Wafer-Level Packaged MEMS Resonators with a Highly Vacuum-Sensitive Quality Factor

Seok Jin Kang\textsuperscript{1,3}, Young Soon Moon\textsuperscript{2}, Won Ho Son\textsuperscript{1}, and Sie Young Choi\textsuperscript{1}

Abstract—Mechanical stress and the vacuum level are the two main factors dominating the quality factor of a resonator operated in the vacuum range 1 mTorr to 10 Torr. This means that if the quality factor of a resonator is very insensitive to the mechanical stress in the vacuum range, it is sensitive to mainly the ambient vacuum level. In this paper, a wafer-level packaged MEMS resonator with a highly vacuum-sensitive quality factor is presented. The proposed device is characterized by a package with out-of-plane symmetry and a suspending structure with only a single anchor. Out-of-plane symmetry helps prevent deformation of the packaged device due to thermal mismatch, and a single-clamped structure facilitates constraint-free displacement. As a result, the proposed device is very insensitive to mechanical stress and is sensitive to mainly the ambient vacuum level. The average quality factors of the devices packaged under pressures of 50, 100, and 200 mTorr were 4987, 3415, and 2127, respectively. The results demonstrated the high controllability of the quality factor by vacuum adjustment. The mechanical robustness of the quality factor was confirmed by comparing the quality factors before and after high-temperature storage. Furthermore, through more than 50 days of monitoring, the stability of the quality factor was also certified.

Index Terms—Resonator, quality factor, mechanical stress, air damping, vacuum sensitivity

I. INTRODUCTION

There are several methods for measuring a vacuum in a microcavity. One is the membrane deflection method, which evaluates the deflection of the thin packaging lid resulting from the difference between the inner and outer pressure of the package [1]. This is a rather simple method, but the resolution of the pressure prediction is low. Another method uses an integrated vacuum sensor such as a Pirani gauge, which consists of a suspended resistor in which the resistance changes as a function of the ambient pressure [2]. However, this method has the disadvantage of consuming a few milliwatts of electrical power for driving the gauge; further, the additional sensor requires more space. All vibratory structures have mechanical resonance characteristics that depend on the ambient pressure. That is, resonance characteristics can be used to estimate the ambient pressure [3-5]. Eq. (1) shows the relationship between the ambient pressure \( p \) and the quality factor \( Q \), one of the resonance characteristics:

\[
Q = \frac{\rho h d}{p} \frac{1 + (\omega \tau)^2}{\tau}
\]

where \( \rho \) is the density of the spring material, \( h \) is the height of the spring, \( d \) is the average distance between the moving part and the fixed wall, \( \omega \) is the resonance angular frequency, and \( \tau \) is the diffusion time of the gas molecules.

In many MEMS applications, the method of estimating...
the vacuum level from the quality factor of a resonator has an advantage over other methods because many MEMS devices are a type of mechanical resonator and do not need to integrate an additional device to measure the pressure of the package. However, the quality factor is also severely affected by the mechanical stress of a resonator as well as air pressure. This is because frequency shift and geometric deformation due to the mechanical stress are major factors affecting air damping.

The quality factor can be expressed as a function of the mass, frequency, and damping coefficient as shown by Eq. (2) [6]:

$$Q = \frac{m \cdot \omega}{C_d} \tag{2}$$

where \(m\) is the proof mass, \(\omega\) is the resonant frequency, and \(C_d\) is the damping coefficient. Air damping in typical actuation using a comb drive structure can be modeled as a Couette flow. In this case, the damping coefficient can be expressed by Eq. (3) [7]:

$$C_d = \mu_e \frac{A}{g_e} + \mu_p \frac{2N_e l_e}{g_e} \tag{3}$$

where \(A\) is the area of the proof mass, \(g_e\) is the gap between the proof mass and the substrate, \(t\) is the thickness of the structure, \(N_e\) is the number of comb drive fingers, \(g_e\) is the gap between the fingers, and \(l_e\) is the overlapping length of the fingers. \(\mu_e\) is the effective viscosity, which is defined by \(\mu_e = \mu_p p\cdot\), where \(p\) is the ambient pressure; and \(\mu_p = 3.71 \times 10^{-5} \text{ kg/m}^2 \cdot \text{s} \cdot \text{torr}\) is the viscosity constant of air. Eqs. (2) and (3) show that the geometric deformation and the frequency shift due to mechanical stress can influence on the quality factor.

In practice, most wafer-level packaged MEMS resonators, which are undergone a high-temperature (>300°C) wafer bonding process, have mechanical stress due to thermal mismatch. This results in frequency changes and shape deformation of the resonators. As a result, vacuum measurement using the quality factor of the MEMS resonator cannot be expected to be accurate and reliable. To circumvent this problem, it is necessary to design a mechanically robust resonator.

II. DESIGN OF WAFER-LEVEL PACKAGED MEMS RESONATORS

A wafer-level packaged MEMS resonator with a highly vacuum-sensitive quality factor was designed. The basic structure of the package, which is shown in Fig. 1, consists of three parts. The top and bottom parts are patterned glass wafers, and the intermediate part is a silicon resonating structure. A glass–silicon–glass sandwich structure such as this is immune to thermal deformation owing to its symmetry. Bonding between wafers was achieved using anodic bonding, which allows for reliable hermetic sealing at a lower temperature. Anodic bonding is one of the most widely used processes for micromechanical devices. Anodic bonding parameters have been analyzed in many publications [8-11].

The top glass wafer provides an external interconnection channel and serves as a supporting substrate for a suspending structure. Metal patterns formed on the via-hole of the wafer function as electrodes for the signal path of the resonator. Other metal patterns formed on the inner surface act as electrodes for sensing the torsion displacement of the resonating structure. These electrodes also function as an ion neutralizing layer for preventing overetching damage caused by the accumulation and scattering of ions when the etch ions encounter an insulating layer during the silicon DRIE (deep reactive-ion etching) process that is used to make a suspending structure.

The primary function of the bottom glass wafer is to perform anodic bonding. For stable bonding, the wafer function as an electrostatically isolating layer for preventing overetching damage caused by the accumulation and scattering of ions when the etch ions encounter an insulating layer during the silicon DRIE (deep reactive-ion etching) process that is used to make a suspending structure.

Fig. 1. Basic structure of the resonator embedding micropackage.
provide a vacuum cavity for the device. This cavity offers space for vibration and room for getter material deposition to prevent vacuum degradation.

A micromechanical gyroscope was selected as the resonating device to verify the vacuum sensitivity of a quality factor. The device has a biaxial structure that is capable of not only driving-axis motion but also sensing-axis motion. Thus, two different ranges of quality factors may be obtained, which means the device can be used as a vacuum sensor to cover two separate ranges. However, in this study, only driving-axis actuation is used for measuring a quality factor in the vacuum range 1 mTorr to 10 Torr.

Fig. 2 shows the layout and detailed design parameters of the device. As shown in the layout, the structure is characterized by a suspending structure with only a single anchor, in which one side of a floating mass is fixed and the other side is freestanding.

Fig. 3 is a 3D concept diagram to help explain the detailed structure of the proposed resonators based on the SOG (silicon on glass) structure. In this figure, the comb drive gap and the vertical gap between the substrate and the floating mass, which are critical parameters of air damping, are shown.

Fig. 4 compares the single-anchored structure with the double-anchored structure. The double-anchored structure is deformed depending on the shape of the package, as shown in Fig. 4(a), while the single-anchored structure retains its flat shape in spite of the external deformation as shown in Fig. 4(b).

In general, a deformed structure possesses a residual stress. If the suspension of the structure is under tensile stress, the resonant frequency of the structure increases. However, if the suspension of structure is under compressive stress, the resonant frequency of the structure decreases. Because a single-anchored structure has the freedom to expand or shrink without constraints, it has no residual stress. Therefore, the structure retains the original frequency. However, even if the structure undergoes no deformation, its package is deformed by asymmetric geometry as shown in Fig. 4(b), air damping for the resonating structure varies depending on the
change in the distance from the fixed wall. In this respect, a packaged resonator should have a completely symmetric structure as shown in Fig. 4(c).

Therefore, we designed the wafer-level packaged MEMS resonator having stress-free package and suspending structures. The device ensures stable resonance characteristics, even after harsh environment tests including thermal cycling. Thus, the device can be used as accurate vacuum sensors.

**III. FABRICATION PROCESS**

The fabrication process of a wafer-level packaged MEMS resonator consists of (1) a top glass process to create a mechanical supporter, (2) an SOG process to form the primary micromechanical structure, (3) a bottom glass process to prepare the vacuum cavity with the getter, and (4) an encapsulation process to complete the vacuum packaging, as shown in Fig. 4.

As shown in Fig. 5(g), the resonator structures, including the moving parts, driving electrodes, and lateral sensing electrodes, are formed by the deep RIE process. Unlike the micromachining processes that use other SOI (silicon-on-insulator) substrates, our process is almost free of notches and stiction because of the effect of ion neutralization by an aluminum electrode and the purely dry release process. Fig. 6 shows our notch-free structure in comparison with a conventional structure fabricated on an SOI wafer. To prevent vacuum degradation during the bonding, titanium metal as a getter material is deposited on the cavity by an e-beam evaporator, as shown in Fig. 5(j). A shadow mask is used to evaporate the getter material selectively. The primary reason for using the shadow mask instead of photolithography is that the getter effect of titanium could become ineffective after exposure to various chemicals during photolithography. The thickness of the titanium getter material is designed to be more than 3000 Å so as to absorb most of the oxygen by-product in the bonding process. Even though the anodic bonding process allows reliable hermetic sealing in vacuum packaging applications, a large amount of oxygen is released during the bonding process. As a result, a getter to absorb the oxygen by-product must be integrated into
the package to maintain a high vacuum level [12, 13].

Figs. 5(k) and (l) show the vacuum-sealing fabrication process. The SOG wafer shown in Fig. 5(g) and the bottom glass wafer shown in Fig. 5(j) are bonded to each other at a specific vacuum level. Before bonding, the two wafers are aligned with a bonding chuck, and the chuck is moved into the bonding chamber. The chamber is pumped out to 1 mTorr, and the aligned two wafers are heated to 450°C, which is sufficient to bake out any foreign substance adsorbed at the bonding surface and activate the getter material. Argon gas is then injected into the chamber, and the flow rate is controlled. The specific vacuum condition is maintained for more than 30 min to guarantee uniformity.

IV. QUALITY FACTOR MEASUREMENT

Before measuring the quality factor of the packaged resonator, the correlation between the quality factor and the pressure was investigated through a preliminary experiment. The experiment was performed by measuring the quality factor of the unpackaged resonator in a vacuum chamber where the chamber pressure can be adjusted. The vacuum chamber used for the experiments is shown in Fig. 7.

The chips separated from the SOG wafer shown in Fig. 5(g) were used in the experiment through solder bonding on the printed circuit board. The measurement was performed thrice with three different vacuum levels at 5 mTorr intervals.

Fig. 8 shows the quality factor versus pressure relationship measured in the vacuum chamber. As shown in this figure, the experiment demonstrates that in the absence of packaging stress, the quality factor of the unpackaged resonator perfectly depends on the operating pressure. The experiment result was used as a reference to determine the vacuum level from the quality factor of the packaged resonators.

The equipment setup to measure the quality factor for wafer-level vacuum-packaged devices is shown in Fig. 9. A custom-made auto-prober was used for fast evaluation of all the devices in a packaged wafer. The packaged devices were driven by two input voltage signals, which were out of phase to cancel noise loaded on the signal. The movement of the micromechanical structure due to the driving force caused a capacitance change in the
lateral sensing electrode. The capacitance change was converted to a voltage change by a charge amplifier. The sensing voltage signal appeared on the oscilloscope, and the frequency response was displayed on the signal analyzer. From the frequency response, the quality factor was calculated by using Eq. (4),

$$Q = \frac{f_r}{2 \times B}$$  \hspace{1cm} (4)

where \(f_r\) is the resonance frequency, \(B\) is the bandwidth.

The vacuum level inside the vacuum-packaged device can be estimated from the quality factor calculated above and the relationship between the quality factor and pressure that was discussed earlier.

V. RESULTS AND DISCUSSION

Fig. 10 shows the quality factor distributions of the devices packaged under pressures of 50, 100, and 200 mTorr. The average of the quality factor measured in each wafer is 4987, 3415 and 2127 respectively, and approximately 80% of the packages in each wafer indicate almost equal values within the margin of error. These results show that the resonator can accurately measure the real pressure of the package from the relationship between the quality factor and pressure shown in Fig. 8.

For some packages, the quality factors before and after high-temperature storage were compared. The data are summarized in Table 1. From this table, it is confirmed that the quality factor, and thus the vacuum level, did not change considerably. In addition, the vacuum tightness was monitored for more than 50 days. Five of the devices packaged with getter film in argon ambient at a pressure of 50 mTorr were used, and observations were made at 24-h intervals. Fig. 11 shows the monitoring results of the quality factor. The vertical bar in the figure shows the quality factor range of the five devices. As shown in Fig. 11, no significant variation in the quality factors was observed.
VI. CONCLUSION

Wafer-level packaged MEMS resonators with highly vacuum-sensitive quality factors were discussed. The results of the quality factor measurement exhibited a very uniform distribution: most devices in 4-in. s wafer showed almost equal values and vacuum sensitivity, thus allowing the devices to be used as accurate vacuum sensors. The mechanical insensitivity of the devices was also verified by comparing the quality factor before and after high-temperature storage. Furthermore, more than 50 days of durability testing was performed, and no significant variation in the vacuum level was observed.

ACKNOWLEDGMENTS

This study was supported by the BK21 Plus funded by the Ministry of Education, Korea (21A20131600011).

REFERENCES


Seok Jin Kang received the B.S. and M.S. degrees in electronics engineering from Kyungpook National University in 1991 and in 1993, respectively. From 1993 to 2008, he worked as a research staff member at the Samsung Advanced Institute of Technology. During this period, he developed the fabrication and packaging process for the laser diode, MEMS gyroscope, RF MEMS switch, MEMS scanner, etc. In 2008, he joined the DMC R&D center of Samsung Electronics Co., where he did research on image drums for direct printing, a lens-integrated LED array for an LED printer, self-powered sensors using energy harvesting, etc. Currently, he is pursuing his Ph.D. in electronics engineering from Kyungpook National University, Daegu, Korea. The focus of his work is highly reliable design of fabrication and packaging processes for micromechanical devices.

Young Soon Moon received the B.S. degree in electronics materials engineering from Gyeongsang National University, Gyeongnam, Korea, in 2000. He took the M.S. degrees in sensor and display engineering from Kyungpook National University, Daegu, Korea, in 2011 and He is currently a Ph.D. candidate in the same university. His interests include MEMS physical sensors and WIM systems.

Won Ho Son received the B.S. degree in electrical engineering from Pukyong National University, Busan, Korea, in 2008. He took the M.S. degrees in electronics engineering from Kyungpook National University, Daegu, Korea, in 2011, and he is currently a Ph.D. candidate in the same university. His interests include thin-film solar cells and DNA chips.

Sie Young Choi received the B.S. and M.S. degrees in electronics engineering from Kyungpook National University, Daegu, Korea in 1972 and 1974 and the Ph.D. degrees in electrical engineering from Tohoku University, Sendai, Japan in 1986. Since 1974, he has been a professor with the School of electronics engineering, Kyungpook National University, Daegu, Korea. His research interests include thin-film solar cells, TFT, MEMS physical sensors, and FET biosensors.