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An all-glass chip-scale MEMS package with variable cavity pressure

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Abstract
A dielectric, chip-scale MEMS packaging method is discussed. The packaging method uses wafer-to-wafer bonding of micromachined glass wafers with a reflowed, glass, sealing ring. The glass wafers are micromachined and have metal and silicon structures patterned on them with metal and fluidic feedthroughs. A variety of getters and sealing designs are disclosed to vary the pressure of the microcavity by many orders of magnitude from under 1 mTorr up to 1 atm (760 000 mTorr), enabling either vacuum or damped packaging of the device elements on the same chip. The final singulated, all-glass, chip-scale package can have electrical, optical/IR and fluidic interfaces. Applications for resonators, switches, optical sensors and displays are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A variety of microelectromechanical system (MEMS) devices, such as resonators, displays, gyroscopes, digital micromirrors and microfluidic devices rely on hermetic and/or vacuum packaging for improved performance [1–6]. Glass frit, solder, fusion, anodic and eutectic sealing have been used for many years to provide a vacuum seal [1–3, 6–15]. Reflowed glass frit sealing has traditionally been used in pressure sensors, accelerometers and switches to join two silicon wafers together with a dielectric seal that can conformally cover minor surface steps [1, 3, 7–11]. Glass sealing has recently been employed to bond silicon to Pyrex to vacuum seal resonant density and Coriolis mass flow sensors [3, 6]. In this paper an all dielectric chip-scale package will be disclosed. This glass MEMS package is formed via wafer-to-wafer bonding. Avoiding the use of silicon or metal in hermetic packaging material will offer a path to higher speed and higher voltage devices with less chance of feedthrough coupling through the package itself as well as new means of packaging optical sensors and displays.

Hermetic sealing using a damping ambient is required for some devices such as accelerometers and switches, while for many resonators a vacuum is desired. A design and process that can adjust the microcavity pressure, not just minimize it, is of use to enable the application of a MEMS packaging process to a wide array of devices, forming complex systems on a chip. This study covers an evaluation of different thin film getters, used to reduce the microcavity pressure. Without a getter the microcavity pressure is limited by desorption of surface molecules. This desorption can cause sensor hysterisis and is a potential failure mode in high-performance devices. To overcome the surface desorption limit found with wafer bonding, getters have been employed. Metallic getters have been used for decades dating back to vacuum tubes to obtain lower pressures in hermetic packages [16]. These metals trap various gases through oxide and hydride formation and by simple surface adsorption. Capture of oxygen, nitrogen and hydrocarbons requires elevated temperatures (200 to 550 °C), while trapping of hydrogen by the metals occurs at room temperature. Getters were first applied to MEMS devices in the mid 1990s [17–19]. In these early studies, nonevaporable getters (NEGs) either in tablet or strip form were placed in an extra micromachined cavity or adjacent to the chip in a ceramic package. Problem encountered with sintered getters is particle generation and getter integration. The 2 to 3 μm diameter metal particles can cause electrical shorts, impede motion and shift resonant frequencies. Thin film getters have been developed in the last few years to overcome the problems noted with NEGs in MEMS applications

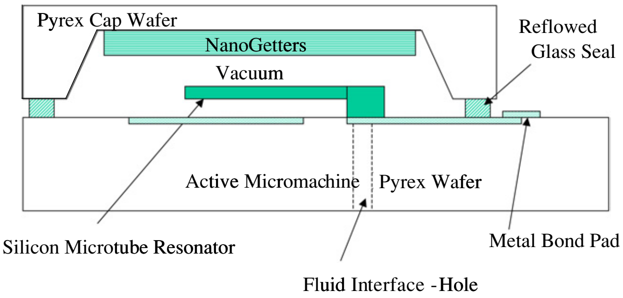

Figure 1. A side cross-sectional diagram of the MEMS silicon resonator and all-glass packaged device used in this study.

[20, 21]. In this paper different types of getters and/or sealing methods are employed to vary the cavity pressure. The sealing and packaging methods discussed can also be applied to devices that require gas damping for reduced ringing of internal components and even produce both damped and vacuum packaged devices on the same chip.

2. Experimental proceedings

The micromachined resonators used in this study are hollow silicon resonators [3, 6]. The hollow resonators are used in producing fluidic density sensors or Coriolis mass flow sensors. The resonators are formed by anodically bonding a patterned silicon wafer to a metallized, etched glass wafer. Figure 1 illustrates the different elements in this device. Metal electrodes are formed on the glass wafers to act as drive and capacitive sense elements. The electrodes are linked to the bond pads with narrow feedthroughs. The glass frit, in the form of a thixotropic paste is screen printed onto the glass cap wafer and dried. The printed annular glass frit ring will eventually form the hermetic seal for the individual chips. A final wafer bonding process, to melt the glass particles, is performed to seal the resonator in a vacuum. The glass reflow and bonding temperature is 400 °C under vacuum and with an applied wafer-to-wafer force between 300 and 400 N. No special thermal activation was used during bonding, only the heat of the vacuum bonding process is employed for the getter to gas reaction to occur. The time at temperature is under 30 min. One of the advantages of the reflowed glass frit sealing process is that the glass can hermetically cover relatively small steps and particles. The frit thickness is in the 10 to 20 micron range and so can cover substantial step heights. This is a feature that the anodic, eutectic and fusion bond processes do not provide.

If a thin film getter is to be integrated into the process, the getter is deposited under vacuum and patterned after the glass seal layer is in place on the capping wafer, as shown in figure 1. For this comparative study, 500 nm thick getter layers were employed. A 10 mm^3 cavity region enclosed the resonator. Since thin film deposition techniques are employed in a cleanroom environment, the thin film getters are virtually particle free compared to an NEG. The thin film deposition method also enhances the ability to easily integrate the getter into a typical MEMS process flow at the wafer level [20]. Adding the thin film getter does not impact the chip size. Vacuum wafer-to-wafer bonding to reflow the glass seal, is performed next in this process and the getter traps desorbed gas molecules during the vacuum bonding process without the need for a subsequent getter activation step. A vacuum wafer bonding system, an Electronic Visions 501S, was employed in this study. During vacuum wafer bonding the 501S system manometer indicates that the chamber pressure is 0.06 mTorr.

An HP 4194A Phase-Gain Analyzer was employed to take test results on vacuum quality, and resonant frequency. The Q was calculated using the frequency bandwidth where the gain for each of both frequencies is 3 db down from the peak gain. Uncapped reference resonators were tested in a vacuum chamber. A Varian V-250 turbo pump was used to pull a vacuum in the test system when examining decapped resonators. To determine what pressure the Q values corresponded to, a resonator was decapped and tested in a vacuum chamber equipped with a manometer.

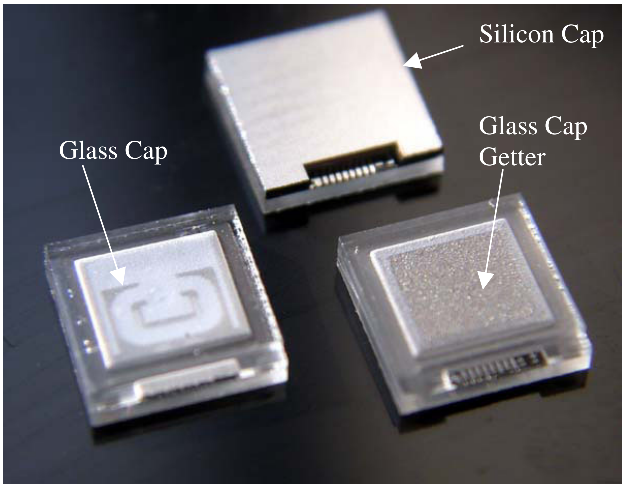

Figure 2. Photograph of a silicon capped device (top), an all-glass chip-scale package without a getter (bottom left) and an all-glass chip-scale package with the thin-film getter in the cap cavity (bottom right).

3. Results and discussion

Figure 2 shows three chips produced using this process. The top chip in figure 2 used a conventional silicon top cap, that has been employed for many years to produce density and flow sensors [3, 6, 21, 22]. On the bottom left of figure 2 is an all-glass chip-scale package with no thin film getter. The microresonating tube, oval shape, can be seen through the transparent glass top cap. On the bottom right of figure 2 is an all-glass package with a square shaped, thin-film getter patterned in the cavity of the glass top cap portion of the package. Getter adhesion was found to be comparable between silicon and glass top caps. Another advantage to using glass wafers with reflowed frit bonding is the ability to visually inspect the glass seal, metal runners and the resonator. With silicon wafers infrared (IR) inspection must be used for such an inspection which limits resolution.

Previous results for microtube resonators, employing thin film getters, have reported Q values ranging from 2000 to 60 000 when a silicon top cap was utilized [22]. Q values were observed to vary with resonator design and cavity volume in

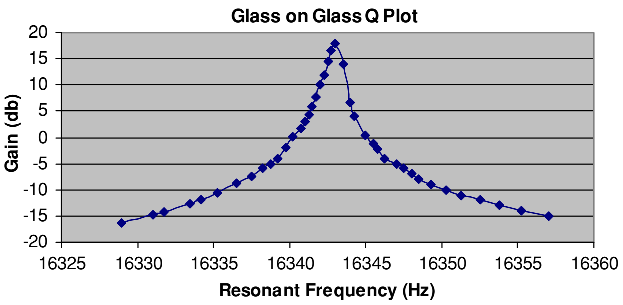

Figure 3. The Q-plot for the all-glass vacuum sealed resonator chip employing a getter.

Table 1. Q data for the same vacuum packaged resonator without getters and with three different metallic thin-film getters

Getter metal	Q (avg)	Standard deviation	Cavity pressure estimate (mTorr)
None	36	17	1400
Al	70	66	420
Cr	363	268	70
NanoGetter	7378	503	0.79

these earlier studies. Figure 3 shows a Q plot for an all-glass chip-scale packaged 16.3 KHz, resonating microtube, this part has a Q of 30 800, within the range of Q values previously reported for silicon top caps. Also the glass frit seal with Nanogetter material has been shown to produce resonators with constant Q values after 3000 h at 95 °C [22]. No pressure change or leakage was detectable over that time period using the resonators described in this paper.

Next the type of getter material deposited in the microcavity was varied to test the impact on cavity pressure. To reduce wafer-to-wafer confounding, different metals were deposited onto a quadrant of the same wafer cap. In this manner three metals and a group with no metal getter could be compared from the same wafer. Table 1 shows how the average Q value for the same resonators on a 100 mm wafer varied with the getter employed. A sample size of 12–15 parts is used in each group. All chips were hermetically sealed with a reflowed glass ring as illustrated in figures 4(*a*) and (*c*). An estimate of cavity pressure was made by comparing the Q result to the Q value of a decapped resonator that was tested in a vacuum chamber. This test device was tested at different pressure, measured with a manometer.

Without a thin film getter the average Q value was 36, corresponding to a pressure of 1400 mTorr. Since the bonder pressure gauge under vacuum read 0.06 mTorr, wafer surface desorption is dominating the final cavity pressure. With aluminum as the thin film getter an average Q value of 70 was observed. With chromium the Q value went up to 363, or a pressure of 70 mTorr. With the NanoGetter formulation, the average Q value went up to 7378, which extrapolates to a pressure of less than 1 mTorr. It should be noted that Q values flatten out at very low pressure ($<$10 mTorr), so accurate pressure measurements in the low-pressure range are not possible using Q as a measurement method.

Optical and IR sensing and display application with a glass, or IR transparent silicon top cap require changes to the thin film getter design. The thin film metal generally block or attenuates IR and optical radiation. Figure 4(*d*) shows how the getter can be patterned to form a transparent window enabling this packaging technology to be used in these applications.

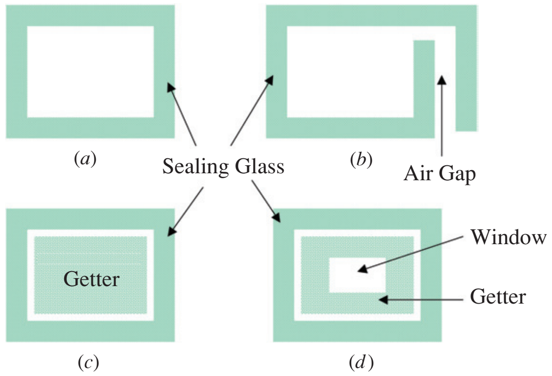

Figure 4. Top-view illustration of the glass sealing pattern for (*a*) a hermetic or vacuum chip, (*b*) an air-damped device, (*c*) a vacuum sealed chip-scale package with a getter and (*d*) a patterned getter with an optical or IR window.

With hermetic vacuum sealing, the pressure of the microcavity can be varied by more than three orders of magnitude using different interior surface materials (getters). By performing the wafer bonding step at high pressure, using any variety of gases, the upper range of cavity pressures can be increased significantly using a hermetic seal like that shown in figure 4(*a*). Employing a getter in a gas filled cavity could be used to getter water vapor or oxygen from an inert gas. An alternate nonhermetic sealing design, shown in figure 4(*b*), can be employed to let ambient pressure into the microcavity, so that the pressure is 1 atm (760 000 mTorr). It should be noted that an unsealed cavity, as shown in figure 4(*b*), can lead to problems with water condensation and ice crystal formation in humid environments. These different chip-scale packaging methods with and without getters, with vacuum or gas wafer bonding or with a hermetic seal or a gap glass seal design allow cavity pressures to vary from under 1 mTorr to 760 000 mTorr.

It would be advantageous to have the capability of having two different cavity pressures on the same MEMS chip. For motion sensors a vacuum-sealed resonant gyroscope and damped accelerometers could be combined on a single chip. For RF applications vacuum packaged RFMEMS resonators could be combined on the same chip as gas damped RF switches. High-speed switches would benefit from the all dielectric package described in this paper. The ability to have two different cavity pressure values on the same chip expands the capability of system integration for single-chip microsystems.

Optical and IR sensors could employ different gases and/or vacuum levels in adjacent cavities to change absorption characteristics across a sensor array. Obviously an all-glass package would be useful for optical devices and displays. Scaling this technology up for larger displays is feasible since screen printing and wafer bonding can be employed with 150 to 200 mm wafers and square panels instead of round wafers can be used with these fabrication methods.

4. Conclusions

A dielectric, chip-scale MEMS packaging method was discussed. The packaging method uses wafer-to-wafer bonding of micromachined glass wafers with a reflowed, glass, sealing ring. The glass wafers are micromachined and have metal and silicon structures patterned on them. A variety of getters and sealing design were disclosed to vary the pressure of the microcavity from under 1 mTorr up to 1 atm (760 000 mTorr), enabling either damped or vacuum packaging of the device elements. The final singulated, chip-scale package can have electrical, optical/IR and fluidic interfaces. Applications include resonators, switches, optical sensors and displays.

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References

[1] Eddy D and Sparks D 1998 Application of MEMS technology in automotive sensors and actuators *Proc. IEEE* **86** 1747–55
[2] Sparks D, Slaughter D, Beni R, Jordan L, Chia M, Rich D, Johnson J and Vas T 1999 Chip-scale packaging of a gyroscope using wafer bonding *Sensors Mater.* **11** 197–207
[3] Sparks D, Smith R, Straayer M, Cripe J, Schneider R, Chimbayo A, Ansari S and Najafi N 2003 Measurement of density and chemical concentration using a microfluidic chip *Lab Chip* **3** 19–21
[4] Nguyen C and Howe R 1993 CMOS micromechanical resonator oscillator *IEDM 93, IEEE* pp 199–203
[5] Bhave S, Bircumshaw B, Low W, Kim Y, Pisano A, King T and Howe R 2002 Poly-SiGe: a high-Q structural material for integrated RF MEMS *Solid-State Sensors, Actuators and Microsystems Workshop (Hilton Head Island, SC)* pp 34–37
[6] Sparks D, Smith R, Massoud-Ansari S and Najafi N 2004 Coriolis mass flow, density and temperature sensing with a single vacuum sealed MEMS chip *Solid-State Sensors, Actuators and Microsystems Workshop (Hilton Head, SC)* pp 75–8
[7] Park K 1980 Capacitive pressure transducer *US Patent* 4227419
[8] Gragg J 1982 Silicon pressure sensor *US Patent* 4317126
[9] Sparks D, Rich D, Gerhart C and Frazee J 1997 A bi-directional accelerometer and flow sensor made using a piezoresistive cantilever *Proc. European Automotive Engineers Coop. 6th European Congress* pp 1119–25
[10] Rich D, Kosiak W, Manlove G and Schwartz D 1997 A remotely mounted crash detection system *SAE Tech Proc.* No 973240 pp 53–56
[11] Majumder S *et al* 2002 An electrostatically actuated broadband MEMS switch *Sensors Expo Fall (Boston, 2002)* pp 205–209
[12] Anthony T 1983 Anodic bonding of imperfect surfaces *J. Appl. Phys.* **58** 2419–24
[13] Schmidt M 1998 Wafer-to-wafer bonding for microstructure formation *Proc. IEEE* **86** 1575–80
[14] Sparks D, Queen G, Weston R, Woodward G, Putty M, Jordan L, Zarabadi S and Jayakar K 2001 Wafer-to-wafer bonding of nonplanarized MEMS surfaces using solder *J. Micromech. Microeng.* **11** 630–4
[15] Mei D, Lahiji R and Najafi K 2002 A robust gold-silicon eutectic wafer bonding technology for vacuum packaging *Solid-State Sensors, Actuators and Microsystems Workshop (Hilton Head Island, SC)* pp 86–9
[16] Giorgi T 1974 Getters and gettering *Japan. J. Appl. Phys. Suppl.* **2** 53–8
[17] Henmi H, Shoji S, Shoji Y, Yoshimi K and Esashi M 1994 Vacuum packaging for microsensors by glass-silicon anodic bonding *Sensors Actuators* A **43** 243–9
[18] Esashi M, Sugiyama S, Ikeda K, Wang Y and Miyashita H 1998 Vacuum-sealed silicon micromachined pressure sensors *Proc. IEEE* **86** 1627–31
[19] Najafi N, Massoud-Ansari S, Tadigapada S and Zhang Y 2002 Methods for prevention, reduction and elimination of outgassing and trapped gases in micromachined devices *US Patent* 6499354
[20] Sparks D, Massoud-Ansari S and Najafi N 2003 Chip-level vacuum packaging of micromachines using NanoGetters *IEEE Trans. Adv. Packag.* **26** 277–82
[21] Sparks D, Massoud-Ansari S and Najafi N 2004 Reliable vacuum packaging using NanoGetters$^{\mathrm{TM}}$ and glass frit bonding *Reliability, Testing and Characterization of MEMS/MOEMS III, Proc. SPIE* **5343** pp 70–8
[22] Sparks D, Massoud-Ansari S and Najafi N 2005 Long-term evaluation of hermetically glass frit sealed silicon to Pyrex wafers with feedthroughs *J. Micromech. Microeng.* **15** 1560–4