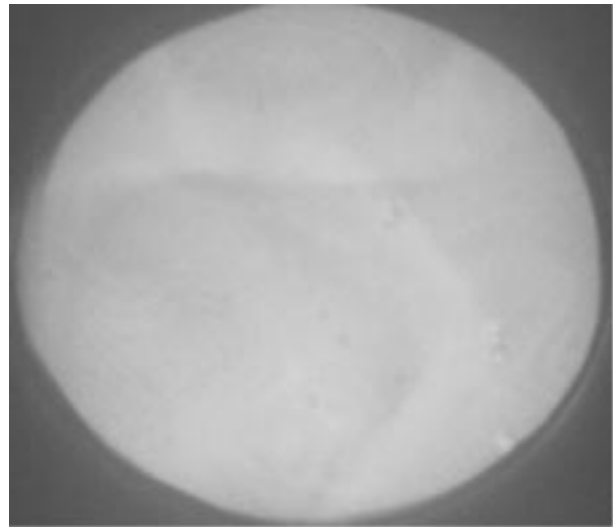


Fig. 11. IR image of wafers with 2500 angstroms oxides bonded by a 4-min microwave EMIH anneal at 1000 °C.

when slower ramp rates ( $\sim 20$  seconds to reach 1000 °C) were used to heat the wafers.

As indicated earlier, SOI wafer technology may benefit significantly from EMIH bonding, particularly in manufacturing wafers for which the buried oxide layer must be relatively thick or located far below the wafer surface. This can be accomplished by growing a thick oxide on two wafers, bonding them, and polishing back one of the wafers until the desired thickness of silicon remains.

A set of experiments examined the feasibility of SOI bonding. Several 75 mm diameter wafers with  $\sim 2500$  Å of thermally grown oxide were plasma cleaned as in the previous experiment, dipped in dilute (100:1) HF for 1 min, and ultrasonically rinsed in DI water for 5 min. The wafers were then pressed together and heated by microwave radiation. Infrared images of the results indicate a very uniform bond (Fig. 11). In this experiment the relatively thick layer of oxide is thought to prohibit the immediate reaction of oxygen freed from water adsorbed onto the silicon surface, thus eliminating the localized oxidation that occurred in the previous experiment, and allowing the bond to set uniformly.

In the final set of experiments, multiwafer bonding was tested in the microwave system. Four pairs of 50 mm diameter wafers, each 250  $\mu\text{m}$  thick, were individually pressed together, stacked on top of each other, and placed on the quartz chuck. The wafers were then heated as in the previous experiments for 5 min. Knife-edge tests were unable to delaminate the bonds at either the edges or at any point in the center of the wafer. This experiment demonstrates the potential for multiple stack rapid bonding using EMIH. If double-polished wafers had been used in this experiment, it is expected that all eight wafers would have bonded together.

## VI. CONCLUSION

The fundamental theory behind EMIH has been discussed and successfully applied to bonding silicon wafers on timescales

not possible in conventional furnaces. Furthermore, this volumetric heating technique may be preferable to typical RTA systems, which rely on surface absorption of the heat. These surface absorption techniques have trouble uniformly heating materials of varying emissivity and the heat transfer through insulating layers, such as the thick oxides required for SOI, may be inefficient. The low thermal budget and potential for batch processing also makes it suitable for high volume manufacturing. For example, this technique may be used to manufacture SOI wafers on a large scale. Finally, the necessary equipment is already available in conventional fabrication facilities, drastically reducing maintenance and availability concerns.

Future work will concentrate on the study of EM sources and fields through numerical simulations, and the modeling of this heating phenomenon.

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