ROOM TEMPERATURE SEAL-RING AU-TO-AU BONDING HERMETICITY AND RELIABILITY TESTING

Amrid Amnache[1,2], Paul Gond-Charton[3] and Luc G. Fréchette[1,2]*
[1]Institut Interdisciplinaire d'Innovation Technologique (3IT), Université de Sherbrooke, Sherbrooke, Canada
[2]Laboratoire Nanotechnologies et Nanosystèmes (LN2), CNRS UMI-3463, Université de Sherbrooke, Sherbrooke, Canada
[3]Teledyne Dalsa Semiconductor, Canada

ABSTRACT

Room temperature Au-to-Au bonding has shown a promising potential for microelectromechanical systems (MEMS) encapsulation. However, the long-term reliability remains one of the critical concerns for the integration of this bonding technology in MEMS wafer-level fabrication. We have demonstrated the hermeticity and reliability of room temperature Au-to-Au bonding of thin seal-rings as narrow as 40 µm. Hermiticity was demonstrated over more than one-year at ambient conditions, corresponding to a leak rate below 10^{-12} $Pa.m^3s^{-1}$. Also, accelerated hermeticity testing in an elevated temperature and humid environment has shown excellent reliability for the first time. This type of bonding appears to be a suitable method for MEMS wafer-level packaging that requires low temperatures and/or operation in harsh environments.

KEYWORDS

Wafer Bonding, Gold-to-Gold, Room Temperature, Hermeticity, Reliability.

INTRODUCTION

Microelectromechanical systems (MEMS) often require hermetic packaging to ensure their functionalities for long-term operation. The encapsulation serves to avoid damaging of the MEMS components during the fabrication steps e.g. dicing and chip handling, and to avoid contamination e.g. moisture and particles during the lifetime of the MEMS devices. For some MEMS such as inertial sensors [1], [2], the encapsulation serves also to maintain a certain ambient pressure inside the cavity to keep the operation stable during the MEMS lifetime. Those MEMS often require vacuum inside the cavity to keep their mechanical damping characteristics. Leakage overtime can result in lowering the sensitivity of the device and thus degradation of its functionalities. Today's robust and hermetic wafer-level bonding technologies, including thermocompression bonding [3], direct bonding [4], anodic bonding [5] and eutectic bonding [6], enable excellent encapsulation hermeticity even for prolonged lifetime of over 20 years [3]. Compared to components-level packaging, wafer-level bonding has a cost saving benefit since it enables batch processing [7], [8]. These wafer-level bonding technologies unfortunately need high thermal budget (>200°C) which limits the use of temperature-sensitive materials and the control of post-bonding thermomechanical stress.

Recently, a promising direct bonding method has been demonstrated at room temperature (RT) using thin gold films as intermediate bonding layers [9], [10]. Preliminary studies have shown excellent hermeticity with this bonding approach [9], but reliability test and the impact of seal-ring width have however not been reported before. It is important to predict how long the package formed using this bonding technology will remain hermetic overtime.

The objective in this work is to demonstrate the hermetic reliability of thin seal-rings formed by RT Au-to-Au bonding. This work also aims to obtain a quantitative study of the RT Au-to-Au bonding reliability in harsh environments.

HERMETICITY MEASUREMENT

The quality of RT Au-to-Au bonding is evaluated by studying the hermeticity. There are many test methods to evaluate hermeticity [11] including and not limited to helium leak test, Q-factor measurement, and Raman spectroscopy. In this work, the hermeticity is evaluated with two different methods: the membrane deflection and the Krypton-85 leak testing.

Membrane deflection method

We used the membrane deflection method to evaluate the hermeticity of the bond. It consists of a hermetically closed chamber formed by bonding a seal-ring between cap and cavity wafers under vacuum. The pressure difference between the cavity and the ambient induces deflection of a membrane formed in the cap wafer. The membrane needs to be flexible enough in order to obtain measurable deflection values. By measuring shift of the membrane deflection over time, the hermeticity can be estimated using the elasticity equations [4].

The membrane deflection, ω, can be calculated by the following equation [4]:

$$\omega = \alpha \frac{\Delta P\, a^4}{\delta^3} \frac{1-\gamma^2}{E} \tag{1}$$

where E is Young modulus, γ is Poisson's ratio, α is a constant (1/66 for square membranes), a is the membrane side length, δ is the membrane thickness, and ΔP is the pressure difference between the inside and outside of the cavity.

The maximum leak rate (MLR) can be estimated by the following equation [4]:

$$\text{MLR} = \frac{\alpha\,(1-\gamma^2)}{E} \frac{a^2}{\delta^3 d} \frac{\Delta t}{\Delta\omega} \tag{2}$$

where d is the depth of the cavity, Δt is the elapsed time after bonding, and $\Delta\omega$ is the membrane deflection change over time.

This method has advantages to be non-destructive and simple for implementation. However, for accurate measurement, a long time would be necessary to measure any change of the membrane deflection.

Krypton-85 leak testing

The hermeticity of the bonded samples is also measured using the Kypton-85 leak testing method. This highly sensitive method has an advantage to be capable to measure lower leak rates with fast test time and relatively low cost. The method consists of using Kr-85 as a tracer gas to estimate the hermeticity of the sealing. The sample is first put into a bombing chamber with a pressurized gas mixture of air and small quantities of Kr-85. If the sealing has a leak, the gas will enter the cavity. After the bombing cycle, the sample is analyzed using a scintillation counter, which is capable of detecting residual Kr-85 that have entered the cavity. The total leak rate can then be calculated. This method is also used to validate results from the membrane deflection method.

RELIABILITY VERIFICATION

The reliability of the Au-to-Au bonding is evaluated using autoclave standard testing. This known testing method [12]–[14] determines if the bonding can withstand temperature, humidity corrosion and pressure simultaneously. The samples to be tested are subjected to hot pressurized water vapor in an autoclave.

By assuming that the leak is caused by a capillary flow through the seal ring, the leak rate Q can be calculated by the Knudsen formula [15]:

$$Q = \frac{2\pi}{3}\frac{r^3}{l}\sqrt{\frac{8RT}{\pi M}}(P_2 - P_1) \quad (3)$$

where r is the capillary radius, l is the capillary length, R is the universal gas constant, T is the temperature, M is the molecular mass of gas, P_2 is the high pressure and P_1 is the low pressure.

The acceleration factor AF due to the pressure in the autoclave can be evaluated as the ratio between the leak rate at normal conditions of the product and the leak rate at the accelerated conditions. When using same gas at the accelerated test than at the normal conditions, the accelerated factor can be calculated by the following formula:

$$AF = \frac{(P_2 - P_1)_{normal}}{(P_2 - P_1)_{accelerated}} \quad (4)$$

BONDING PROCESS

Figure 1 illustrates the fabrication process flow of a wafer-level Au-to-Au bonding prior to hermeticity and reliability testing. A pair of two silicon wafers of 100 mm diameter are used to perform this bonding. One wafer of 350 µm thickness named cavity wafer and another wafer of 525 µm thickness named cap wafer. The cavity wafer serves to create the square cavity chamber and the deflecting membrane. First, the wafer is cleaned with RCA and then thermally oxidized to form 100 nm of SiO_2. This thin layer serves to protect the bonding surface from degradation through the microfabrication process, and will be removed before bonding. Lithography is performed followed by reactive ion etching (RIE) of the oxide layer. Using the same photoresist mask, 130 µm of silicon is etched by deep reactive ion etching (DRIE). The cavity, seal ring and the support walls are therefore patterned as illustrated in Fig.1a. Four different seal-ring widths are formed, 40, 80, 120 and 160 µm. In order to support the stress induced by the membrane deflection, thick walls are formed from each side of the seal ring. Intentional openings are created in the support walls to ensure access of environment gas to the seal ring. The photoresist is striped after etching using acetone and the cavity wafer is cleaned with Piranha solution (1:2 mixture of H_2O_2:H_2SO_4) for 10 min. Afterwards, the oxide layer is removed using hydrofluoric solution (HF 49%) for 15 s. The cap wafer as illustrated in Fig.1b serves to close and seal the cavity chamber once bonded to the cavity wafer. Prior to bonding,

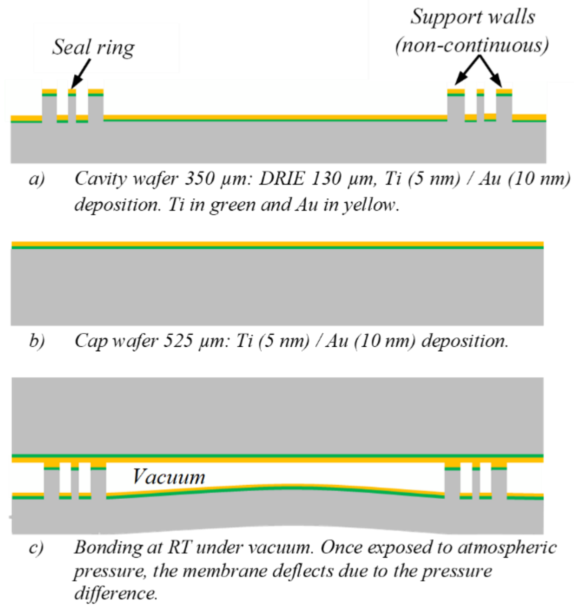

Figure 1: Process flow of RT Au-to-Au bonded devices prior to hermeticity and reliability testing.

the cap and cavity wafers are cleaned with RCA and then coated with 5/10 nm of Ti/Au by evaporation. Bonding is done under vacuum at ambient temperature creating hermetic vacuum chambers with membranes as illustrated in Fig.1c. The air pressure inside the bonding chamber is set to 1×10^{-5} mbar. Membranes are 3 or 10 mm width and 230 µm thick. Note that the variation of the membrane thickness is +/- 10 µm. The variation comes from the DRIE nonuniformity. A uniform contact load of 200 N is applied in order to initiate the bonding. It is important to note that the dwell time between the deposition of Ti/Au and the bonding was less than 15 min.

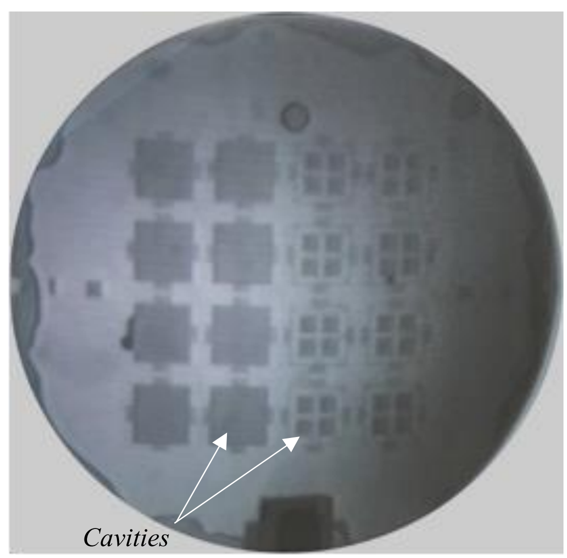

Figure 2: Infrared photograph showing the quality of Au-to-Au bonding at room temperature. Wafer diameter is 100 mm. It shows two set of cavities: 8 cavities with 10 mm membrane (left side) and 32 cavities with 3 mm membranes (right side).

Figure 2 shows an infrared characterization of the bonded wafers. It shows uniform bonding except defect on the wafer edges and random voids that can be caused by dust particles. This process otherwise shows high quality wafer bonding at room temperature. The bonded wafers are diced into individual square chips to evaluate the hermeticity of the bond. Two set of cavities were fabricated: 8 cavities with 10 mm membrane and 32 cavities with 3 mm membranes as shown in Fig. 2. The curvature of the deflected membranes was seen just after dicing for the larger membranes.

EXPERIMENTS AND RESULTS

Storage life testing

A total of seven samples (10 mm square membranes) with different seal-ring widths were stored in air environment with controlled humidity and temperature (20°C, 1 atm, 40% RH). Results of the measured membrane deflection over time are shown in Fig.3. The maximum deflection (center of the membrane) was measured by a mechanical profilometer. In respect of the measurement errors, the experimental results match well with the analytical deflection calculated by eq. 1 to be 7.5 µm. It is observed that for all samples, the deflection remained unchanged over more than 400 days of storage. It can be concluded that there is no significant change in hermeticity of the seal. Furthermore, for the characterized elapsed time, the results show that there is no impact of the seal-ring width on the hermeticity. Additional time may be needed to observe such effect.

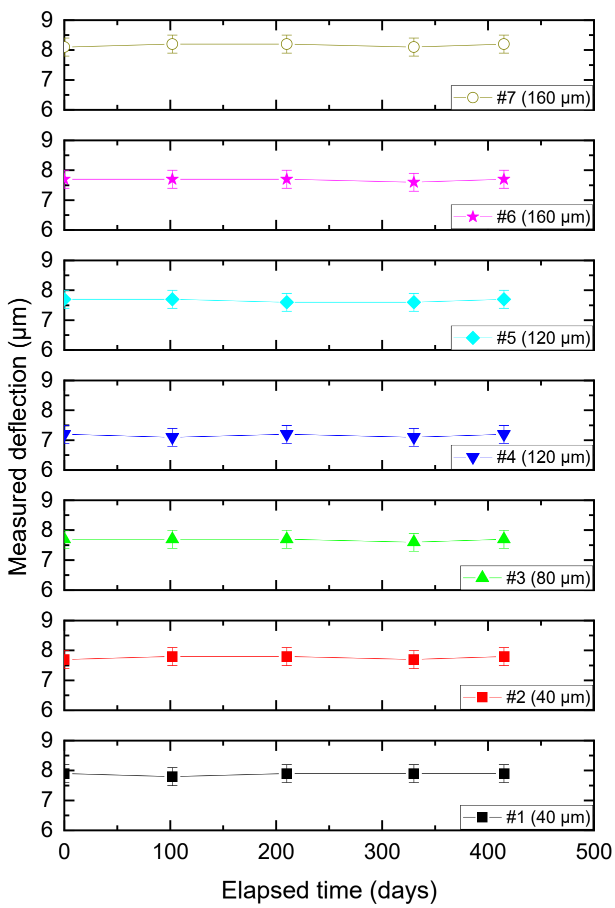

Figure 3: Measured membrane deflection with different seal-ring widths showing no leakage for over a year. The error bars of +/- 0.3 µm come from the profilometry measurement. Measurement began the same day after dicing the bonded wafers.

Figure 4 is the plot of the measured membrane deflection overtime of sample #1 (as plotted in Fig. 3) with the calculated deflection by eq. 2 assuming two different MLR (10^{-11} and 10^{-12} Pa.m^{3}s^{-1}). From the plot, it can be observed that there is a large difference between the deflection calculated for MLR of 10^{-11} Pa.m^{3}s^{-1} and the real deflection change overtime of the sample #1. There is however no significant difference of the measured deflection and the calculated deflection for MLR of 10^{-12} Pa.m^{3}s^{-1}. The MLR is then estimated to be equal or less than 10^{-12} Pa.m^{3}s^{-1} in this study. It is five orders of magnitude greater than the minimum leak rate required for various MEMS [11]. Additional testing time would be required to measure lower leak rate.

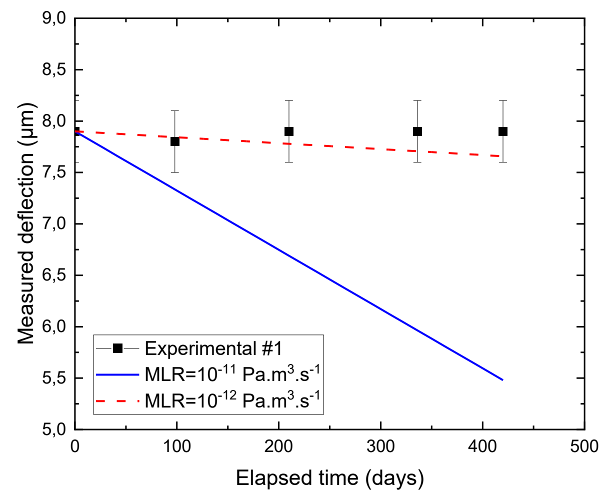

Figure 4 Evaluation of the maximum leak rate based on the membrane deflection change for sample #1.

Krypton-85 gross and fine leak testing

The hermeticity of the bonded samples was also analyzed using the Kypton-85 leak testing method (test done by Oneida Research Services) according to Mil-std-750F, method 1071.16. A total of 24 samples with membranes of 3 mm width are used to perform this test (cavities on the right side in Fig.2). Dry and wet gross leak tests, and fine leak test were conducted successively. Table 1 shows the leak test conditions and the failure criteria. A total of 18 samples passed the fine leak test with a detected leak rate <5×10^{-11} Pa.m^{3}s^{-1}. This result validated the measurement done using the membrane deflection method and shows one more time the high hermetic performance of the Au-to-Au bonding. Only 6 samples failed the wet gross leak. Bonding defects (random voids) as shown in Fig.2 are probably the reason. Same as for the membrane deflection results, there is no observed impact of the seal-ring width on the hermeticity.

Table 1 Kr-85 gross and fine leak test conditions.

Test method	Bombing time (hrs)	Bombing pressure (psia)	Failure criteria
Dry gross leak	0.05	30	Kr-85 counting >500 c/m
Wet gross leak	0.2	50	Red dye observed and/or Kr-85 detection
Fine leak	16.03	45	Leak rate >5×10^{-11} Pa.m^{3}s^{-1}

Accelerated reliability testing

In order to demonstrate the robustness of the RT Au-to-Au bonding, we pursue further with reliability testing. The same samples used to measure the membrane are put into a heated autoclave filled with steam at 120°C/2 bars/100% RH. Based on visual observation, it was shown that all the seven samples survived testing. Quantitatively, the membrane deflection remained unchanged after testing for 216 hours., as shown in Fig. 5. As observed for the storage life testing, there is no impact of the seal-ring width on the membrane deflection change overtime. Probably, more testing time is needed to be able to detect any effect. By assuming the normal conditions for the product to be 50% RH and 20°C with the partial water vapor pressure of 12 mbar, the AF calculated by eq. 4 is 166. Thus, based on the testing results of 216 hours of autoclave, the bonding lifetime in the normal conditions can extend to more than 4 year.

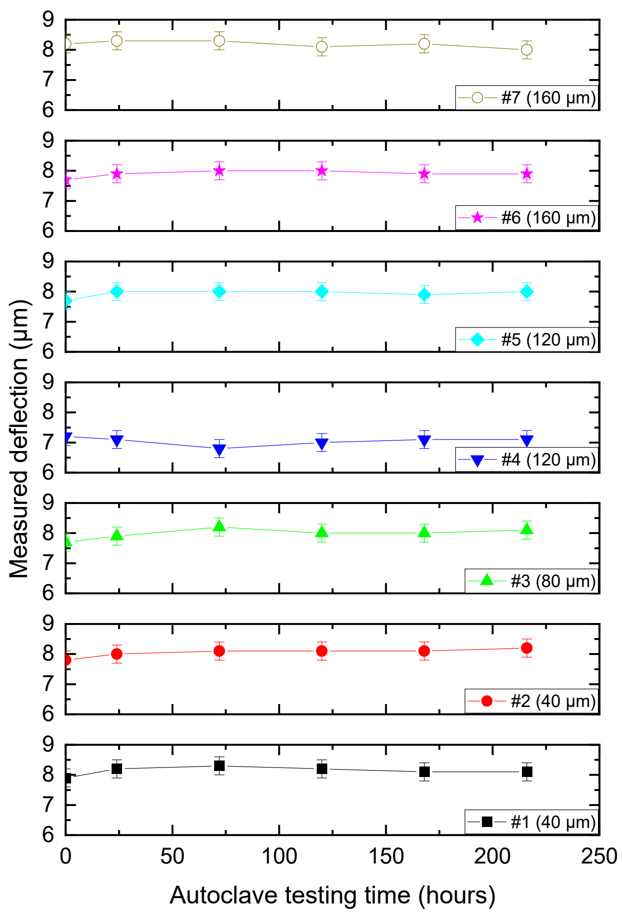

Figure 5: Measured membrane deflection with different seal ring widths showing no leakage for over 200 hr of autoclave testing.

CONCLUSION

The room temperature Au-to-Au bonding performed in this work showed potential for hermetic and reliable sealing with thin seal-rings, as narrow as 40 µm. The measured leak rate was found to be below 10^{-12} Pa.m^{3}s^{-1} using the membrane deflection method and below 5×10^{-11} Pa.m^{3}s^{-1} using the Kr-85 leak test method. Also, reliability testing has shown that this bonding method offers excellent reliability in harsh (hot and humid) environments. This allows MEMS researchers to consider this type of bonding in their applications needing hermetic and reliable operation, but with temperature sensitive materials that could not withstand traditional wafer bonding techniques.

ACKNOWLEDGEMENTS

The authors would like to thank Vincent Pares, Mohamed Walid Hassen and Doriane Hassaine Daoudji for their help towards the testing procedures. Support from the Canada Research Chair Program (NSERC), Canadian Foundation for Innovation (CFI) are gracefully appreciated.

REFERENCES

[1] I. B. Flader *et al.*, “Micro-tethering for fabrication of encapsulated inertial sensors with high sensitivity,” *Journal of Microelectromechanical Systems*, vol. 28, no. 3, 2019.
[2] A. Efimovskaya *et al.*, “Compact roll-pitch-yaw gyroscope implemented in wafer-level Epitaxial Silicon Encapsulation process,” 2017.
[3] J. Fan, L. Peng, K. H. Li, and C. S. Tan, “Wafer-level hermetic packaging of 3D microsystems with low-temperature Cu-to-Cu thermo-compression bonding and its reliability,” *Journal of Micromechanics and Microengineering*, vol. 22, no. 10, 2012.
[4] R. Stricher *et al.*, “In Situ Doped Polysilicon (ISDP) Hydrophilic Direct Wafer Bonding for MEMS Applications,” *ECS Journal of Solid State Science and Technology*, vol. 10, no. 6, 2021.
[5] A. Duan, K. Wang, K. Aasmundtveit, and N. Hoivik, “Characterization of wafer-level bonded hermetic packages using optical leak detection,” in *International Symposium on Photoelectronic Detection and Imaging 2009: Material and Device Technology for Sensors*, 2009, vol. 7381.
[6] T. Akashi, H. Funabashi, H. Takagi, Y. Omura, and Y. Hata, “Wafer-level hermetic vacuum packaging by bonding with a copper-tin thin film sealing ring,” *Journal of Micromechanics and Microengineering*, vol. 28, no. 4, 2018.
[7] C. S. Tan, J. Fan, D. F. Lim, G. Y. Chong, and K. H. Li, “Low temperature wafer-level bonding for hermetic packaging of 3D microsystems,” *Journal of Micromechanics and Microengineering*, vol. 21, no. 7, 2011.
[8] J. Xu, Y. Du, Y. Tian, and C. Wang, “Progress in wafer bonding technology towards MEMS, high-power electronics, optoelectronics, and optofluidics,” *International Journal of Optomechatronics*, vol. 14, no. 1. 2020.
[9] M. Yamamoto *et al.*, “Room-temperature pressureless wafer-scale hermetic sealing in air and vacuum using surface activated bonding with ultrathin Au films,” *Japanese Journal of Applied Physics*, vol. 59, no. SB, 2020.
[10] T. Shimatsu and M. Uomoto, “(Invited) Room Temperature Bonding of Wafers with Thin Nanocrystalline Metal Films,” *ECS Transactions*, vol. 33, no. 4, 2019.
[11] S. Millar and M. Desmulliez, “MEMS ultra low leak detection methods: A review,” *Sensor Review*, vol. 29, no. 4, 2009.
[12] Y. T. Cheng, L. Lin, and K. Najafi, “A hermetic glass-silicon package formed using localized aluminum/silicon-glass bonding,” *Journal of Microelectromechanical Systems*, vol. 10, no. 3, 2001.
[13] P. J. van der Wel *et al.*, “Hermeticity testing of capacitive RF MEMS switches,” 2008.
[14] S. J. Ham *et al.*, “Characterization and reliability verification of wafer-level hermetic package with nano-liter cavity for RF-MEMS applications,” 2007.
[15] Y. Tao and A. P. Malshe, “Theoretical investigation on hermeticity testing of MEMS packages based on MIL-STD-883E,” *Microelectronics Reliability*, vol. 45, no. 3–4, 2005.

CONTACT

*Amrid Amnache, tel: +1-819-919-2628;
amrid.amnache@usherbrooke.ca