SI-SI BONDING USING RF AND MICROWAVE RADIATION

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ABSTRACT

Electromagnetic radiation ranging in frequency from a few MHz to tens of GHz has been used to volumetrically heat silicon above 1000°C in only a few seconds. Typical power is <1.5 kW. This technique has successfully produced direct Si wafer-to-wafer bonds in only five minutes without the use of any intermediate glue layer. Infrared images indicate void free bonds, and knife-edge tests could not delaminate the wafers. In addition, four pairs of stacked wafers have been bonded simultaneously in 5 min., demonstrating the potential for multi-wafer bonds and high-throughput batch processing.

Keywords: Bonding, electromagnetic radiation, RTA

I. INTRODUCTION

In the past decade, silicon-silicon bonding has received increasing use in the fabrication of micromechanical structures and power electronics. It is also a candidate technology for manufacturing silicon-on-insulator (SOI) wafers, which are attractive for high speed digital microelectronics. In MOS transistors fabricated on SOI wafers, the parasitic capacitance associated with source and drain junctions is minimal.

In the bonding process, the polished surfaces of the silicon wafers to be bonded are pressed together at moderate temperatures to form an initial pre-bond. To complete the bond and achieve full strength, the wafers require baking at ≈1000°C [1]. 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 process integration difficult. In addition, furnaces lack the flexibility to adapt to unconventional bonding requirements such as multi-wafer stacks.

Silicon bonding through electromagnetic induction heating (EMIH) overcomes many conventional limitations. Initially intended as a means to control dopant diffusion during the formation of ultra shallow junctions [2,3], EMIH has now been applied to heating wafers for low thermal budget wafer bonding. Although the use of electromagnetic radiation for wafer bonding has been reported in the past, intermediate glue layers of metal were used to absorb the radiation [4]. It has been assumed that silicon is transparent to electromagnetic radiation because of its small imaginary dielectric response [5]. In reality, however, the ohmic response of silicon to an oscillating magnetic flux can be used to directly heat the silicon. This paper reports on direct bonding of silicon wafers by electromagnetic radiation without the use of any intermediate metal layers.

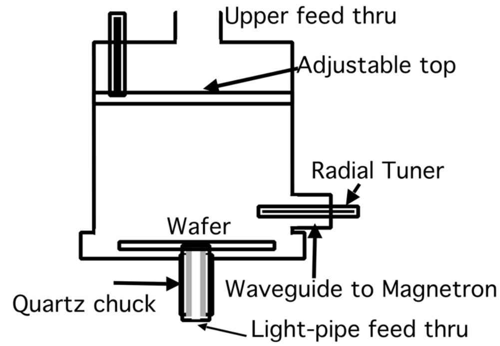

Fig. 1: Schematic of the cylindrical resonant cavity used for microwave heating. The cavity is azimuthally symmetric.

In EMIH, intense electromagnetic fields are used to induce currents to flow through the silicon wafer. The highly energetic electrons collide with the lattice, transferring their energy to it in the form of heat. As the wafer temperature rises, additional electrons move into the conduction band and are available to flow as current, thereby increasing the power absorbed by the wafer. This process continues until radiation losses equal the power absorbed, forcing a steady state operating point. The wafers can be rapidly ramped to temperatures above 1000°C in a small, easily adaptable chamber, which always remains at room temperature. The volumetric nature of the heating contrasts with conventional rapid thermal annealing (RTA), which relies on surface absorption. This make EMIH more suitable for simultaneously bonding stacks of silicon wafers as efficiently and rapidly as single wafer bonding. It allows for a low thermal budget process that limits high temperature degradation of devices, especially the undesirable diffusion of dopants. Details are provided in [2,3].

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II. EXPERIMENTAL APPARATUS

In the microwave regime, EMIH was performed in a resonant cavity of radius 17 cm (Fig. 1). 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 watts at a frequency of 2.45 GHz was available from a magnetron source, but to date no more than 1500 watts 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. Figure 2 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 field intensity, the uniformity of these modes can have a strong influence on the uniformity of the heating.

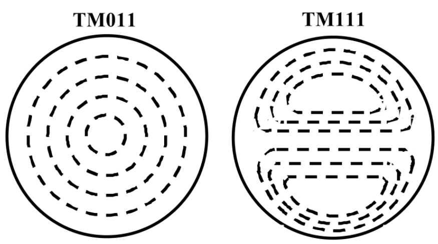

Fig. 2: Magnetic field patterns in the microwave cavity for TM011 and TM111 modes in the plane of the wafer.

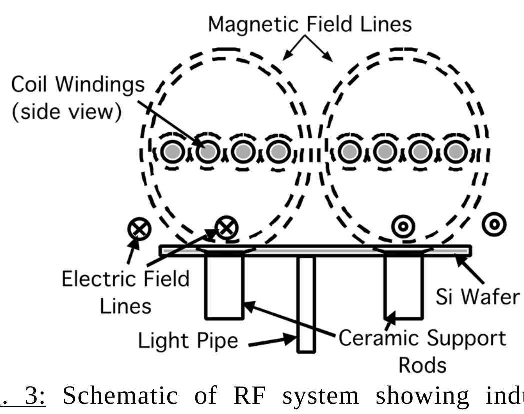

Fig. 3: Schematic of RF system showing induced magnetic an electric field lines.

In an alternate approach, RF magnetic flux was excited with a spiral copper antenna, because EMIH in the RF regime is not practical in a resonant cavity (Fig. 3). Up to 1000 Watts 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 heated to 150°C if necessary. Examination of the fields in Fig. 3 reveals a drawback to this source design. The center of the wafer, acting as a semi-infinite plane, experiences some reduction of the local magnetic flux density due to the presence of induced current. Near the edges, however, boundary conditions drastically limit this effect. Since the induced currents are ultimately determined by the net magnetic flux density (field imposed by the antenna currents minus field arising from the induced wafer currents) less field reduction occurs at the edge of the wafer. This results in a significantly non-uniform heating pattern in the radial dimension. A semi-analytical solution for the heating profile (Fig. 4), was obtained by assuming quasi-static fields (wavelength long compared to wafer thickness); using mixed boundary value conditions [6] to define the electric flux density inside and outside the radius of the wafer; and fitting empirical temperature measurements from the center and edge of the wafer.

Temperature measurement in the presence of intense electromagnetic fields is difficult under the best circumstances [2]. Use of an optical pyrometer or light-pipe – calibrated to the specific emissivity of silicon in the temperature range of interest (800-1100°C) – allowed the temperature to be accurately measured without perturbing the field patterns [2,3]. 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.

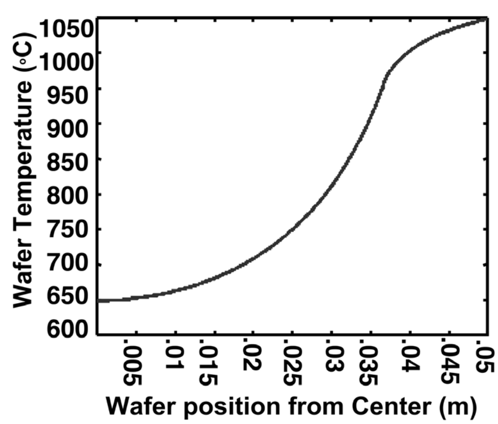

Fig. 4: Semi-analytical solution to the temperature distribution on a 100 mm diameter wafer during RF heating with a spiral coil antenna.

III. 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 silicon at room temperature, wafers in the RF system were pre-heated to

150°C to help initiate coupling [3]. Power losses from radiation dominate in this temperature regime, and because radiation losses are proportional to power$^{1/4}$, the data is plotted in Fig. 5 as steady state temperature vs. power$^{1/4}$. EMIH heating in the microwave regime illustrates the potential to perform multi-stack wafer bonds. At a given power level, the same temperature can be achieved for simultaneously heating several wafers or a single wafer (Fig. 5a). The radial temperature gradient present during RF heating, discussed earlier, is shown more quantitatively in Fig. 5b. This temperature gradient poses an obstacle to practical implementation, but alternative source designs are currently being investigated.

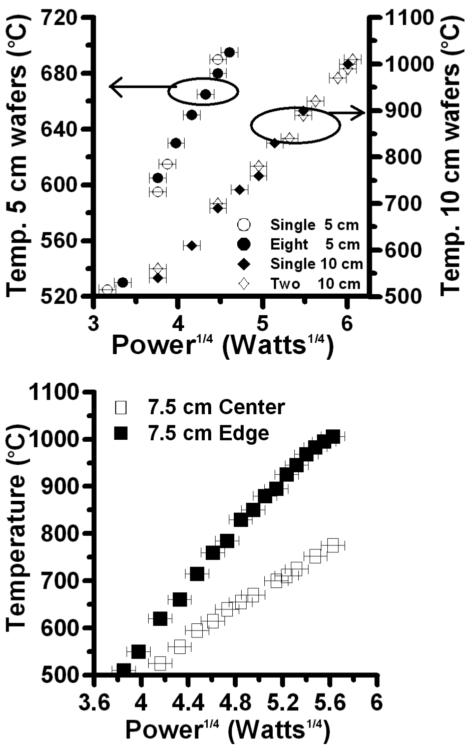

Fig. 5: (a-upper) Steady-state temperature for single and paired 50 mm and 100 mm wafers. The 50 mm wafers were in TM011 mode, while the 100 mm wafers were in TM111 mode. (b-lower) Center and edge temperatures of a 75 mm wafer in the RF system.

IV. BONDING RESULTS

Several <100> silicon wafers were bonded in the microwave and RF systems. The bond uniformity and strength was evaluated by infrared imaging and knife-edge delamination tests. Excellent bonds were obtained in only 5 minutes 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 $NaOH:H_2O_2:H_2O$ (5:1:1) solution at 80°C, followed by $H_2SO_4:H_2O$ (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/sec, soaked at 1000°C for 5 minutes, and cooled to room temperature in ≈5 seconds. Infrared images of the resulting EMIH bonds were void free. Figure 6 shows both microwave and RF bonded wafers of 75 mm diameter and ≈375 μm thickness.

Surface preparation is well known to be an important step in conventional wafer bonding [1]. 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]. This pressure can force the surfaces apart, creating voids in an otherwise uniform bond. Furthermore, the oxygen present in the water may react locally with the silicon surface to form silicon dioxide, making uneven the surface over which the bond is formed. In extreme cases, wafers may delaminate during the temperature ramp. The creation of voids from surface moisture was observed when very rapid temperature ramps were used. Prior to bonding, the wafers were cleaned in an RIE, oxygen plasma (30 mTorr, 250 watts) for 5 minutes, rinsed in an ultra-sonic bath for an additional 5 minutes, and spun dry. No HF dips were used to remove residual oxide and no effort was made to minimize moisture adsorption to the wafer surface. After pressing together, the wafers were ramped to 1000°C at a rate of ≈125°C/sec, soaked at 1000°C for 5 minutes and cooled to room temperature in ≈5 seconds. 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. 7). In this experiment Si wafers of 100 mm diameter and ≈500 μm thickness were used. To attain void-free bonds, the ramp rate must be reduced.

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 ≈2500 Å thermally grown oxide were plasma cleaned as in the previous experiment, dipped in dilute (100:1) HF for 1 minute, and ultrasonically rinsed in DI water for 5 minutes. The wafers were then pressed together and heated by microwave radiation. Infrared images of the results indicate a very uniform bond (Fig. 8). In this experiment the relatively thick layer of oxide is thought to prohibit the immediate reaction of freed oxygen with the silicon surface, thus eliminating the localized oxidation that occurred in the previous experiment, and allowing the bond to set uniformly.

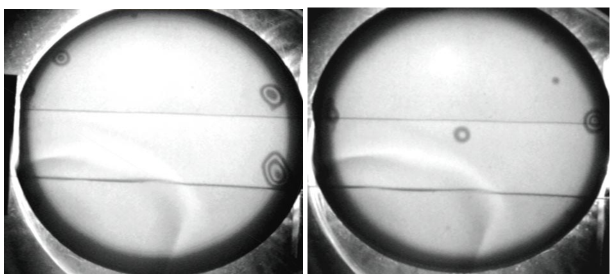

Fig. 6: IR images of EMIH bonded wafers heated for 5 minutes at 1000°C. Left: microwave. Right: RF

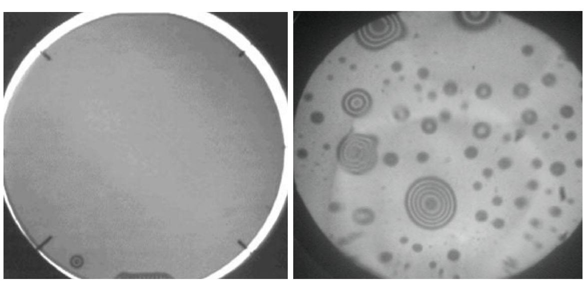

Fig. 7: IR images of a wafer pair before (left) and after (right) anneal for 5 min. at 1000°C. Voids are created from residual water when very high ramp rates are used with either RF or microwave heating.

In the final set of experiments, multi-wafer bonding was tested in the microwave system. Four pairs of 50 mm diameter wafers, each 250 µm 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 minutes. Knife-edge tests were unable to delaminate the bonds. This experiment demonstrated the potential for multiple stack rapid bonding using EMIH: if double-polished wafers had been used in this experiment, all eight would have bonded together.

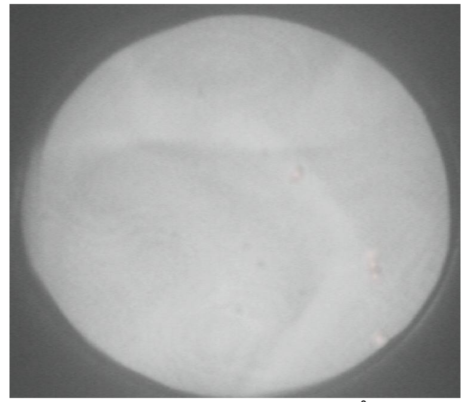

Fig. 8: IR image of wafers with 2500 Å oxides bonded by a 4 min. microwave EMIH anneal at 1000

V. CONCLUSION

The EMIH technique has been 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 heat. The low thermal budget and potential for batch processing makes it suitable for high volume manufacturing. Manufacturing SOI wafers is just one example of how this technique may be used in this capacity.

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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