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Combined Surface-Activated Bonding Technique for Low-Temperature Hydrophilic Wafer Bonding with Interfacial Water Management

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Abstract

This work developed a combined surface-activated bonding (SAB) technique for low-temperature wafer bonding. This technique involves a combination of Ar beam bombardment, Si deposition, and water vapor exposure for prebonding surface activation prior to bonding in vacuum. It's found that a prebonding wafer attach step significantly improves the bonding strength. A high bonding energy close to Si bulk fracture energy was achieved after postbonding annealing in air at 200 °C. We suggest the increased bonding energy is due to the increase of chemisorbed water (–OH linked to Si sites) on the activated surfaces and prebonding removal of excess physisorbed water (H_2O).

1. Introduction

Wafer bonding is an important enabling technology for manufacturing silicon-on-insulator (SOI), micro-electromechanical systems (MEMS), and the emerging three-dimensional (3D) integration. Low-temperature wafer bonding techniques are highly desired to avoid thermal-related issues, such as thermal stress and damage. Hydrophilic wafer bonding approaches with wet chemical or plasma activation have been widely studied to improve bonding quality at decreased temperatures.[1] Typically, hydrophilic bonding is performed in humid air after prebonding surface treatment, followed by postbonding annealing. A hydrophilic wafer is prone to water physisorption (H_2O adsorption), which follows the water chemisorption (–OH adsorption on Si sites) in additional multilayers. A physisorbed water film of about 3 monolayers or 1 nm thick is covered on a hydroxylated SiO_2 wafer if it is exposed to an atmosphere at ~40% relative humidity.[2] During the bonding, the excess physisorbed water is trapped at the bonding interface and induces interfacial voids. In case of Si-Si bonding, hydrogen-filled voids are produced through the oxidation of the Si bulk by water. In case of SiO_2-SiO_2 bonding, water remains at the bonding interface even after a 400-600 °C annealing, generating water-filled voids.[3] The remaining water may also prevent bonding gap closure at a low temperature and weaken the bonding interface due to the water stress corrosion effect. Therefore, interfacial water management is a critical issue to improve the bonding quality in low-temperature hydrophilic wafer bonding. A main challenge of this task is that it is difficult to remove the trapped water by either prebonding or postbonding annealing.[3][4]

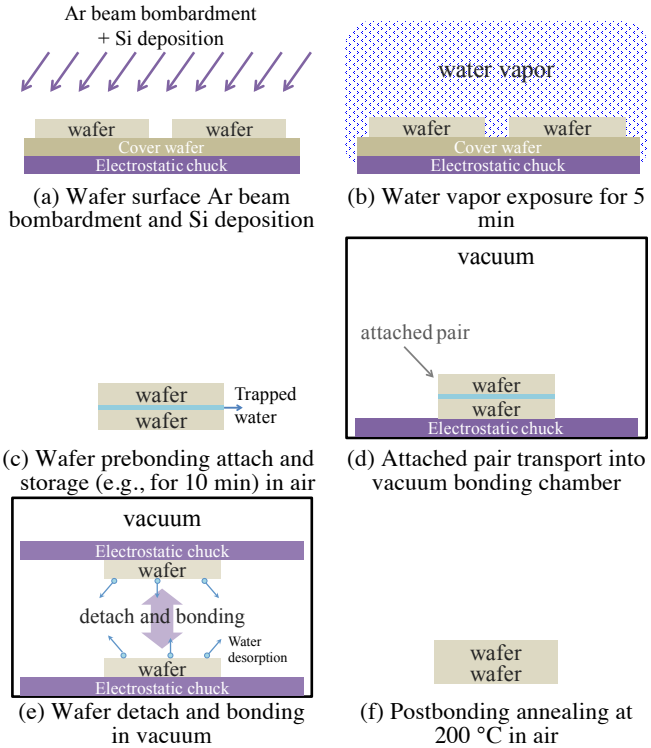
Wafer bonding in vacuum is a promising approach to minimize the trapped water, which easily desorbs from the wafer surfaces exposed to vacuum. However, performing wafer bonding in vacuum conditions does not simply improve the hydrophilic bonding quality. For instance, Q.-Y. Tong et al. reported that hydrophilic Si-Si bonding in vacuum after a wet cleaning results in a higher bonding energy,[5] but the improvement couldn't be reproduced according to later literatures.[6][7] Also, it's reported that SiO_2-SiO_2 yields a much lower bonding energy than Si-Si and Si-SiO_2 pairs by using the in situ plasma activation bonding performed in vacuum.[3]

Recently, a combined surface-activated bonding (SAB) technique was proposed for hydrophilic wafer bonding. This technique involves a combination of Ar ion beam bombardment, in situ silicon deposition, and water vapor exposure processes for surface activation prior to bonding in vacuum. An increased surface energy of more than 1 J/m^2 was achieved after 200 °C annealing through the increased Si–OH bonding sites on the activated surfaces.[8] In this paper, by using the combined SAB, a prebonding water attach in air was carried out after the water vapor exposure to further enhance the –OH chemisorption, i.e. Si–OH bonding sites formation. Surface and interface analysis were conducted to investigate the mechanism of the present bonding technique.

2. Experimental Methods

100-mm p-type Si wafers with a 500-nm-thick SiO_2 film thermally grown at 1050 °C were used for the wafer bonding experiments. The process flow of the combined SAB is shown in Fig. 1. The wafers were treated by Ar ion beam bombardment and simultaneously subjected to in situ silicon deposition. Line-type Ar ion beam bombardment at a power of 1.0 kV × 100 mA and a scanning speed of 7.5 mm/s was carried out to irradiate the wafers under ultrahigh vacuum at a pressure of less than 10^{-4} Pa. The in situ silicon deposition was carried out by using a Si-walled ion beam source. Then the wafers were exposed to water vapor for 5 min. Subsequently, the wafers were attached manually in air, with physisorbed water trapped between the wafers. After storage of the attached pairs in air for 3 min, 10 min, 3 hours, and 3 days, respectively, the wafer pairs were

transport into a vacuum bonding chamber with a pressure of 10^{-2} Pa. The wafers are detached by the electrostatic forces of the chucks to remove the interfacial excess water, and then bonded in vacuum at room temperature under a 5 kN loading force for 5 min. Finally, the bonded pair were annealed in air at 200 °C for 7 hours. The relatively long annealing was carried out to ensure the achievement of the saturated bonding energy at the given temperature.



(a) Wafer surface Ar beam bombardment and Si deposition

(b) Water vapor exposure for 5 min

(c) Wafer prebonding attach and storage (e.g., for 10 min) in air

(d) Attached pair transport into vacuum bonding chamber

(e) Wafer detach and bonding in vacuum

(f) Postbonding annealing at 200 °C in air

Fig. 1 Process flow of combined SAB for low-temperature hydrophilic wafer bonding.

Bonding energy was measured by the crack opening method performed in air and at room temperature. Wafer surfaces were analyzed by X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FT-IR). The bonding interface was inspected by infrared transmission imaging and transmission electron microscopy (TEM). Elemental analysis of the bonding interface was performed using an energy dispersive spectroscopy (EDS) attached to the TEM system.

3. Results and Discussions

Fig. 2 shows the surface energies of the SiO_2–SiO_2 interface measured by the crack opening method. Wafers were attached in air and stored in air after water vapor exposure and before transportation into the vacuum bonding chamber where the wafers were detached and bonded. The surface energy increases to 2.5 J/m^2 when the storage duration is 10 min or longer. We suggest that the enhanced bonding energy is due to the increased –OH chemisorption, which confirmed by XPS and FT-IR measurement, and prebonding removal of physisorbed H_2O.

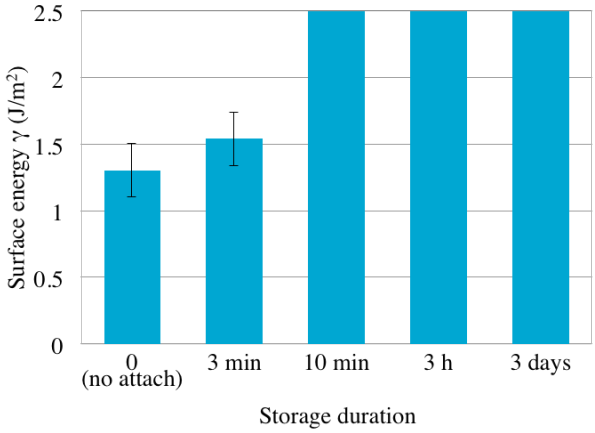


Fig. 2 Surface energies of SiO_2-SiO_2 bonded pairs versus storage duration of prebonding attached wafers.

4. Conclusions

In this work, hydrophilic SiO_2–SiO_2 bonding was studied by utilizing the combined SAB technique. Interfacial water was managed to increase Si–OH bonding sites and to remove excess trapped water prior to wafer bonding. A high bonding energy close to Si bulk fracture energy was achieved after postbonding annealing in air at 200°C.

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