Wafer Bonding Techniques for Microsystem Packaging

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Abstract. In this paper, the development of wafer bonding techniques of the most frequently used materials Si-to-glass, glass-to-glass and Si-to-Si is reported. To improve the bond quality of Si-to-glass and make glass-to-glass bonding viable at bonding temperatures less than 300 °C, a hydrogen-free amorphous silicon layer of 20-100 nm thickness is deposited as an intermediate layer. For Si-to-glass bonding, without applying the amorphous film, both the bond efficiency and bond strength are low. With the assistance of the amorphous film, the bond quality is significantly improved and the bonding temperature is reduced. Glass-to-glass bonding has also been successfully achieved at low temperatures, the high bond quality is still maintained. For Si-to-Si bonding, a tempered sol-gel film is deposited on Si wafer surface. The results show that promising Si-to-Si can be realized at bonding temperatures less than 300 °C. It is also suitable to III-V semiconductor compounds bonding. Based on the bonding techniques obtained above, any combination of Si, III-V semiconductor compounds and glass wafers can be bonded and integrated. The bonding techniques can be widely used for various microsystems packaging at low temperatures.

1. Introduction
Wafer bonding has increasingly become a key technology for materials integration in various areas of microelectromechanical systems (MEMS), microelectronics, and optoelectronics [1-3]. It is also widely used for vacuum packaging, hermetic sealing and encapsulation.

To bond wafers or substrates together, numerous techniques have been developed. These techniques can be categorized into anodic bonding, intermediate layer bonding, and direct bonding.

2. Experimental
2.1. Wafer Preparation, Film Deposition and Pre-cleaning
The silicon wafers used in the study are 4-inch, p-type, (100) standard bare wafers. The glass wafers used are 4-inch Pyrex 7740 borosilicate glass wafers. The surface roughness of the glass wafers, Ra, is less than 15 Å, and the flatness is better than 5 μm. The thicknesses of both silicon wafer and glass wafer are about 500 μm. To achieve low temperature bonding, an amorphous silicon thin film with thickness of 20-100 nm was deposited by sputtering onto the Si wafer for Si-to-glass bonding and onto one glass wafer for glass-to-glass bonding respectively. Si-to-Si bonding was carried out using direct bonding and with sol-gel intermediate layer. The sol-gel intermediate layer, which was prepared by adding diluted HNO₃ solution into a solution of tetraethylorthosilicate (TEOS) in ethanol, was obtained by spinning and tempering at different temperatures.
Prior to alignment, the surfaces of the silicon and glass wafers were cleaned in standard RCA solutions to remove the surface contaminants and imparted hydrophilic property. The surfaces of the film coated silicon wafer and glass wafer were cleaned in RCA solutions at a temperature of 60-80 °C. RCA is a solution with the following chemicals; RCA-1 (NH₄OH:H₂O₂:H₂O = 0.25:1:5) and/or RCA2 (HCl:H₂O₂:H₂O = 1:1:6). The clean wafers were rinsed with deionized (DI) water and dried in pure N₂. It is observed that the RCA cleaning caused the silicon and glass wafers to become hydrophilic.

2.2. Experimental Setup
After alignment, the stacked Si-to-glass, glass-to-glass and Si-to-Si wafers were placed in a bonding chamber. To avoid wafer contact during vacuumizing, the two wafers were separated by 20-50 microns thick spacers that were placed at the edges of the stacked wafers. During vacuumizing, both wafers were heated to the predetermined temperature. On reaching the predetermined temperature setting, the two wafers were initially brought into contact under pressure in the central area. Next, the spacers were removed to allow the rest of the surface of the wafers to come into contact.

2.3. Bond Strength and interface integrity
After bonding, the bonded pair was checked with scanning acoustic microscopy (SAM) and the micrographs were analyzed with an image analysis tool. For each bonding condition, three pairs of wafers were bonded. The wafers were diced into 10×10 mm² pieces for tensile strength measurement with an Instron tensile testing machine.

3. Anodic Bonding
Anodic bonding is widely used for bonding glass substrate to other conductive materials due to its good bond quality. It can serve as a hermetic and mechanical connection between glass and metal substrates or as a connection between glass and semiconductor substrates [4-7]. In anodic bonding, the substrates are typically heated to a temperature between 350 and 450 °C. A voltage of 400 to 1200 V is applied across the glass and the other substrate to be bonded. Glass-to-glass wafer bonding has not been investigated extensively. However, glass-to-glass bonding has found useful applications in bio-MEMS, microfluidic, displays and other areas due to the unique property of glass materials [8, 9].

![Figure 1](image)

**Figure 1.** Unbonded area versus bonding temperature at voltage of 600 V, bonding force of 200 N, bonding time of 10 minutes and vacuum of 1 Pa.

In our study, an amorphous Si film was applied on the Si or glass wafer prior to bond with another glass wafer. After SAM analysis, the unbonded area was measured and plotted in Figure 1. For Si-to-glass bonding, the unbonded area decreases markedly from 1.55% to 0.13% when the bonding
temperature is increased from 200 to 300 °C. However, the bubble-free interface can not be achieved. For a-Si-to-glass bonding, the unbonded area is largely reduced. The unbonded area decreases from 0.4% to 0.13% when the bonding temperature is increased from 200 to 225 °C. On increasing the bonding temperature to higher than 250 °C and the voltage is increased beyond 600 V, the total wafer area becomes bonded together. For glass-to-glass bonding, bubble-free interface can be achieved when the bonding temperature is higher than 275 °C.

The bond strength is an important factor for bond quality and reliability. Figure 2 shows the bond strength versus bonding temperature. The tensile strength of the bonded pairs is higher than 10 MPa for Si-to-glass and glass-to-glass bonding and higher than 20 MPa for the amorphous film coated silicon to glass bonding under all the bonding conditions.

![Bond strength versus bonding temperature.](image)

The bond strength increases with an increase in the bonding temperature. It is believed that the glass is annealed during bonding process and the fracture strength of the glass is improved. The bond strength of the bonded pairs of amorphous silicon film coated silicon and glass is higher than that of the bonded pairs of bare silicon and glass, especially at low bonding temperatures.

4. Direct Bonding
To achieve low temperature Si-Si, SiO₂-SiO₂ and Si-SiO₂ bonding, medium vacuum bonding was employed in our studies. With careful control of the cleaning process and bonding process, direct bonding at temperature of 400 °C and varied applied loads, bond efficiency of above 90% and bond strength of above 10 MPa have been obtained. The scanning acoustic microscopy (SAM) micrographs of the directly bonded wafers are shown in Figure 3. The bubble size, bubble number and the percentage of the unbonded area increase with an increase in the applied load. High applied loads keep the two wafer surfaces in tight contact at the early stage of wafer bonding. If there are impurities such as gases, water molecules and water rings are entrapped during bonding process, the tight contact prevents them from escaping from the bonding interfaces, with the result that bubbles and/or cavities are formed.

The applied loads have an effect on the bond strength (see upper curve in Figure 4. A higher applied load results in a lower bond strength. The bonded pairs have the highest bond strength when no load is applied. In all cases of vacuum wafer bonding, the bond strengths are above 19 MPa, which is high enough for practical applications, such as dicing and device fabrication.
Figure 3. C-SAM micrographs of the bonded wafers under different applied loads at temperature 400 °C, annealing time 2 h and vacuum $10^{-3}$ mbar (black area is bubble). (a) Applied load of 0 kN; (b) applied load of 1 kN; (c) applied load of 2 kN; and (d) applied load of 3 kN.

Figure 4. Comparison of bond strength under different loads.

5. Intermediate Layer Bonding

Normally, direct wafer bonding requires very smooth and clean wafer surface. Hence, high vacuum equipment are required for direct bonding. Intermediate layer bonding techniques have been developed for low temperature wafer bonding because of the less stringent requirements of the surface topography and cleanroom environment. Various low temperature wafer bonding processes using intermediate layers have been reported, such as with intermediate layers of sodium-rich glass, metal and polymer. The intermediate layers have been deposited on the wafer surface with thicknesses in the range of several microns. For polymers, sodium ions can degrade the performance of electronic devices and the thermal stability of polymers can be problematic if subsequent processing stages require heat treatment at elevated temperatures. Metal intermediate layers increase the difficulty of leading out the electrical circuit from a sealed cavity. Besides, these techniques may generate problems such as outgassing, low positioning accuracy, poor long-term reliability and uncertain bond quality.

To avoid the above problems, sol-gel amorphous silica layers can be used. Furthermore, there are several advantages. Firstly, sol-gel processing is essentially a low temperature process as the conversion of Si-OH groups into Si-O-Si units can occur at low temperatures [10, 17-19]. Secondly, it is possible to deposit a thin, uniform and homogeneous layer of amorphous silica on the substrates.
This effectively smoothen the initial wafer surface and enables rough surfaces to be bonded. Thirdly, the sol-gel films can be coated both the inside or outside of complex shapes over large areas. Finally, sol-gel processing is simple and low cost [11].

Sol-gel intermediate layer bonding is attractive in the applications such as transferring a CMOS circuit to a foreign substrate, combining MEMS and microelectronic circuits on silicon, combining photonic devices such as lasers and detectors with driver or amplifier circuits, or monolithic integration, which describes the integration of disparate devices onto a single chip [12]. The devices inside the wafers usually cannot endure high temperatures and high voltages, which is used in direct bonding and anodic bonding, respectively. Sol-gel intermediate layer bonding can provide a stable and insulated interlayer for these applications.

Some research results on sol-gel intermediate layer bonding have been reported [13]. Si-to-Si bonding has been achieved at a temperature of 300 °C, as shown in Figure 5. Prior to bonding, the sol-gel coating is annealed at different temperatures. The bonded area for room temperature annealing is about 55% and that for 100 °C annealed sol-gel bonding is about 60%. The low bonding areas are due to the incomplete depletion of the residual organic species in sol-gel intermediate layer. The bond efficiency of sol-gel bonding is improved to about 85% with an annealing temperature of 300 °C. Similar results are obtained using an annealing temperature of 500 °C. The bond strength of annealed sol-gel bonding is increased to about ~20 MPa when the annealing temperature is as high as 500 °C.

The above results show that the unbonded area is quite low. Further studies are being carried out to modify the bonding process to eliminate the bubbles in the interfaces. There is good potential for the bonding techniques to be developed for integrating and packaging various micro/nanosystems with a wide range of materials including Si, III–V semiconductor compounds, glass, and ceramic.

6. Conclusions
Low temperature wafer bonding has been successfully developed. For anodic bonding, the amorphous silicon nano-scale film plays an important role in the bonding process. High bond quality, such as high bond strength and high bond efficiency, has been obtained. The bond strength of Si/glass and glass/glass wafers is higher than 10 MPa, and the unbonded area in the whole wafer is less than 2.5%. Higher bonding temperatures and voltages are beneficial to achieve higher bond quality. The anodic bonding mechanisms are comprised of the oxidation of silicon and the hydrogen bonding between hydroxyl groups. For Si-to-Si bonding, it can be realized by using direct bonding approach or intermediate layer bonding approach. The bond strength higher than 10 MPa can be achieved, and the bond efficiency is above 85%. To achieve very low temperature bonding, an intermediate layer is essential, while the bond efficiency is becoming the concern.
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