

# Comparison of medium-vacuum and plasma-activated low-temperature wafer bonding

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**APC:** **Comparison of medium-vacuum and plasma-activated**  
**#1** **low-temperature wafer bonding**

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Two low-temperature wafer bonding methods, namely the medium-vacuum level wafer bonding (MVWB) and plasma-activated wafer bonding (PAWB), are performed. After low-temperature annealing (500 °C) for a short time (<5 h), the bond strength of these two low-temperature methods is improved as compared to the conventional air wafer bonding. The bond efficiency of MVWB is found to be better than the conventional air wafer bonding, but PAWB contains more bubbles. The qualitative mechanisms of these two low-temperature wafer bonding methods are proposed. © 2006 American Institute of Physics. [DOI: 10.1063/1.2185467]

Direct wafer bonding has attracted significant attention in the fields of microelectronics, three-dimensional (3D) device integration, system on chip (SOC), and microelectromechanical systems (MEMS). The trend now is toward low-temperature wafer bonding as conventional air wafer bonding requires high-temperature annealing above 800–1000 °C that would produce undesirable effect on the bonded materials and devices.

There are several methods to achieve high bond strength at low temperature, such as plasma-activated wafer bonding (PAWB),<sup>1</sup> nitric acid dipping wafer bonding<sup>2</sup> and vacuum wafer bonding.<sup>3–6</sup> Among them, vacuum bonding and PAWB have the potential of becoming a reliable low temperature bonding methods.

In this work, conventional air wafer bonding, medium-vacuum wafer bonding (MVWB) (with a vacuum level of 10<sup>-4</sup> mbar) and *ex situ* PAWB are performed for comparison. In this work, direct wafer bonding of one silicon wafer and another oxide wafer was conducted. The silicon wafers used are 4 in., 500 μm thick, *p*-type (100) standard bare wafers with resistivity of 1–50 Ω cm. The oxide wafers are silicon wafers with 500–600 nm thick thermal oxide, and the total thickness of the wafers is 500 μm. The details of the experiments can be found elsewhere in Refs. 5 and 7.

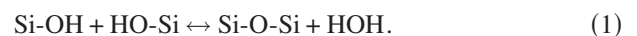
To assess the quality of wafer bonding, two basic but most important parameters are the bond strength and bond efficiency (i.e., the percentage of bonded area over the entire wafer area). The effects of annealing temperature and time on the three bonding methods are investigated here. The results of mean bond strength (as measured by pull test) within 5 h of annealing are shown in Fig. 1. Note here that the pull test is used instead of bond energy measurement because certain bonding in our work is so strong that we can hardly introduce the blade without cracking one of the bonded wafers. Also, the samples chosen for the pull test are those without bubbles, as observed under the scanning acoustic microscope (SAM).

From Fig. 1, it is apparent that MVWB and PAWB enhance the bond strength as compared to the conventional bonding, and MVWB achieves higher bond strength than

PAWB does. In all cases of MVWB and PAWB under different annealing temperatures (except 200 °C for PAWB), the bond strengths are above 10 MPa, which is high enough to withstand wafer dicing. Moreover, in the case of annealing over 400 °C in MVWB, most of the breakages are found to occur inside the silicon wafer during the pull test rather than at the bonded interface.

To show the bond efficiency of three bonding methods, SAM results of the bonded wafers with 4 h of annealing time at different annealing temperatures from 200 to 500 °C are shown in Fig. 2. One can see from Fig. 2 that MVWB reduces the number of bubbles at the bonding interface (in particular, the bond efficiency improves tremendously when the annealing temperature is above 300 °C). On the contrary, PAWB produces more bubbles as compared to the conventional air wafer bonding.

To explain the phenomena observed above, qualitative mechanisms of MVWB and PAWB are proposed. It is known that “vacuum” acts as a powerful “pump” that can suck the trapped gas, including water, out of the interface, and water will evaporate from the wafer even at room temperature for the vacuum level used.<sup>6</sup> The reduction of trapped air and water at the bonding interface under vacuum significantly increase the bonding sites and allow covalent bond (siloxane) to be developed through the polymerization of silanol bonds on the bonding surfaces, i.e., through the reverse reaction in Eq. (1), thus resulting in higher bond strength. This effect was proven by low-vacuum bonding<sup>6</sup> and it is believed that the medium vacuum used in this work takes the similar but stronger effect. Similarly, the bond efficiency is also improved because of the accelerated out-diffusion of trapped gas due to vacuum. Hence, the increase in the bonding strength is likely to be due to fewer and smaller interface bubbles rather than an increase of the bonding energy:



The qualitative mechanism of MVWB is modeled mathematically<sup>8</sup> and the modeling results agree well with the experimental data.

To explain the enhancement of the bond strength of PAWB, the mechanism of PAWB at low temperature is proposed here, which includes the following effects.

(1) *Removal of contaminants on the surface:* The presence

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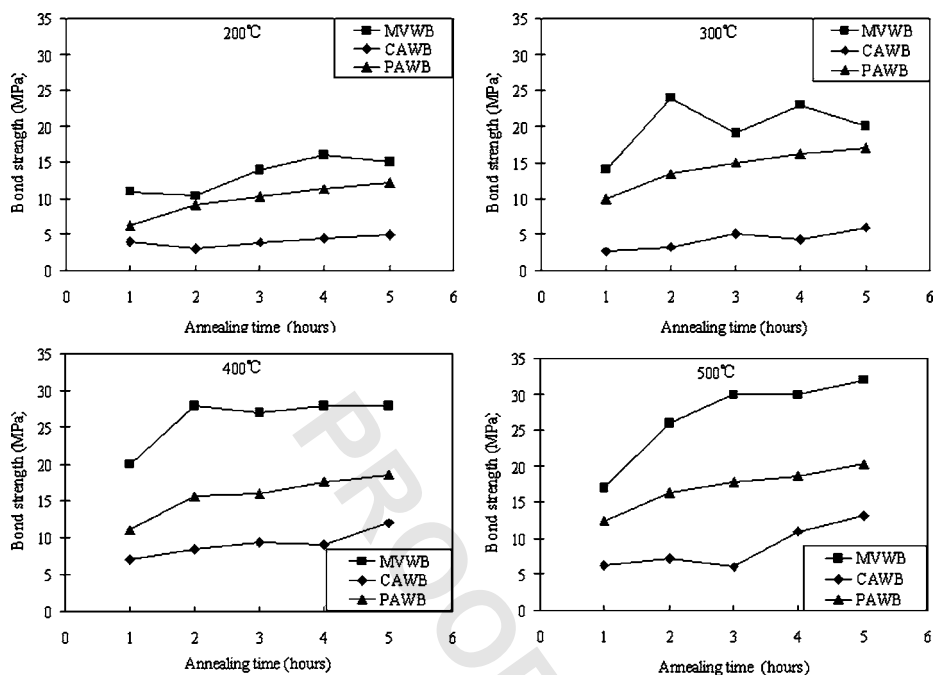


FIG. 1. Bond strength of conventional air wafer bonding, MVWB, and *ex situ* PAWB after different annealing temperature and time.

of contaminants and absorbents on wafer surface increase the surface potential barrier and avoids strong bonds. During plasma treatment, the surface is cleaned and more dangling bonds are produced which can contribute to the enhancement of the bonding energy.<sup>8,9</sup>

- (2) *Increase in the amount of silanol groups*: Bond strength usually correlates to the number of siloxane bonds, which are assumed to be generated by surface silanol groups through the chemical reaction shown in Eq. (1).<sup>10</sup> The plasma treatment prior to bonding has been thought to increase the number of silanol groups on the surface. However, Wiegand *et al.*<sup>11</sup> showed that the amounts of water and hydroxyl groups on the wafers treated by plasma are almost the same as that without plasma treatment. This is consistent with our contact angle measurement that measures the hydrophilicity of a surface, i.e., the density of the OH groups.<sup>8</sup>

To investigate if the number of silanol groups on the

wafer surfaces are indeed increased due to plasma treatment, we study the surface roughness after the treatment. Referring to Fig. 3, surfaces A and B have peaks and valleys equidistant from the mean surface centerline, i.e., both surfaces are considered statistically to have the same “roughness” based on the definitions of  $R_q$  and  $R_a$ , even though surface A contains noticeably more peaks than surface B. Hence, a better way to distinguish them is to characterize each surface’s feature frequency or wavelength by a method called power spectral density (PSD).<sup>12</sup>

The results of PSD measurement by atomic force microscopy (AFM) on different wafer pairs are shown in Fig. 4. One can see that the proportion of the small wavelength is increased after the Radio Corporation of America (RCA) cleaning and plasma treatment, which implies that the total surface area increases after the treatment. Thus, the total amount of the silanol groups indeed increases, even though the surface density of the silanol groups remains unchanged, and the bond strength is improved.

- (3) *Improvement of the diffusivity of water and gas trapped at the interface*: The creation of a damaged layer induced by plasma treatment is widely accepted, and it is considered to be a reason for the improvement of the bond strength at low temperature. The enhanced diffusivity of the water or gas at the interface will accelerate

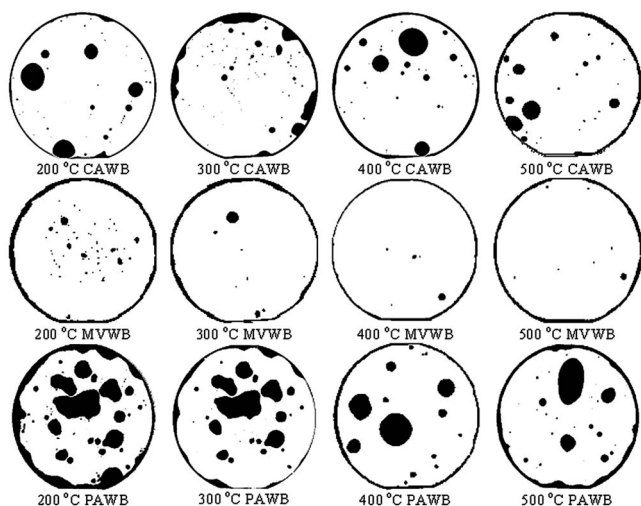


FIG. 2. SAM pictures of conventional bonding, MVWB, and *ex situ* PAWB after different annealing temperature.

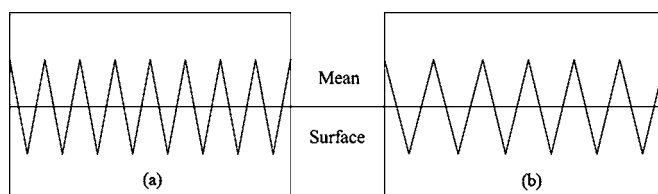


FIG. 3. Schematic of two surfaces with the same  $R_q$  and  $R_a$ , but different PSD.

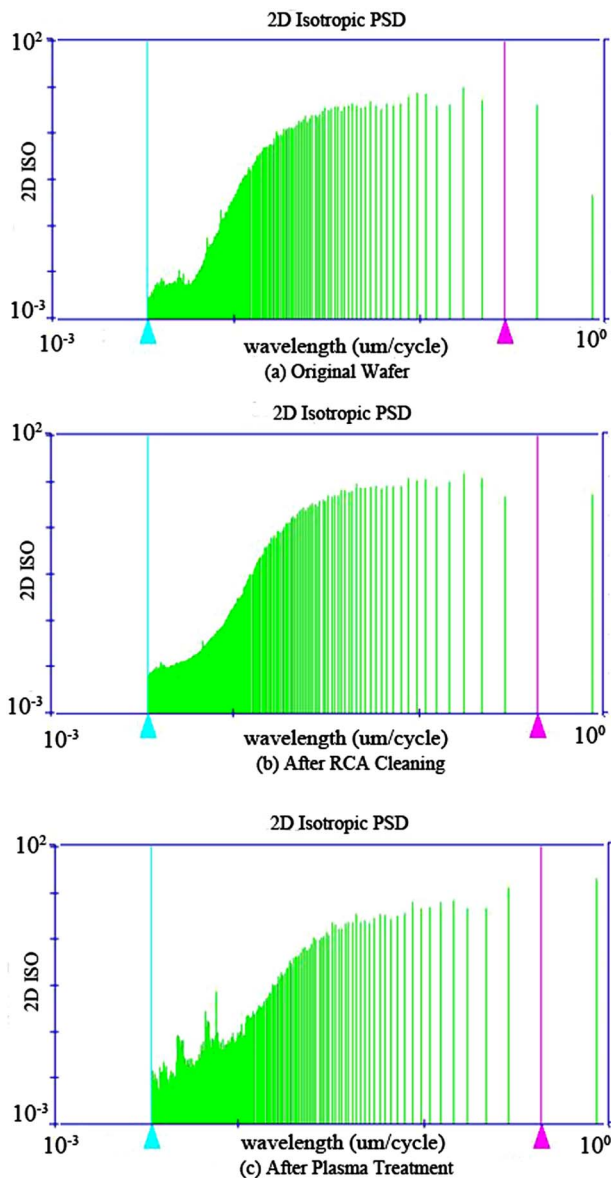


FIG. 4. (Color online) PSD of wafer surface after different processes.

the reversible chemical reaction in Eq. (1), thus enhancing the bond strength.

- (4) *Enhancement of viscous flow*: In the mechanism of conventional air wafer bonding, complete bonding is achieved via viscous flow of the surface layer at high temperature over 800 °C. Thus, to achieve high bond strength at low temperature, viscous flow of the surface

layer should have occurred at low temperature after PAWB treatment.

It was reported that the viscosity of SiO<sub>2</sub> is greatly reduced when the SiO<sub>2</sub> contains H<sub>2</sub>O (Ref. 13) at 600 °C, and since the damaged oxide layer by plasma treatment is porous and contains more water than it does before plasma treatment, its viscosity might be lower and viscous flow might take place at low temperature. As a result, the bond strength increases as larger contact area may now be available at low temperature. Further investigation of the reduction of the viscosity of SiO<sub>2</sub> after plasma treatment is required.

The higher number of bubbles at the bonding interface after PAWB can be understood from the contamination point of view. As our PAWB is an *ex situ* process, the plasma treated wafer surface is highly reactive and can easily absorb particles and contaminants in the air before bonding, causing a large number of bubbles at the interface after bonding. This is consistent with the work done by Tong *et al.*,<sup>14</sup> who showed that hydrocarbon related contaminants are the main source of bubbles in wafer bonding.

To summarize, MVWB and PAWB enhance the bond strength compared with conventional bonding. Cleaning, roughening, enhanced diffusivity, and lower viscosity of oxide are attributed to the increase of bond strength of MVWB and PAWB.

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