Sensors and Actuators A 224 (2015) 169–176

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Wafer level hermetic sealing of MEMS devices with vertical feedthroughs using anodic bonding[☆,☆☆]

Mustafa Mert Torunbalci[a,*], Said Emre Alper[a], Tayfun Akin[b]

[a] *Middle East Technical University, MEMS Research and Applications Center, 06530, Ankara, Turkey*
[b] *Middle East Technical University, Department of Electrical and Electronics Engineering, MEMS Research and Applications Center, and Micro and Nano Technology Graduate Program, Ankara, Turkey*

ARTICLE INFO

Article history:
Received 1 October 2014
Received in revised form 23 January 2015
Accepted 29 January 2015
Available online 7 February 2015

Keywords:
Wafer level hermetic packaging
Vertical feedthroughs
Anodic bonding
Advanced MEMS (*aMEMS*) process

ABSTRACT

This paper presents a new method for wafer-level hermetic packaging of MEMS devices using a relatively low temperature anodic bonding technique applied to the recently developed advanced MEMS (aMEMS) process. The aMEMS process uses vertical feedthroughs formed on an SOI cap wafer, eliminating the need for any complex via-refill or trench-refill steps while forming the vertical feedthroughs. The hermetic sealing process is achieved at 350 °C by using an anodic bonding potential of 600 V. The bonding process does not require any sealing material on neither the cap nor the sensor wafer. The packaging yield is experimentally verified to be 94% for 4 wafers packaged up to date, and the cavity pressure is measured to be as low as 1 mTorr with successfully activated Titanium thin film getter. The cavity pressure can be set to different levels ranging from 1 mTorr up to 5 Torr, simply by varying the outgassing period and utilization of the getter material, enabling the proposed method be used for various types of MEMS devices with different pressure requirements. The pressure inside the encapsulated cavities has been monitored for 6 months since the first prototypes, and it is observed that pressure is stable below 5 mTorr throughout this period. The shear strength of 6 packages is measured to be above 10 MPa, whereas the shear failure occurs not at the bonding interface but the vertical feedthroughs, which have lower strength compared to the bonding region. The robustness of the packages is tested by subjecting them to cyclic thermal tests between 100 °C and 25 °C, and no degradation is observed in the hermeticity of the packages at the end of this period. The vacuum level of the packages is also verified to be unchanged by storing the packages at 150 °C for 24 h. Moreover, it is experimentally verified that the hermeticity of the packaged chips can withstand ultra-high temperature shocks as high as 400 °C for 5 min.

1. Introduction

Micro-electro-mechanical systems (MEMS) is key enabling technology that combine electronics with tiny mechanical devices to develop the state-of-the-art transducers, sensors, actuators, resonators, etc. used in a variety of applications ranging from consumer electronic market towards the automotive and other industrial products. MEMS products offer the advantages of lower cost, better compatibility with high-volume batch fabrication, smaller size, and higher reliability compared to the conventional electromechanical systems. The core of the MEMS products includes high precision micromachined electro-mechanical components that transduce physical, chemical, biological, etc. signals to electrical signals. Some of these components such as gas flow and pressure sensors must have a direct physical contact with the outer world. On the other hand, a great variety of the components, including but not limited to the inertial sensors, resonators, and infrared detectors, must be isolated from the atmosphere of the ambient in which they are operated. This isolation is necessary for two reasons: (i) forming a strictly-controlled operating atmosphere for the MEMS component, (ii) keeping these fragile components mechanically safe from dust, vibration, or any other kind of physical damage [1]. Isolation of the MEMS components from the external ambient is simply achieved by encapsulating them in hermetically-sealed packages.

There are two common methods for the hermetic sealing of MEMS packages: (i) die level packaging and (ii) wafer level

---

[☆] Manuscript submitted September, 2014. An earlier version of this paper was presented at the 2014 Eurosensors Conference (Paper ID 5275, A method of fabricating vacuum packages with vertical feedthroughs in a wafer level anodic bonding process); and was published in its proceedings.

[☆☆] Selected papers presented at EUROSENSORS 2014, the XXVIII edition of the conference series, Brescia, Italy, September 7–10, 2014.

[*] Corresponding author. Tel.: +90 312 210 63 36; fax: +90 312 210 2304.
E-mail addresses: mert_torunbalci@hotmail.com, mtorunbalci@mems.metu.edu.tr (M.M. Torunbalci), said@metu.edu.tr (S.E. Alper), tayfun-akin@metu.edu.tr (T. Akin).

http://dx.doi.org/10.1016/j.sna.2015.01.034

packaging [2]. Die level packaging is the way of sealing each MEMS device individually, which not only increases the packaging cost and labor time but also decreases the process yield and reliability. An obviously better alternative is to seal the MEMS devices at the wafer level, which reduces the packaging costs significantly by minimizing the labor and time as well as increasing the process yield and reliability.

Wafer level packaging typically refers to the use of wafer level MEMS processing techniques to form a capping element, which can be a thin-film layer or a separate wafer, on top of a sensor wafer that contains the devices to be packaged [3]. This way, all the MEMS devices located on the sensor wafer can be encapsulated simultaneously. In the thin film packaging approach, various types of thin films are deposited on top of MEMS device wafer as a capping layer by using the conventional thin film deposition techniques for the hermetic sealing [4–7]. Although the thin-film capping layer may provide sufficient hermeticity for the sensors that it encapsulates, the robustness of the packaged chip would be quite limited, and possibly require an additional mechanical protection [7]. Moreover, this technique does not typically allow the use of thin film getters inside the capping thin-film layer, which limits the cavity pressure to levels that are not sufficient for many MEMS devices. On the other hand, hermetic sealing by conventional wafer bonding techniques typically use a separate cap wafer for the wafer level hermetic encapsulation, which provides not only perfect mechanical robustness but also enables excellent vacuum levels by using thin film getters.

There are already well established wafer-level hermetic vacuum packaging methods for MEMS, where the glass frit [8], Au–Si eutectic [9], and Au–In, Au–Sn, and Cu–Sn Transient Liquid Phase (TLP) bonding [10,11] techniques are a few examples. However, these techniques require an intermediate bonding material, increasing not only the fabrication process steps in the metal-based bonding approaches due to the need of using an isolation layer between metal sensor lead and sealing material but also the bonding temperature and packaging stress in the glass frit bonding approach. The anodic bonding technique [12], however, does not require a special intermediate bonding layer, provides a simple, relatively low temperature (possible down to 250 °C [13]), and uniform hermetic bonding between glass and silicon wafers. On the other hand, this technique cannot be applied to the MEMS devices with lateral feedthroughs for two main reasons: (1) The step heights formed by the lateral feedthroughs can easily destroy the hermeticity of the anodic bonding, (2) The bonding process requires an electrical isolation layer covering the lateral feedthrough lines, which must withstand high bonding voltage, seals the step heights caused by the feedthrough lines hermetically, and be compatible with an anodic bonding process. These problems can all be eliminated by using vertical feedthroughs, but such vertical structures typically require complex via-refill or trench-refill steps [14–19], which makes the process difficult and costly. METU-MEMS Center has recently developed and reported a new wafer-level packaging process using vertical feedthroughs [20,21], called the aMEMS process, which does not require any complex via-refill or trench-refill steps. The hermetic sealing in aMEMS is achieved by different eutectic bonding methods [20,21].

This paper reports an evolution of the aMEMS process by adapting it to the anodic bonding based hermetic sealing, which allows not only a wide bonding temperature range from 250 °C up to 450 °C but also provides a thermocompression-free, very high-yield, high-strength, repeatable, and reliable packaging [22].

2. Package design and fabrication

Fig. 1 shows the three-dimensional (3-D) view of the wafer level encapsulation method which is achieved by adapting the aMEMS process to the anodic bonding technique. Vertical feedthroughs and the sealing wall are made from highly doped silicon and formed simultaneously by etching the device layer of an SOI cap wafer, whereas the via openings are formed by etching the handle layer. The exposed faces of the vertical feedthroughs can be accessed externally by wire bonds, eliminating any need for via-refill as in [23].

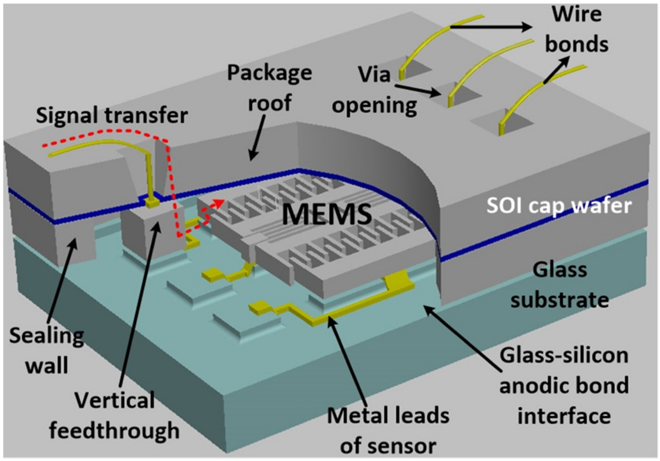


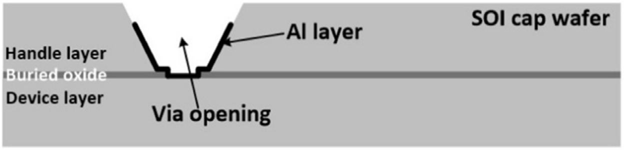
Fig. 1. Three-dimensional (3-D) view of the wafer level encapsulation method which is achieved by adapting the aMEMS process to the anodic bonding technique.

Fig. 2 shows the major fabrication process steps of the proposed method. The process starts with an SOI cap wafer on which the via openings are formed by using the KOH wet etch (Fig. 2(a)). The 300 μm thick handle layer of the SOI cap wafer defines both the thickness of the package roof in Fig. 1 and also specifies the dimensions of the vertical feedthroughs. Next, the handle and device silicon layers of the SOI cap wafer are electrically shorted with a thin film Aluminum layer prior to the anodic bonding. This is achieved by first etching the buried oxide (Fig. 2(b)) and then patterning the Aluminum layer (Fig. 2(c)) inside the via opening. The final step of the cap wafer process is to simultaneously form the vertical feedthroughs, sealing walls, and cavity on the device layer of the SOI wafer with DRIE. Two different device layer thicknesses, namely 100 μm and 300 μm, are used in this work in order to check the effect of different cavity volumes on the package vacuum level. After the cap wafer fabrication, thin film getters are deposited inside the cavities by using a custom designed shadow mask. The getter material consists of 1 μm thick 4.3 mm × 2.6 mm Titanium film for the maximum available area in the cavity, having a volume of $11.2 \times 10^6\ \mu\text{m}^3$. The getter material can be deposited either with evaporation or sputtering techniques (Fig. 2(d)). The corresponding sensor wafer is fabricated by using a modified silicon-on-glass (M-SOG) technology as in [24] which includes suspended silicon resonators on the glass substrate and additional glass anchors without any sealing material for the hermetic sealing with the anodic bonding. The sensor wafer also contains Cr/Au shield metal which is used to prevent the unintentional stiction of suspended silicon sensors during the anodic bonding (Fig. 2(f)). The SOI cap wafer is then anodically bonded to the sensor wafer by applying 600 V at about 350–400 °C (Fig. 2(e)). The Titanium getter is inherently activated during the anodic bonding, improving the package pressure. After the wafer level encapsulation process, the Aluminum layer inside the via opening is stripped and Cr/Au pad metals are formed inside the via openings by using the lift-off technique. The signal transfer is then achieved by conventional wire bonds (Fig. 2(f)).

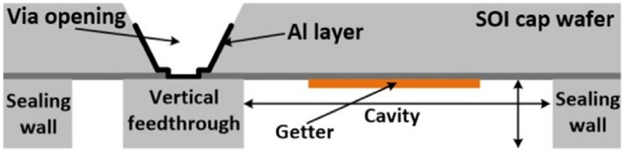
Fig. 3 shows the SEM pictures of the MEMS dies fabricated using the proposed method, providing the details of the via openings,

a) Formation of via openings on the handle layer with KOH

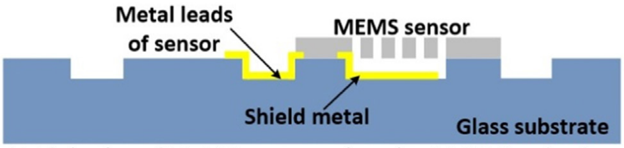
b) Buried oxide etching with BHF



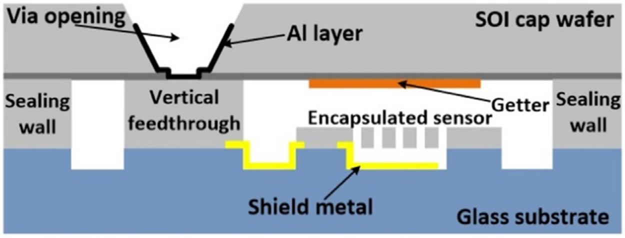
c) Handle and device silicon layers of the SOI cap wafer is electrically shorted with Al layer



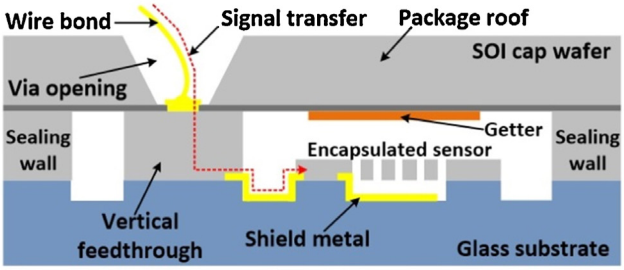
d) Vertical feedthroughs and sealing walls are simultaneously formed with DRIE, getters are deposited with shadow mask



e) Fabrication of MEMS sensor wafer using M-SOG technology



f) Wafer level hermetic packaging with anodic bonding



g) Removal of Al layer, pad metal formation, and wire bonding

Fig. 2. Major fabrication steps of the proposed method.

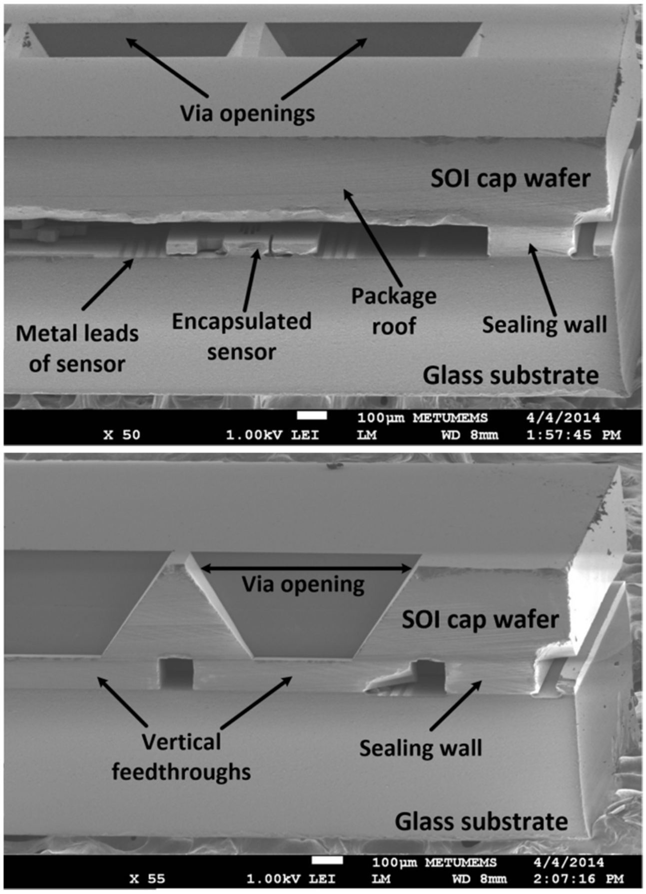


Fig. 3. SEM pictures of MEMS dies using the proposed method.

sealing wall, and vertical feedthroughs. Fig. 4 shows the photographs of MEMS dies from the top and bottom faces, fabricated using the proposed method. The die size of the hermetically sealed package is 5.5 mm × 6 mm for this particular design, which contains a single MEMS resonator, in order to estimate the pressure level inside the cavities. Fig. 5 presents a magnified view of the sealing region, vertical feedthroughs, shield metal, and the encapsulated sensor as seen through the bottom face of the packaged chip.

3. Experimental results

Experimental tests have been performed to measure the vertical feedthrough resistance, package vacuum level, production yield, package strength, and thermal robustness of the packages fabricated using the proposed method.

3.1. Measurement of feedthrough resistances

One of the most critical issues in the proposed method is the resistance of the vertical feedthroughs. In this work, the vertical feedthroughs are made from low resistive silicon (less than or equal to 0.005 Ω cm) and then bonded to the gold metal leads of the sensor, forming Au-Si ohmic contacts. The resistances of fabricated vertical feedthroughs are measured by using a HP 34401A digital multimeter. It is observed that the resistance values are in the range of 150–200 Ω which is an acceptable value for a large variety MEMS applications that do not require RF and higher frequencies.

3.2. Estimation of package vacuum and yield

In this work, MEMS resonators are used to estimate the pressure levels inside encapsulated cavities. The package vacuum is

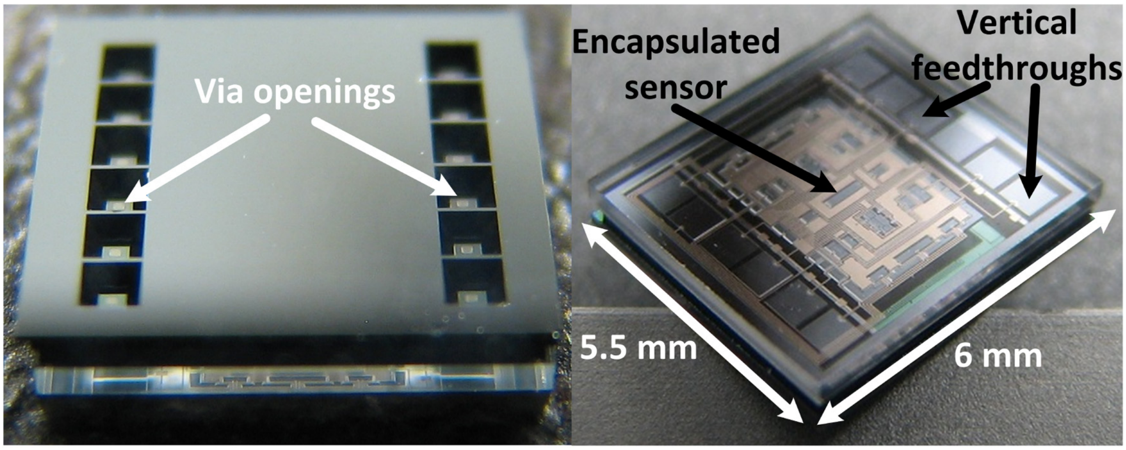


Fig. 4. Photographs of MEMS dies from the top and bottom faces, fabricated using the proposed method.

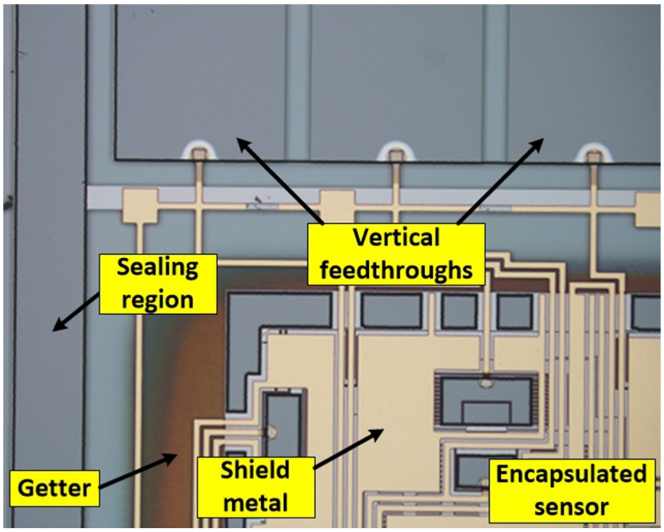


Fig. 5. Magnified view of the sealing region, vertical feedthroughs, shield metal, and the encapsulated sensor as seen through the bottom face of the packaged chips.

measured indirectly by measuring the quality factor of the MEMS resonators, which is a good way to measure the pressure change inside the packages since it directly depends on the air damping. Fig. 6 presents the measurement setup for the characterization of MEMS resonators at different pressure levels before the wafer level hermetic encapsulation process. Therefore, the MEMS sensor wafer is placed into a controlled vacuum chamber in which pressure can be adjusted from 10 μTorr to 10 Torr for the characterization of MEMS at different pressure levels. The resonators are actuated with an AC signal at frequencies ranging from 10 kHz to 15 kHz by using the Agilent 35670A Dynamic Signal Analyzer while the proof mass and the transimpedance amplifier circuit (TIA) are biased with DC voltage by using the Agilent E3631A Power Supply. The quality factors of the resonators are extracted according to their resonance characteristics at different pressure levels.

After the hermetic encapsulation process, the resonance characteristic of the same MEMS resonator is measured and the package vacuum is estimated. Fig. 7(a) demonstrates the quality factor versus pressure characteristics of a sample MEMS resonator before the packaging process, and Fig. 7(b) presents the resonance characteristics of the same resonator after wafer level packaging, showing a measured quality factor corresponding to a cavity pressure of almost 1 mTorr according to the results in Fig. 7(a).

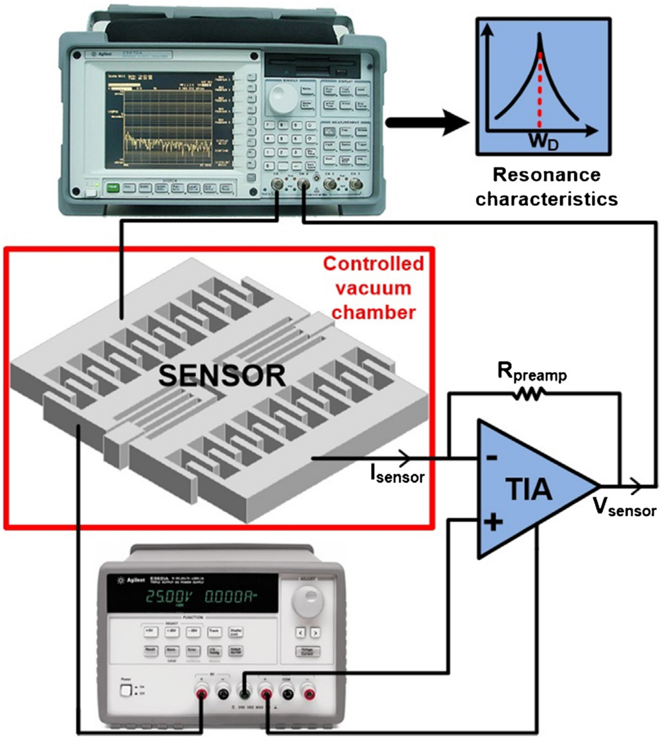
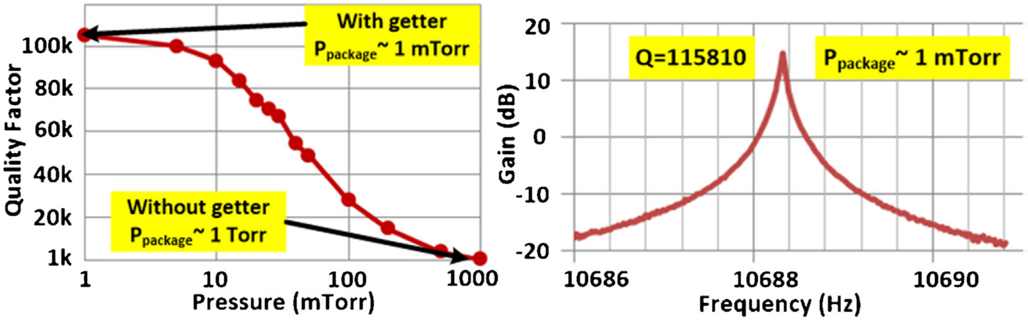


Fig. 6. Measurement setup for the characterization of MEMS resonators under different pressure levels before the wafer level encapsulation.

The robustness of the proposed method is checked by encapsulating different MEMS sensor wafers by using different process conditions. Table 1 presents the summary of the wafer level encapsulation process as well as the yield analysis for four different MEMS sensor wafers by using outgassing and gettering options. The cavity pressures can be set to different levels ranging from 1 mTorr up to 5 Torr, simply by varying the outgassing period and

Table 1
Summary of the wafer level encapsulation process as well as the yield analysis of 4 different MEMS sensor wafer by using different process conditions and use of getter.

Bond#	Outgas/Getter	Package volume	Pressure range	Yield
1	No/No	4.8 mm^3	3–5 Torr	94%
2	60min@300 °C/No	4.8 mm^3	1–3 Torr	96%
3	No/Yes	4.8 mm^3	1–80 mTorr	95%
4	No/Yes	1.6 mm^3	1–80 mTorr	94%



(a) (b)

Fig. 7. Test results of the fabricated prototypes: (a) Quality factor versus pressure characteristics of a MEMS resonator obtained before packaging in a controlled-pressure chamber. (b) Resonance characteristics of the same MEMS resonator after wafer-level packaging, showing a measured quality factor of 115,810 corresponding to a cavity pressure of 1 mTorr according to the results in (a).

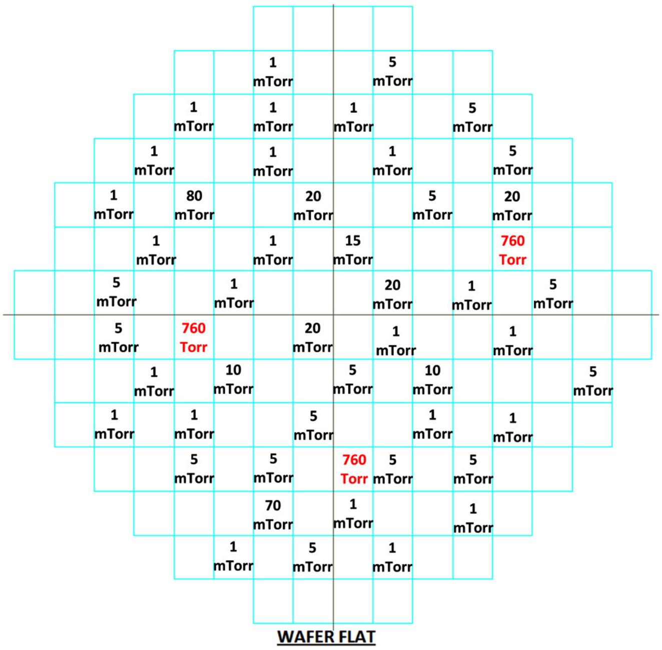


Fig. 8. Wafer map showing the successfully packaged as well as the failed sensor dies. The wafer contains 156 sensors and among randomly selected 50 sensors, 94% have a cavity pressure lower than 100 mTorr, 80% equal or lower than 10 mTorr, and 46% as small as 1 mTorr.

utilization of the getter material, enabling the proposed method be used for various types of MEMS devices with different pressure requirements.

Resonance tests are performed on randomly-selected sensors on all of these packaged wafers, and sensors on these wafers are verified to be packaged successfully with characteristics similar to Fig. 7(b) with an average yield of 95%. Fig. 8 presents the wafer map showing the successfully packaged as well as the failed sensor dies. The wafer contains 156 sensors and among randomly selected 50 sensors, 94% have a cavity pressure lower than 100 mTorr, 80% equal or lower than 10 mTorr, and 46% as small as 1 mTorr.

The long-term package pressure variation is monitored by periodic testing of the randomly selected five packages over a six months period since their fabrication. Fig. 9 presents change in the quality factors of the monitored packages. The lowest measured Q-factor in Fig. 9 is above 105,000. Referring back to the data in Fig. 7, this Q-factor value corresponds to a cavity pressure below 5 mTorr for all of the 5 dies monitored during the six month period. The reduction of the Q-factors in Fig. 9 corresponds to a change from an initial pressure around 1 mTorr to a stabilized pressure less than 5 mTorr within 2–4 months. This result shows that the proposed packaging method achieves a stable cavity pressure below 5 mTorr, which is sufficient for many applications.

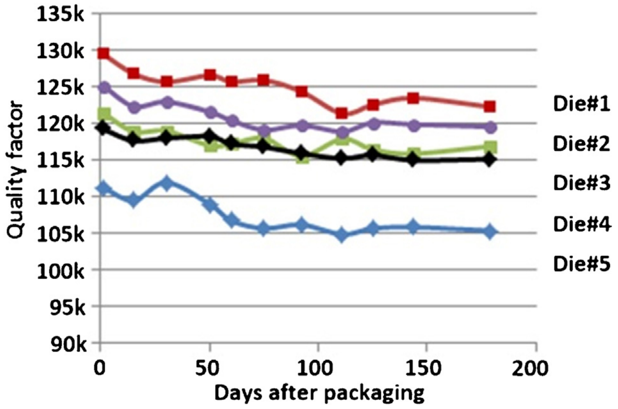


Fig. 9. Quality factor change over time. The pressure inside the cavities is observed to be lower than 5 mTorr for a six months of period after their fabrication.

3.2.1. *Effect of outgassing and thin-film getters*

The hermetic packaging is performed in a bond chamber that can be pumped down to pressure levels around 10 μTorr. Still, the pressures inside the cavities are observed to be as high as 5 Torr after the bonding, if neither an outgassing step nor thin-film getters are used. Outgassing is the desorption of the gas molecules from the devices encapsulated in vacuum cavities. It has a more significant effect on the micro-sealed cavities since they are not continuously pumped and have high surface to volume ratio. A way of minimizing this effect is to do an additional heat treatment for the outgassing inside the bond chamber before the actual encapsulation process. In this work, an outgassing step at 300 °C for 60 min is included before the encapsulation process. Although the outgassing step enhanced the vacuum levels, the better solution is to use thin-film getters in order to reach the package pressures below 100 mTorr. Getters are thin-films or alloys which react with the trapped gases in order to improve the package pressure. Pressures in the range of 1–80 mTorr are achieved by the use of thin-film getters with a yield of 95%. The getter material is capable of pumping the outgassing material until its capacity is reached, irrespective of the cavity volume. Therefore, similar cavity pressures are obtained for sensors encapsulated with 100 μm and 300 μm deep cavities. It is experimentally verified that it is possible to roughly tune the package pressure from 5 Torr to 1 mTorr by varying the outgassing steps and the use of thin film

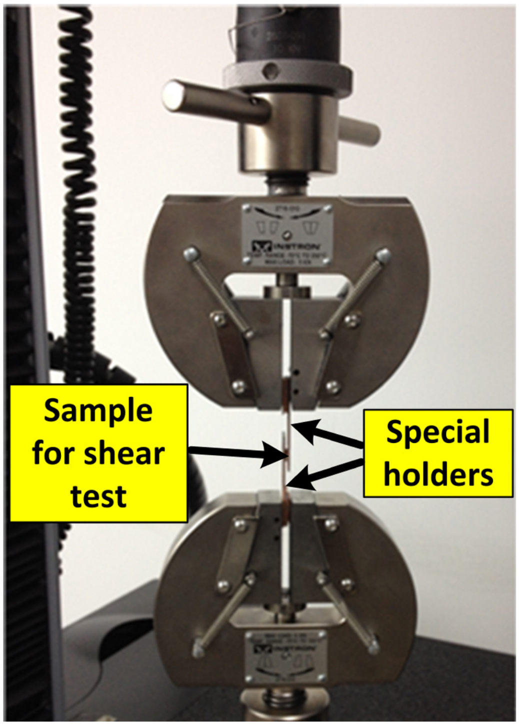


Fig. 10. Shear test setup used to measure the shear strengths of the packaged chips.

getters, providing the proposed method to be used for various types of MEMS devices with different vacuum requirements.

3.3. Shear tests

In order to evaluate the mechanical robustness of the packages, shear tests are performed on 6 packages by using the Instron 5565A shear tester. Fig. 10 shows the shear test setup used to measure the shear strengths of the fabricated chips. Prior to the shear test, chips are mounted on copper holders with a special adhesive. The cap and sensor chips are then separated from each other using the Instron 5565A shear tester. Fig. 11 shows that 5 of 6 randomly selected packaged chips have shear strengths above 10 MPa. Fig. 12 presents the photographs of cap and sensor chips separated from each other during the shear test. The silicon-glass bonding interface is observed to withstand the shear test, as either the silicon cap or the glass substrate is broken, but not the bonding interface. This verifies that the bonding strength of the proposed method is actually higher than the measured 10 MPa value, indicating a mechanically strong bonding.

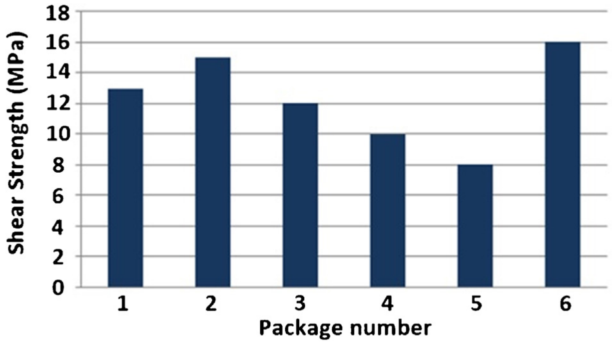


Fig. 11. The shear test results of 6 different packaged chips. The measured shear strengths show that 5 of the packaged devices over 6 are above 10 MPa, indicating a mechanically strong bonding.

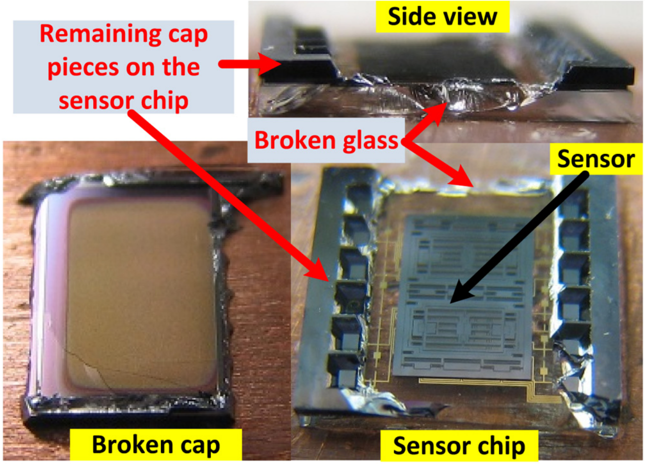


Fig. 12. Photographs of cap and sensor chips separated from each other during shear test. The silicon-glass bonding interface is observed to withstand the shear test, as either the silicon cap or the glass substrate is broken, but not the bonding interface. This verifies that the bonding strength of the proposed method is above 10 MPa.

3.4. Reliability tests

It is important to evaluate the thermo-mechanical robustness of the packaged chips for the reliability issues. Two packaged chips are subjected to cyclic thermal shock tests between 100 °C and 25 °C for 5 cycles with 10 min duration at each temperature value by using a special hotplate which has high heating (20 °C/sec) and cooling (50 °C/min) capabilities. The high heating/cooling capability provides instant movements between the high and cold states. After the temperature cycling test, no degradation is observed in the hermeticity of the packages. Furthermore, a packaged chip is kept at 150 °C for 24 h for the high temperature storage test. First, the hotplate is heated up to 150 °C and then the packaged chip is put on the hotplate for the high temperature storage test. The quality factor of a particular MEMS resonator was initially measured as 117,984 while it was 116,925 after the high temperature test, verifying that there is no change in the package vacuum and it is still around 1 mTorr. Two packaged chips are also subjected to 400 °C using the same hotplate for 5 min. Fig. 13 presents the resonance characteristics of a sample resonator before and after high temperature shock performed at 400 °C for 5 min. The hermeticity of the packaged chip withstands 400 °C and mechanical failures such as crack initiation are not detected even after this test. The reason of the frequency shift may be either due to measurement error in between

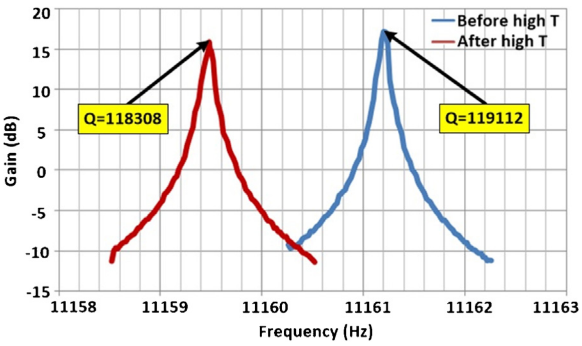


Fig. 13. Resonance characteristics of a sample resonator before and after high temperature shock performed at 400 °C for 5 min. The hermeticity of the packaged chip withstands 400 °C and mechanical failures such as crack initiation are not detected even after this test. The reason of the frequency shift may be due to either measurement error in between two measurements or the getter cannot absorb some gases inside the encapsulated cavity.

two measurements or the temperature fluctuations during the test. Alternatively, the shift may also be due to the outgassing of non-getterable gasses such as Argon. After the temperature shock test at 400 °C, there is a slight reduction in the quality factor, which corresponds to an increase in the package pressure. This may be an expected result since the getter cannot absorb some gases inside the encapsulated cavity.

4. Conclusions

This work reports a simple, sealing-material-free, relatively low-temperature, high-yield, reliable and mechanically-strong wafer level hermetic packaging solution for MEMS devices achieved by adapting the anodic bonding process to the aMEMS process. The hermetic packaging is achieved by anodic bonding at 350 °C using a bonding potential of 600 V without requiring any intermediate sealing material due to the nature of the anodic bonding process. The fabricated prototypes are verified to be operational with cavity pressures as low as 1 mTorr with successfully activated thin-film Titanium getters. The cavity pressure can be roughly tuned in the range 5 Torr to 1 mTorr by using proper combinations of outgassing steps and getter material. The average packaging yield is around 95% for four different bonding trials at various process conditions. The mechanical strength of the packages has been checked with the conventional shear tests and measured to be above 10 MPa, indicating a mechanically-strong bonding. The robustness of the packages is also verified with thermal cyclic and high temperature storage tests. No change has been observed in the package vacuum after subjecting the packaged chips to thermal cyclic tests between 100 °C and 25 °C for 5 cycles with 10 min duration between each cycle. The hermeticity of the packages has not been degraded by storing the packages at 150 °C for 24 h. Moreover, it is experimentally verified that the hermeticity of the packaged chips can withstand high temperature shocks as high as 400 °C for 5 min. In conclusion, the proposed packaging method provides a simple, relatively low temperature, robust, reliable, and mechanically-strong solution for the wafer-level hermetic packaging of MEMS devices.

Acknowledgements

This research is conducted under Industrial MEMS Project funded by State Planning Organization (currently Ministry of Development). The authors also would like to thank to Eyup Can Demir and Inci Donmez for the shear tests of the packages, Hasan Dogan Gavcar for his helps during the fabrication, and Ferhat Yesil for his helps during the electrical tests of the resonators.

References

[1] K. Najafi, Micropackaging technologies for integrated microsystems: Applications to MEMS and MOEMS, Proc. SPIE-Micromachining and Microfabrication Process Technology VIII (2003) 1–19.

[2] K. Gilleo, MEMS/MOEMS Packaging: Concepts, Designs, Materials, and Processes, Mc Graw-Hill, New York, 2005.

[3] M. Esashi, Wafer level packaging of MEMS, J. Micromech. Microeng. 18 (2008) 1–13.

[4] B.H. Stark, K. Najafi, A low temperature thin film electroplated metal vacuum package, J. Microelectromech. Syst. 13 (2004) 147–157.

[5] A.B. Graham, M.W. Messana, P.G. Hartwell, J. Provine, S. Yoneoka, R. Melamud, B. Kim, R.T. Howe, T.W. Kenny, A method for wafer scale encapsulation of large lateral deflection MEMS devices, J. Microelectromech. Syst. 19 (2010) 28–37.

[6] S. Yoneoka, C.S. Roper, R.N. Roper, R.N. Candler, S.A. Chandorkar, A.B. Graham, J. Provine, R. Maboudian, R.T. Howe, T.W. Kenny, Characterization of encapsulated micromechanical resonators sealed and coated with polycrystalline SiC, J. Microelectromech. Syst. 19 (2010) 357–366.

[7] F. Santogato, J.J.M. Zaal, V.G. Huerta, L. Mele, J.F. Creemer, P.M. Sarro, Mechanical design and characterization of MEMS thin film packaging, J. Microelectromech. Syst. 21 (2012) 100–109.

[8] G. Wu, D. Xu, B. Xiong, Y. Wang, Y. Wang, Y. Ma, Wafer level vacuum packaging for MEMS resonators using glass frit bonding, J. Microelectromech. Syst. 21 (2012) 1484–1491.

[9] J.S. Mitchell, K. Najafi, A detailed study of yield and reliability for vacuum packages fabricated in a wafer level Au-Si eutectic bonding process, Proc. Transducers (2009) 841–844.

[10] W.C. Welch, K. Najafi, Au-In transient liquid phase wafer bonding for MEMS vacuum packaging, Proc. of IEEE MEMS (2012) 807–809.

[11] S. Marauska, M. Claus, T. Lisec, B. Wagner, Low temperature transient liquid phase bonding of Au/Sn and Cu/Sn electroplated material systems for MEMS wafer level packaging, Microsyst. Technol. 19 (2012) 1119–1130.

[12] K.B. Albaugh, Electrode phenomena during anodic bonding of silicon to borosilicate glass, J. Electrochem. Soc. 138 (1991) 3089–3094.

[13] J. Wei, H. Xie, M.L. Nai, C.K. Wong, L.C. Lee, Low temperature wafer anodic bonding, J. Micromech. Microeng. 13 (2003) 217–222.

[14] C.W. Lin, H.A. Yang, W.C. Wang, W. Fang, Implementation of three-dimensional SOI-MEMS wafer level packaging using through wafer interconnections, J. Micromech. Microeng. 17 (2007) 1200–1205.

[15] C.W. Lin, C.P. Hsu, H.A. Yang, W.C. Wang, W. Fang, Implementation of silicon-on-glass MEMS devices with embedded through wafer silicon vias using the glass reflow process for wafer level packaging and 3D chip integration, J. Micromech. Microeng. 18 (2008) 1–6.

[16] J. Chae, J.M. Giachino, K. Najafi, Fabrication and characterization of a wafer level MEMS vacuum package with vertical feedthroughs, J. Microelectromech. Syst. 17 (2008) 193–200.

[17] R.M. Haque, D.E. Serrano, X. Gao, A.N. Shirazi, V. Keesara, F. Ayazi, K.D. Wise, Hermetic packaging of resonators with vertical feedthroughs using a glass-in-silicon reflow process, Proc. Transducers (2011) 2303–2306.

[18] J. Zhang, W. Jiang, X. Wang, J. Zhou, H. Yang, Design and fabrication of high performance wafer level vacuum packaging based on glass-silicon-glass bonding techniques, J. Micromech. Microeng. 22 (2012) 1–9.

[19] J.Y. Lee, S.W. Lee, S.K. Lee, J.H. Park, Through glass copper via using the glass reflow and seedless electroplating processes for wafer level RF MEMS packaging, J. Micromech. Microeng. 23 (2013) 1–10.

[20] M.M. Torunbalci, S.E. Alper, T. Akin, Wafer level hermetic encapsulation of MEMS inertial sensors using SOI cap wafers with vertical feedthroughs, Proc. IEEE ISISS (2014) 1–2.

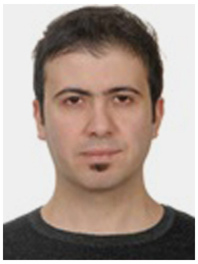
[21] S.E. Alper, M.M. Torunbalci, T. Akin, Method of wafer level hermetic packaging with vertical feedthroughs, PCT/TR2013/000298 (2013).

[22] M.M. Torunbalci, S.E. Alper, T. Akin, A Method of fabricating vacuum packages with vertical feedthroughs in a wafer level anodic bonding process, Proc. Eurosensors XXVIII (2014).

[23] A.C. Fischer, J.G. Korvink, N. Roxhed, G. Stemme, U. Wallrabe, F. Niklaus, Unconventional applications of wire bonding create opportunities for microsystem integration, J. Micromech. Microeng. 23 (2013) 1–18.

[24] M.M. Torunbalci, E. Tatar, S.E. Alper, T. Akin, Comparison of two alternative silicon-on-glass microfabrication processes for MEMS inertial sensors, Proc. Eurosensors XXV (2011) 900–903.

Biographies



Mustafa Mert Torunbalci was born in Ankara, Turkey, in 1985. He received the B.S. and M.S. degrees in the department of Physics Engineering from Ankara University and in the Micro and Nanotechnology Graduate Program from the Middle East Technical University (METU), Ankara, Turkey, in 2008 and 2011, respectively. He is currently working toward the Ph.D. degree in the Micro and Nanotechnology Graduate Program, Middle East Technical University, Ankara, Turkey. Since 2008, he was a Research Assistant with METU-MEMS Research and Applications Center. His major research interests include the design, simulation, fabrication, and wafer level packaging of MEMS inertial sensors.

Said Emre Alper was born in Ankara, Turkey, in 1976. He received the B.S., M.Sc., and Ph.D. degrees in Electrical and Electronics Engineering (with high honors) from the Middle East Technical University (METU), Ankara, in 1998, 2000, and 2005, respectively. From 1998 to 2005, he was a Research Assistant at the MEMS-VLSI Research Group, Department of Electrical and Electronics Engineering, METU, where he has been employed as a Senior Research Scientist and Instructor until 2008. Since 2008, he continued research at METU-MEMS Research and Applications Center, at which he has been the deputy director since 2009. He is also the technical leader of the Inertial Sensors Research and Technology Development Group of the METU-MEMS Center. Major research interests of Dr. Alper include capacitive MEMS inertial sensors, capacitive interface circuits, analog closed-loop control, various microfabrication technologies, packaging and testing of MEMS inertial sensors, and also hybrid system design. Dr. Alper received the "METU Thesis of the Year Award" in 2000 and 2005 for his M.Sc. thesis and Ph.D. dissertation, respectively, which were awarded by the Prof. Mustafa N. Parlar Education and Research Foundation. He is the first author of the symmetric and decoupled gyroscope design, which won the first prize award in the operational designs category of the "International Design Contest" organized by Design, Automation, and Test (DATE) Conference in Europe and CMP in March 2001. He is also the first author of the tactical-grade symmetrical and decoupled microgyroscope design, which won the third-prize award, among 132 MEMS designs from 24 countries and 25 states across the U.S., in the international "3-D MEMS Design Challenge" organized by MEMGEN Corporation (currently Microfabrica, Inc.) in June 2003.

Tayfun Akin was born in Van, Turkey, in 1966. He received the B.S. (Hons.) degree in electrical engineering from Middle East Technical University (METU), Ankara, in 1987, and went to the USA in 1987 for his graduate studies with a graduate fellowship provided by the NATO Science Scholarship Program through the Scientific and Technical Research Council of Turkey. He received the M.S. and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor, in 1989 and 1994, respectively. Since 1995, 1998, and 2004, he has been an Assistant Professor, an Associate Professor, and a Professor, respectively, with the Department of Electrical and Electronics Engineering, METU. He is the Director of the METU-Microelectromechanical Systems (MEMS) Center, which has a 1300-m^2 clean room area for 4″ to 8″ MEMS processing. He raised and managed over 65 M USD funding for several National and International projects, including EU FP6, FP7, NATOSfS, and NSF-USA Projects. His current research interests include MEMS, Microsystems Technologies, uncooled infrared detectors and readout circuits, inertial microsensors, silicon-based integrated sensors and transducers, and analog and digital integrated circuit design. He has served in various MEMS, EUROSENSORS, and TRANSDUCERS Conferences as a Technical Program Committee Member. He was the Co-Chair of the 19th IEEE International Conference of Micro Electro Mechanical Systems (MEMS 2006) held in Istanbul, and he was the Co-Chair of the Steering Committee of the IEEE MEMS Conference in 2007. He is the Steering Committee Member of the 18th International Conference on Solid-State Sensors, Actuators, and Microsystems (Transducers 2015). He is the recipient of the First Prize in Experienced Analog/Digital Mixed-Signal Design Category at the 1994 Student VLSI Circuit Design Contest organized and sponsored by Mentor Graphics, Texas Instruments, Hewlett-Packard, Sun Microsystems, and Electronic Design Magazine. He is the co-author of the Symmetric and Decoupled Gyroscope project, which received the first prize award in the operational designs category of the International design contest organized by DATE Conference and CMP in 2001. He is also the coauthor of the Gyroscope project, which received the third prize award of the 3-D MEMS Design Challenge organized by MEMGen Corporation (currently, Microfabrica).