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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. Microcavities encapsulated between glass and silicon substrate have been sealed with aluminum solder by using RTP at 990°C for 2 s. Reliability experiments of IPA leak and autoclave accelerated tests show that 100% of survival rate can be achieved. The best encapsulation results are accomplished when the aluminum bonding solder is 150 μm wide and 4.5 μm thick. Furthermore, it is found that the activation energy for Al-glass RTP bonding system is 3.5 eV and the lowest successful bonding temperature is 760°C with a processing time of 30 min. In the device-packaging demonstrations, a microheater and a surface micromachined heatuator have been successfully packaged by the RTP bonding method and are operational after the bonding process. This work demonstrates that RTP bonding can provide low thermal budget, insensitivity to rough surfaces, and excellent bonding characteristics. As such, it has promising potential for wafer-level MEMS fabrication and packaging.

Keywords: Rapid thermal processing; Hermetic wafer bonding; MEMS packaging

1. 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 of over 1000°C on two flat substrates [1]. Silicon-glass anodic bonding requires surface roughness of <1 μm [2] for successful bonding results. On the other hand, solder bonding technology is capable of low processing temperature with reflow of solder and may be applicable to MEMS packaging applications. However, flux used in conventional solder to improve wetting capability [3] may cause serious contamination problems for hermetic package [4]. To advance the current wafer bonding processes, new bonding technology should be developed for low thermal budget, wafer-level processing, and insensitivity to surface roughness of the device substrate.

Previously, pure aluminum has been used as solder in the Al-glass bonding system by localized heating and bonding [5]. This bonding method takes the advantage of localized high bonding temperature for strong bonding. At the same time, the global temperature is kept low to avoid possible damages to circuitry or MEMS devices. However, it is difficult to implement localized Al-glass solder bonding massively and in parallel [5].

Rapid thermal processing (RTP) 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 processing and dopant redistribution in microelectronics. The thermal budget can be minimized by using RTP as compared with annealing processes by using regular furnaces. As such, RTP bonding may have the potential to solve specific bonding problems in IC or MEMS processing and provide a new class of wafer bonding technique.

2. RTP bonding characteristics

In order to demonstrate hermetic wafer bonding by using RTP, an experimental set up is illustrated in Fig. 1. The Al-glass bonding systems is used as the demonstration example for the RTP bonding experiment. For Al-glass bonding system, 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 μm × 400 μm. 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

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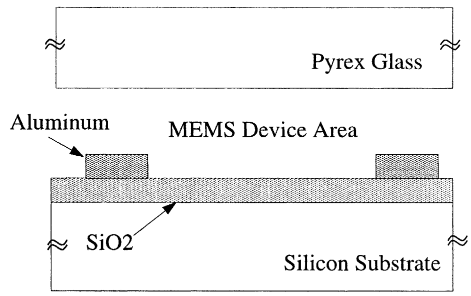

Fig. 1. The set up of Al-glass RTP bonding experiments.

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 of power. The testing specimen is heated up by thermal radiation with the temperature ramp up rate as high as 100°C/s (400–1000°C) and the cool down rate at around 50°C/s. A typical temperature profile for the RTP bonding process is shown in Fig. 2. It only takes about 60 s to ramp up and cool down the system 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 bonding experiments with different combinations of bonding temperature and time have been conducted for the Al-glass bonding system. Fig. 3 shows the bonding

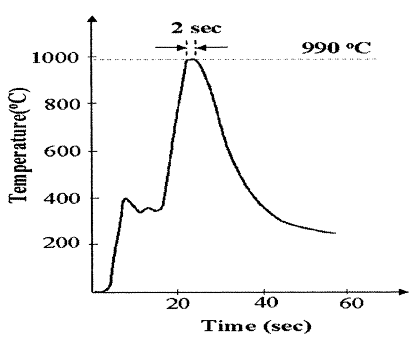

Fig. 2. The temperature vs. time plot in a RTP bonding experiment.

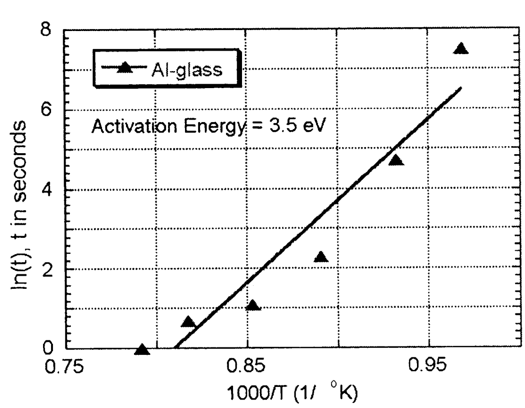

Fig. 3. Bonding experiments of the RTP Al-glass. The activation energy is found as 3.5 eV.

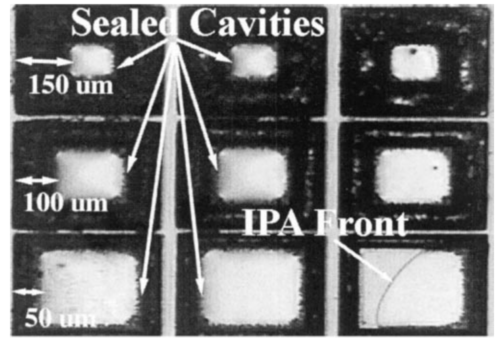

Fig. 4. Leak test in isopropyl alcohol (IPA). Only the right bottom cavity shows leakage.

results by RTP. The symbols represent the successful bonding conditions by using RTP. It is found that correlation of bonding temperature and time is governed by the Arrhenius equation with activation energy of 3.5 eV. In the localized heating and bonding experiment [10], the activation energy is found as 1.0 eV for the Al-glass bonding system. The discrepancy is probably due to different bonding conditions in both bonding methods, such as history of applied pressure and temperature. In the RTP bonding experiments, only 2 s at 990 ± 10°C is needed to complete the bonding. On the other hand, it takes 30 min to complete the bonding at the lowest successful bonding temperature of 760°C.

Fig. 4 shows the bonding result under an optical microscope. Cavities with areas of 200 μm × 200 μm, 300 μm × 300 μm and 400 μm × 400 μm are sealed by Al-glass bonding and the widths of aluminum solder are 150, 100 and 50 μm, respectively. Leak tests are conducted by immersing sealed cavities into isopropanol alcohol (IPA). In this particular case, one of the cavities at the right bottom position 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 after the IPA leak test to examine the bonding interface. Fig. 5 is a close view SEM microphoto of the glass wafer after the bonds are forcefully broken. The original glass wafer now has fractures along the bonding boundaries. For bonding

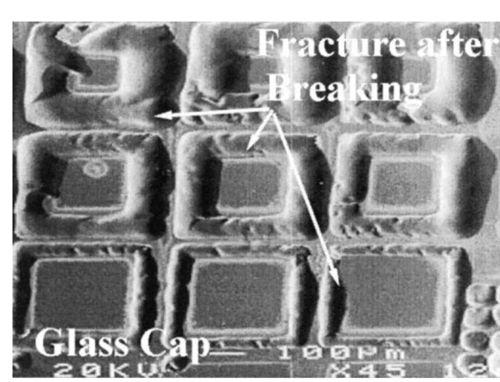

Fig. 5. Glass wafer under SEM showing uniform bonding after breaking the bond.

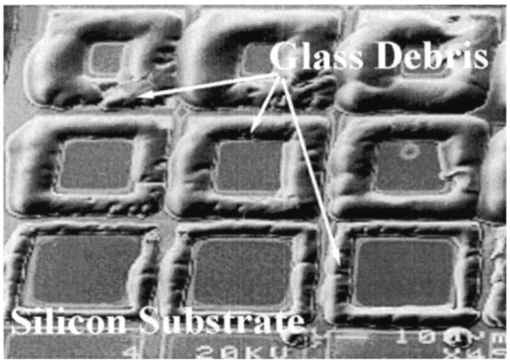

Fig. 6. The SEM microphoto of silicon substrate showing glass debris after breaking the bond.

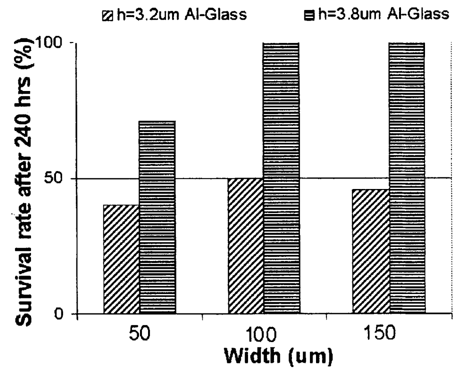

Fig. 8. IPA leak test by immersing packaged dies into IPA for 240 h, "h" is the aluminum solder thickness.

experiments with 100 μm wide of aluminum solder, glass fracture is measured to penetrate about 25 μm deep from the surface and to spread about 35 μm away from the boundary of aluminum solder. The penetration and spreading indicate possible high residual thermal stress in these areas. Furthermore, it has been observed that parts of glass debris are attached to the aluminum solder on the silicon substrate as shown in Fig. 6. This implies that the local bonding strength is comparable to the fracture toughness of glass at around 10 MPa. Occasionally, incomplete bonding area can be identified and becomes 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 bonding pressure to assure intimate contact during the RTP bonding process.

Two kinds of hermeticity tests are conducted: (1) IPA leak test and (2) autoclave test at 120°C and 20.7 psi of steam for 80 min. IPA leak test is chosen because it is easier for IPA than water to penetrate small bonding defects in detecting gross leakage. In the preliminary characterizations, 21 samples have been tested for 240 h as shown in Fig. 8. For Al-glass bonding system, 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, >40% of cavities still passed the IPA leak test. Moreover, for the cavities with 3.2 μm thick aluminum solder, the survival rate for the 150 μm solder width case is less than that of 100 μm case. The inconsistency of experimental trend could come from the insufficient number of samples. Further statistical characterization is needed. The major cause of failure is believed to be the lack of proper bonding pressure. In this bonding set up, the bonding pressure is provided 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, successfully packaged cavities are put into autoclave chamber for tests under harsh environment. The average survival rate after 80 min is 75% and it reaches 100% for cavities with wide and thick (such as 150 μm wide and 4.5 μm thick) aluminum solder as shown is Fig. 9. RTP bonding may have introduced severe thermal stress and planted possible failure mechanisms to cause long

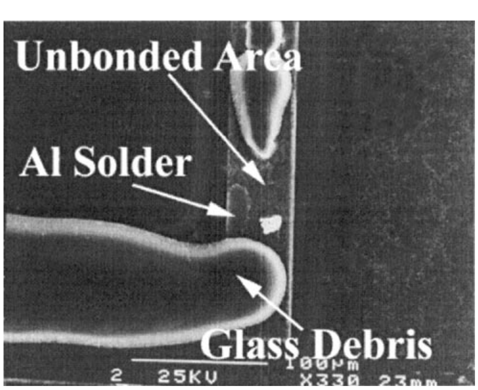

Fig. 7. Non-uniform bonding is identified as the path of leakage.

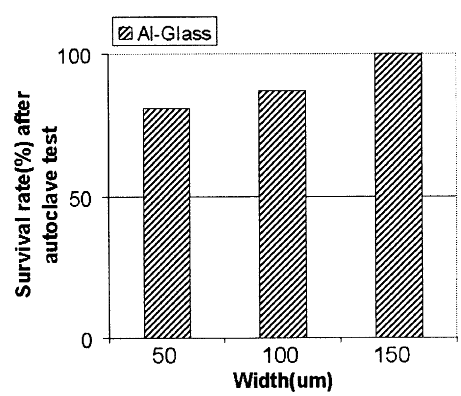

Fig. 9. Autoclave test by putting packaged dies in a 120°C, 20.7 psi steam chamber for 80 min. All the tested dies have passed IPA leak test.

term stability problems. The autoclave testing serves as accelerated testing and the results prove that good reliability by RTP bonding can be accomplished.

3. RTP bonding for MEMS packaging

A microresistive heater array with integrated aluminum solder is used to demonstrate RTP bonding for MEMS packaging as shown in Fig. 10. 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 s, the packaged chip is immersed in IPA as shown in Fig. 11. The device area is 400 μm × 400 μm. From the contrast color in the figure, IPA stays outside and does not go inside the cavity. Heater is operational after the RTP bonding process as shown in Fig. 12. It is found that the resistance of the microheater changes from 0.8 to 0.7 K 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 by this RTP bonding process.

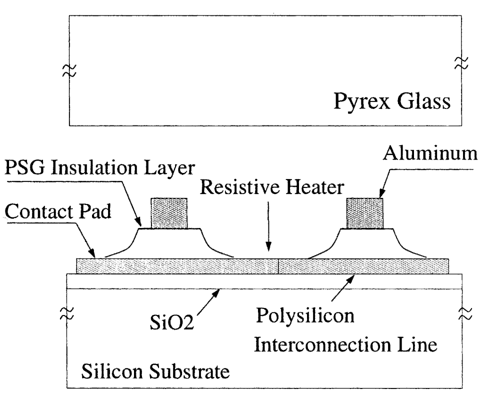

Fig. 10. The cross-sectional view of MEMS device packaging using aluminum-Pyrex glass bonding system by RTP.

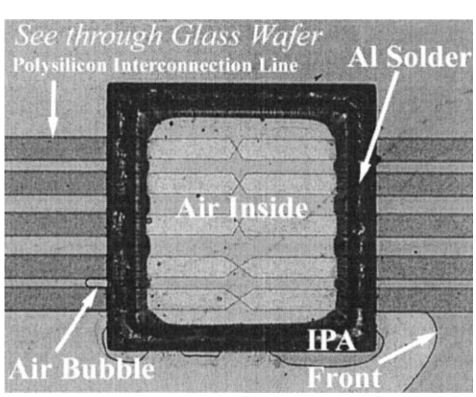

Fig. 11. Hermetically sealed MEMS resistive heaters by RTP bonding under IPA leak test.

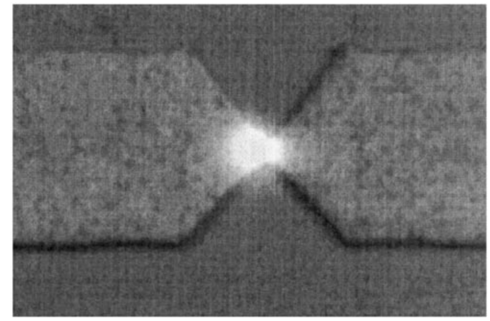

Fig. 12. Glowing heater under glass package.

After forcefully breaking the bond, the silicon substrate is shown in Fig. 13. 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. 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 at least 2 μm.

Microheatuators has also been packaged by the RTP bonding method. The fabrication process of microheatuators is similar to the standard surface micromachining process [11] except that an additional PSG layer of 4.5 μm thick is added to provide enough height to prevent the glass cap from contacting with the suspended MEMS structure. Aluminum

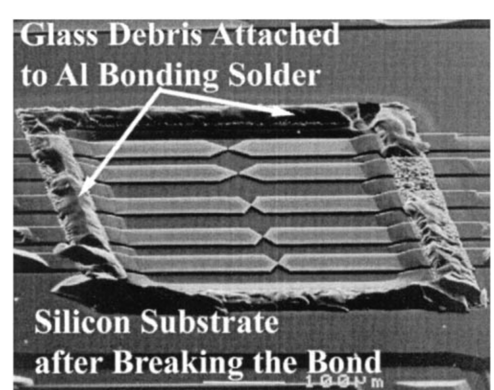

Fig. 13. Silicon substrate after breaking the bond.

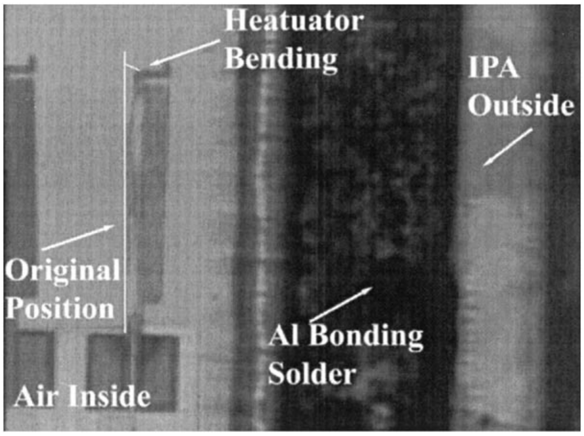

Fig. 14. Heatuator is bending under glass package.

solder of 4.5 μm thick is formed by the lift-off process and the final mask is used to open the device and contact pad areas. After the bonding process, the packaged chip is immersed in IPA and heatuators are found operational as shown in Fig. 14.

4. Conclusion

Hermetic wafer bonding by RTP on the Al-glass bonding system has been demonstrated. RTP bonding characteristics, including width and thickness of aluminum solder, processing time versus temperature, bonding interfaces, and reliability evaluations by using IPA and autoclave tests have been investigated. The activation energy for the Al-glass bonding system is characterized as 3.5 eV by using RTP bonding. Furthermore, it has been demonstrated that 100% survival rate for the encapsulated cavities to pass both the IPA and autoclave tests can be achieved when the aluminum solder is 4.5 μm thick and 150 μm wide. A microheater array and a surface micromachined heatuator have been hermetically packaged by using the RTP bonding process and have been operational afterwards. Three important conclusions have been drawn. First, the RTP bonding process can overcome at least 2 μm step-up surface roughness as created by the polysilicon interconnection line. Second, hermetic sealing is accomplished as the packaged cavities passed IPA tests. Third, MEMS devices are operative after the RTP bonding process.

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