HERMETIC WAFER BONDING BASED ON RAPID THERMAL PROCESSING

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ABSTRACT

Hermetic wafer bonding based on rapid thermal processing (RTP) has been demonstrated for the first time. Micro cavities are sealed by aluminum-glass bonding system under the bonding condition of 990°C for 2 seconds by using RTP. Reliability tests in both IPA and autoclave chamber show that 100 % of survival rate can be achieved when the aluminum bonding solder is 150 μm wide and 4.5 μm thick. It is found that the activation energy for RTP aluminum-to-glass bonding is 2.8 eV and the lowest successful bonding temperature is 760°C with a processing time of 30 minutes. A MEMS micro heater has been successfully packaged by the RTP bonding method and the heater is operational after the bonding process. This package demonstration shows that RTP bonding can overcome surface roughness of 2 μm as created by the interconnection line. Because RTP is a wafer-level process and is capable of providing low thermal budget, RTP bonding has promising potential for wafer-level MEMS fabrication and packaging.

INTRODUCTION

Wafer bonding is an important technology in both IC and MEMS processing. The existing bonding methods such as fusion and anodic bonding suffer from high temperature treatment, long processing time, requirement of flat surface and possible damages to the circuitry. For example, silicon-silicon direct wafer bonding requires bonding temperature over 1000°C on two flat substrates [1]. Solder bonding technology provides low processing temperature and reflow of solder such that it has potential application for MEMS packaging. However, flux used in conventional solder to improve wetting capability [2] may cause serious contamination problems for hermetic package [3]. Previously, pure aluminum has been used as solder in the aluminum-to-glass bonding system by localized heating and bonding [4]. This bonding method has the advantage of providing localized high bonding temperature for strong bonding. At the same time, it avoids possible damages due to global high temperature processing to circuitry or MEMS devices. However, it is difficult to implement localized aluminum-glass solder bonding massively and in parallel [5].

Rapid Thermal Processing is introduced as a bonding method for the first time in this paper. RTP can be easily conducted at the wafer-level and is capable of precise control of thermal budget [6]. Furthermore, RTP has been commonly used in IC post-processing because dopant redistribution in the microelectronics is minimized by using RTP as compared with regular annealing processes. Therefore, RTP bonding such as the one presented in this paper, may have the potential to solve

specific bonding problems in IC or MEMS processing and provide a new class of wafer bonding technique.

RTP BONDING CHARACTERISTICS

In order to demonstrate hermetic wafer bonding by using rapid thermal processing, an experimental set up is illustrated in Fig. 1. The aluminum-to-glass bonding is used as the demonstration example for the RTP bonding experiment. A silicon substrate is oxidized to grow 0.8 μm of thermal oxide. Aluminum is evaporated and patterned to form an encapsulation area around 400 x 400 μm^2 . The width of aluminum solder is designed to be 50, 100 and 150 μm with thickness varying from 2.5 to 4.5 μm to investigate the optimal RTP bonding parameters. A Pyrex glass substrate is placed on top and the whole set up is put into a RTP chamber [7]. The heat source is provided by 13 tungsten-halogen lamps, each produces 1.5 KW power. The testing specimen is heated up by thermal radiation with the temperature ramp up rate as high as 100°C per second (400-1000°C) and the cool down rate at around 50°C per second. A typical temperature profile for the RTP bonding pro-

Figure 1: The set up of aluminum-glass RTP bonding experiments.

cess is shown in Fig. 2. It only takes about 60 seconds to ramp up and cool down during the RTP bonding experiment such that possible dopant redistribution can be minimized [8, 9].

In order to characterize the RTP bonding process, a series of experiments with different combinations of bonding temperature and time have been conducted. Figure 3 shows two bonding curves by RTP and localized heating and bonding [10], respectively. The symbols represent the successful bonding con-

Figure 2: The temperature versus time plot in a RTP bonding experiment.

Figure 3: Aluminum-glass bonding experiments by RTP and localized heating.

ditions by using RTP. The correlation of bonding temperature and time is governed by the Arrhenius equation [10] as depicted by the straight lines. It is found that the activation energy for aluminum-glass RTP bonding is 2.8 eV as compared with 1.0 eV by using localized heating and bonding [10]. The discrepancy is probably due to different bonding conditions in establishing bonding curves such as history of applied pressure and temperature. In the RTP bonding curve in Fig. 3, only 2 seconds at $990 \pm 10^\circ\text{C}$ is needed to complete the bonding. On the other hand, it takes 30 minutes to complete the bonding for the lowest bonding temperature at 760°C .

Figure 4 is the bonding result under an optical microscope. Cavities with area of 200×200 , 300×300 and $400 \times 400 \mu\text{m}^2$ are sealed by aluminum-glass bonding and the widths of aluminum solder are 150, 100 and $50 \mu\text{m}$, respectively. Leak tests are conducted by immersing sealed cavities into IPA (Isopropanol Alcohol). In this particular case, one of the cavities at the right bottom site is not fully sealed such that IPA went into the cavity. Other cavities have survived the leak test since no sign of IPA penetration can be identified.

The aluminum-glass bond is forcefully broken to examine the

Figure 4: Leak test in isopropyl alcohol (IPA). Only the right bottom cavity shows leakage.

Figure 5: The SEM micrograph of glass wafer after forcefully breaking the bond.

Figure 6: The SEM microphoto of silicon substrate showing glass debris after forcefully breaking the bond.

bonding interface. Figure 5 is a close view SEM microphoto of the glass wafer after the bonds are forcefully broken. The originally flat glass wafer now has fractures along the bonding

boundaries. For the samples with 100 μm wide aluminum solder, glass fracture is measured to penetrate about 25 μm deep from the flat surface and to spread about 35 μm away from the boundary of aluminum solder. These indicate that very strong bonding is achieved. Furthermore, it has been observed that parts of glass debris are now attached to the aluminum solder on the silicon substrate as shown in Fig. 6. Therefore, it can be concluded that the bonding strength by RTP is comparable to the fracture toughness of glass at around 10 MPa. Occasionally, incomplete bonding area can be identified as the leakage path as shown in Fig. 7. In this case, a small area of aluminum solder is not bonded with glass probably due to poor mechanical contact between the solder and glass cap during the RTP bonding process. This problem may be solved by applying a proper pressure on the glass cap and the device substrate to assist intimate contact during the RTP bonding process.

Figure 7: Non-uniform bonding is identified as the path of leakage.

Two kinds of hermeticity tests are applied: (1) IPA leak test and (2) autoclave test under 120°C with 20.7Psi of steam for 80 minutes. IPA leak test is chosen because it is easier for IPA than water to penetrate small bonding defects in detecting gross leakage. As expected, cavities with thick and wide aluminum solder have better survival rate. It is found that the survival rate reaches 100 % if the aluminum solder has width of 150 μm and thickness of 3.8 μm . However, even in the worst case when the solder width is 50 μm and the thickness is 3.2 μm , more than 40 % of cavities still passed the IPA leak test. The major cause of failure is believed to be the lack of proper bonding pressure. In the current bonding set up, the bonding pressure comes only from the gravity force of the glass cap. As a result, non-uniform pressure distribution is expected during the RTP bonding process and failure occurs when the glass cap and the aluminum solder failed to have intimate contact. A mechanical fixture is currently under design to provide better bonding pressure and to improve the RTP bonding results. After the gross IPA leak test, packaged cavities are put into autoclave chamber for tests under harsh environment. The average survival rate is 75 % and reaches 100 % for cavities with wide and thick (such as 150 μm wide and 4.5 μm thick) aluminum solder. RTP bonding may have introduced severe thermal stress and planted possible failure mechanisms to cause long term stability problems. The autoclave testing serves as

accelerated testing and the results indicate that good reliability by RTP bonding can be accomplished if design parameters are optimized and bonding process is properly executed.

Figure 8: The cross sectional view of MEMS device packaging using aluminum-Pyrex glass bonding system by RTP.

RTP BONDING FOR MEMS PACKAGING

Figure 8 shows the cross sectional view of a micro resistive heater array with integrated aluminum solder at the boundary as a demonstration example of RTP bonding for MEMS packaging. First, a silicon substrate is grown with a 2 μm thick thermal oxide layer. It is followed by a 2 μm thick undoped LPCVD polysilicon deposition. The first mask is then used to pattern the heater array, electrical interconnection lines and contact pads. A 4.5 μm LPCVD PSG is then deposited as an electrical insulation layer. The wafer is then annealed at 1000°C for 2 hours as the drive-in process to make polysilicon conductive. Aluminum solder of 4.5 μm thick and 50 μm wide is then evaporated and patterned by the lift-off process to form the encapsulation area. The final mask opens the device and contact pad area by selective wet etching of PSG.

After going through the RTP bonding process at 990°C for 2 seconds, the packaged device is immersed in IPA as shown in Fig. 9. The device area is 400x400 μm^2 . From the contrast color in the figure, IPA stays outside and does not go inside the cavity for more than 20 days and this long term testing is still going. Shown in Fig. 10 is one of the micro heaters working under the glass package. It is found that the resistance of the micro heater changes from 0.8 K Ω to 0.7 K Ω before and after RTP bonding process probably due to the activation of dopant. Although further characterizations are required, no major damages to the microelectronics are expected for this RTP bonding process.

After forcefully breaking the bond, the silicon substrate is shown in Fig. 11. The bond appears to be strong and uniform such that breakages occur on glass cap and some glass debris are left on the silicon substrate. A portion of PSG on the top surface of polysilicon interconnection lines seems to react partially with glass substrate as shown in the same figure. This implies that glass-glass fusion bonding may also be achieved by RTP processing. Furthermore, the polysilicon interconnection line creates a 2 μm step higher than the surrounding areas. The fact that hermetic bonding was achieved proves that this

aluminum-glass RTP bonding process can overcome the surface roughness of $2\text{ }\mu\text{m}$ or less during the bonding process.

Figure 9: Hermetically sealed MEMS resistive heaters by RTP bonding under IPA leak test.

Figure 10: Glowing heater under glass package.

CONCLUSION

Hermetic wafer bonding by Rapid Thermal Processing on aluminum-glass bonding system has been demonstrated. RTP bonding characteristics, including width and thickness of aluminum solder, process time versus temperature and bonding interface have been investigated. It is found that the activation energy of RTP bonding for aluminum-to-glass system is 2.8 eV . Packaged dies have been put into both IPA and autoclave tests for reliability evaluation. It is found that if bonding parameters and process are carefully chosen, 100 % survival rate can be achieved. A micro heater array has been hermetically packaged by using the RTP bonding process and three important conclusions have been drawn. First, RTP bonding successfully overcome the $2\text{ }\mu\text{m}$ step caused by interconnection line. Second, hermetic sealing is accomplished because the packaged cavity has passed IPA test. Third, the device is operative after the RTP bonding.

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Figure 11: Silicon substrate after breaking the bond.

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