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Vacuum Packaging Technology Using Localized Aluminum/Silicon-to-Glass Bonding

Y. T. Cheng, W. T. Hsu, L. Lin*, C. T. Nguyen, and K. Najafi

Center for Wireless Integrated Microsystems
The University of Michigan, 1301 Beal Ave., Ann Arbor, MI 48109
* University of California at Berkeley, Berkeley, CA 94720
e-mail: najafi@umich.edu, Fax: (734) 763-6650

ABSTRACT

A vacuum package based on localized aluminum/silicon-to-glass bonding has been successfully demonstrated. With 3.4 watts heating power, ~0.2MPa applied contact pressure, and 90 minutes wait time before bonding, vacuum encapsulation at 25mtorr can be achieved. Folded-beam comb drive μ-resonators are encapsulated and used as pressure monitors. Long-term testing of un-annealed vacuum–packaged μ-resonators with a *Q* of 2500 has demonstrated stable operation after 20 weeks. A μ-resonator with *Q* of ~9600 has been vacuum encapsulated and shown to be stable after 7 weeks.

INTRODUCTION

Vacuum and hermetic encapsulation of resonant devices is required not only to protect them from damage and contamination, but also to provide a controlled low-pressure or vacuum environment for high *Q* operation. Contaminants, like moisture and dust, can greatly affect the sensitivity and resolution of μ-resonant devices. For example, because the typical mass for a VHF μ-resonator mass is about 10^{-13} kg, even small amounts of mass-loading can cause significant resonance frequency shifts and induced phase noise **[1]**. In addition, most surface micromachined resonant devices like comb-drived μ-resonators and ring type μ-gyroscopes have very large surface to volume ratios and vibrate in a very tight space. For such devices, viscous and squeeze-film damping effects can also reduce the *Q* of these devices **[2,3]**.

In MEMS vacuum packaging, two major approaches have been demonstrated: the integrated encapsulation approach and the post-process packaging approach **[3-5]**. Integrated encapsulation can achieve low pressure and high hermeticity in wafer level fabrication and provide lower manufacturing cost. However, the lack of controllability of cavity pressure, which is determined by pressure and the deposition of CVD materials during the sealing process, is a limitations of this approach. The post-process packaging approach has the potential to overcome this problem and is chosen as the preferred method in this work. Previously, we reported a novel hermetic package using localized aluminum/silicon-to-glass bonding with excellent bonding strength and durability under a very harsh testing environment [6]. This paper presents a glass packaging used for vacuum encapsulation of standard surface micromachined μ-resonators, and testing and characterization of packaged μ-resonators. The post-process packaging method can be applied to a variety of MEMS devices which require controllability of the cavity pressure, low-temperature processing at the wafer-level, excellent bonding strength, low fabrication cost and high reliability.

DESIGN AND FABRICATION

The vacuum packaging presented here is based on the hermetic packaging technology using localized aluminum/silicon-to-glass solder bonding technique reported previously **[6]**. Built-in folded-beam comb drive μ-resonators are used to monitor the pressure of the package. Figure 1 shows the fabrication process of the package and resonators. Thermal oxide (2μm) and LPCVD Si_3N_4 (3000Å) are first deposited on a silicon substrate for electrical insulation followed by the deposition of 3000Å LPCVD polysilicon. This polysilicon is used as both the ground plane and the electrical interconnect to the μ-resonators as shown in Figure 1(a). Figure 1(b) shows a 2μm LPCVD SiO_2 layer that is deposited and patterned as a sacrificial layer for the fabrication of polysilicon μ-resonators using a standard surface micromachining process. A 2μm-thick phosphorus-doped polysilicon is used for both the structural layer of micro resonators and the on-chip microheaters. This layer is formed over the sacrificial oxide in two steps to achieve a uniform doping profile. The resonators are separated from the heater by a short distance to prevent their exposure to the high heater temperature as shown in Figure 1(c). This concludes the fabrication of μ-resonators.

In order to prevent the current supplied to the microheater from leaking into the aluminum solder during bonding, a LPCVD Si_3N_4 (750 Å)/ SiO_2 (1000 Å)/ Si_3N_4 (750 Å) sandwich layer is grown and patterned on top of the microheater as shown in Figure 1(d). Figure 1(e) and (f) show that aluminum (2.5μm) and polysilicon (5000Å) bonding materials are deposited and patterned. The sacrificial release is the final step to form free standing μ-resonators. Figure 1(f) shows a thick AZ 9245 photoresist is applied to cover aluminum/silicon-to-glass bonding system to ensure that the system withstands the attack from concentrated hydrofluoric acid. After 20 minutes sacrificial release in concentrated HF, the system as shown in Figure 1(g) is ready for vacuum packaging. Figure 2 shows SEM photos of a number of released μ-resonators surrounded by a 30μm wide microheater with aluminum/silicon bonding layer on top. A Pyrex glass cap with a 10μm deep recess is then placed on top with an applied pressure of ~0.2 MPa under a 25mtorr vacuum, and the heater is heated using 3.4 watts input power (exact amount depends on the design of the micro-heaters) for 10 minutes to complete the vacuum packaging process as shown in Figure 1(h).

EXPERIMENTAL RESULTS

To evaluate the integrity of the resonators packaged in this manner, the glass cap is forcefully broken and removed from the substrate. It is observed that no damage is found on the μ-resonator and a part of the microheater is stripped away as shown in Figure 3, demonstrating that a strong and uniform bond can be achieved without detrimental effects on the encapsulated device. Outgassing from the glass and gas resident

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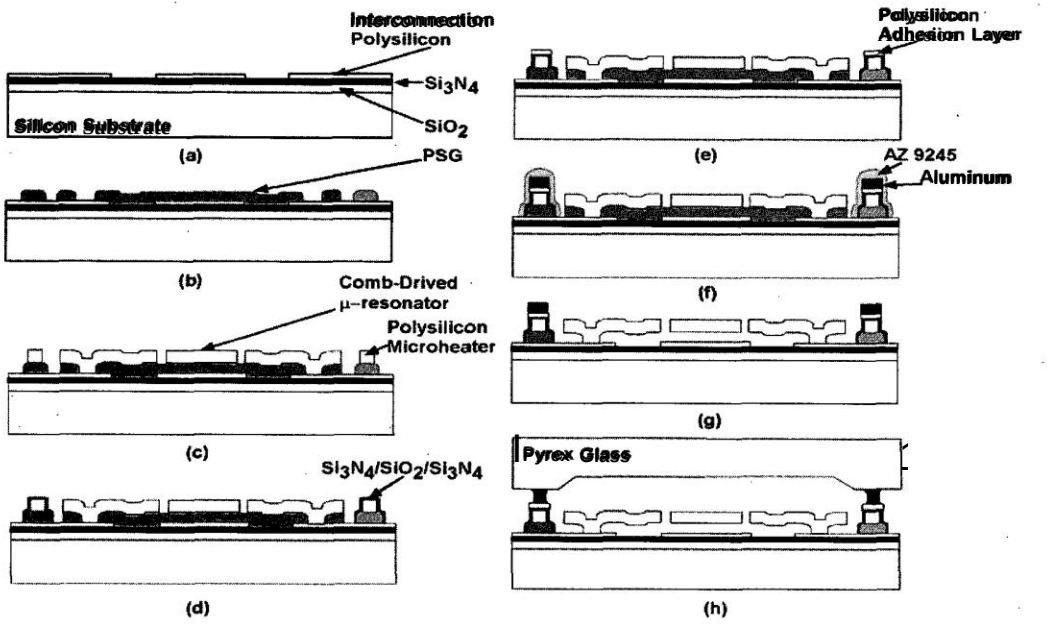

Figure 1. *Fabrication process flow of vacuum encapsulation using localized aluminum/silicon-to-glass bonding.*

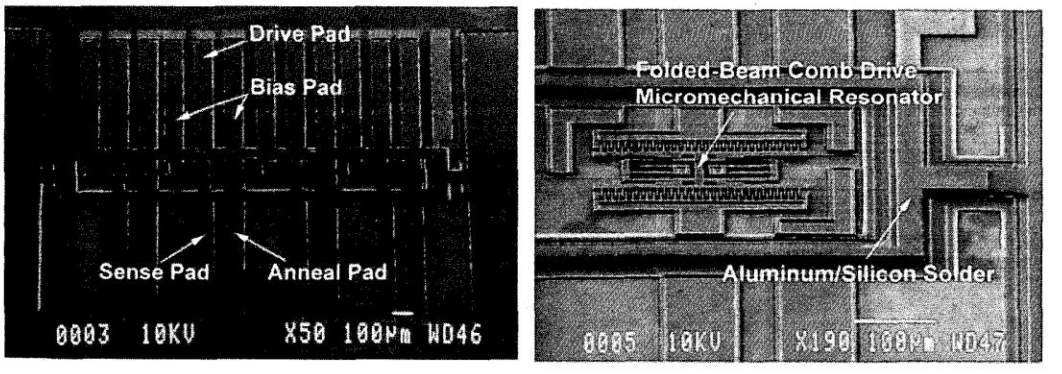

Figure 2. *SEM microphotos of folded-beam μ-resonators.*

inside the cavity are two major factors that should be minimized in order to achieve a low pressure environment in all vacuum based encapsulation processes.

During the bonding and encapsulation process, outgassing from the glass capsule could degrade the vacuum quality of the package [7,8]. In this encapsulation process, the volume of cavity formed by the recessed Pyrex glass cap and the device substrate as shown in Figure 3 is about 1.2×10^{-8} liter. Any outgassing would result in a drastic increase of pressure in such a small volume. Two possible outgassing mechanisms could happen during the fabrication of vacuum packages: 1) desorption of moisture or gases absorbed on the glass surface, and 2) out-diffusion of gases which are resident in the glass. Desorption of moisture or gases can be easily eliminated by baking the glass and device substrates at a temperature above 150°C in a vacuum oven for several hours before bonding [9]. For the case of out-diffusion of gases, the amount of gas out-diffusion is determined by the solubility difference of gases in the glass at different temperature and pressure environments. Since the glass cap is heated up during the bonding process, out-diffusion of gases from glass will occur and becomes the major factor affecting the vacuum level of the sealed cavity.

A two step pretreatment of Pyrex glass can potentially reduce the influence of gas out-diffusion. A recessed glass cap is first baked under 25 mtorr and 300°C for 1 hour, and then coated with 3000Å Ti/1000Å Au layers on the recessed surface. Vacuum baking can reduce the total amount of gases trapped inside the glass and metal coating can provide a good diffusion barrier to gas atoms. Furthermore, Ti is a good getter material for common gases that will further reduce the amount of trapped gases inside the package and out-gassing during the bonding process. Figure 4 shows the Q of p-resonators (~103kHz resonant frequency) encapsulated by glass caps with or without pretreatment and with Ti/Au layer on the recessed surface of glass. Since Ti/Au layer effectively prevents outgassing from the glass cap during bonding, the quality factor improvement from 25 to 500 is observed.

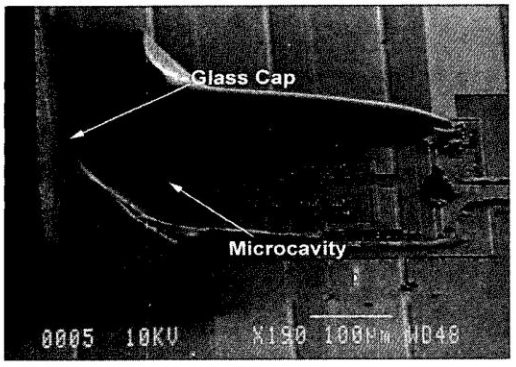

Figure 3. The SEM photograph of encapsulated μ-resonators after the glass cap is forcefully broken away.

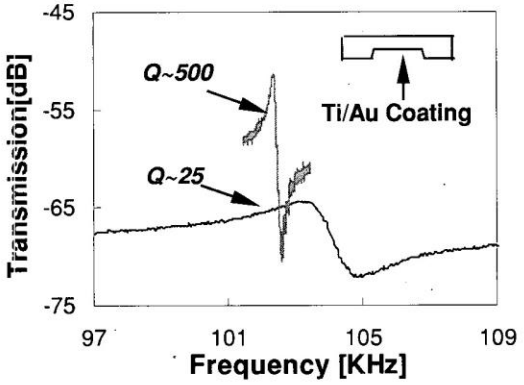

Figure 4. Measured Q of glass encapsulated μ-resonators with or without Ti/Au coating on the surface of recessed glass

In the final vacuum encapsulation process, the whole packaging system is placed inside a vacuum chamber and the aluminum/silicon solder is heated up locally to initiate the bonding. Since the air trapped inside the cavity has to diffuse out, it takes time for the micro-cavity to reach the same vacuum level as the outside environment in the vacuum chamber. Gas resident time is an important experimental parameter to determine when the bonding process should start after the system is placed into the chamber. It can be estimated by using fluid mechanic theory **[10]**. Figure 5 shows the simulation results of residual pressure of cavity versus gas resident time. The cavity pressure can reach lower than 30 mtorr after inserting the system into 25 mtorr vacuum chamber for 90 minutes. Therefore, the Q-factor can be increased by keeping the package under vacuum for an extended period of time (>10 minutes) before the cap is bonded to the substrate. Figure 6 shows a μ-resonator (~81kHz) with a Q-factor of ~2500 bonded at 25 mtorr after ~90 minutes of pump down.

DISCUSSION

Although these two experimental factors, outgassing and gas resident time, have been considered in the fabrication of vacuum encapsulation, the measured Q of 2500 is lower than typical values for polysilicon resonators in high vacuum. The Q

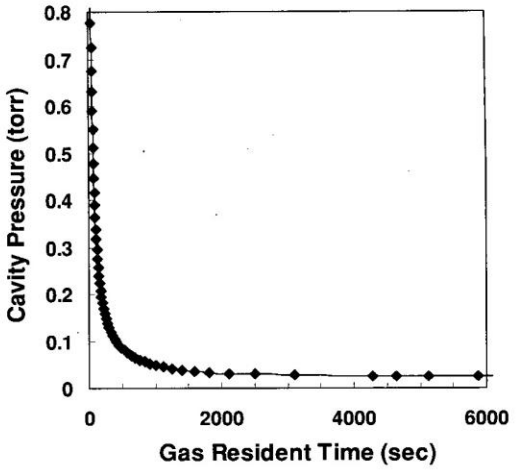

Figure 5. Simulation result of the cavity pressure versus the gas resident time inside the cavity

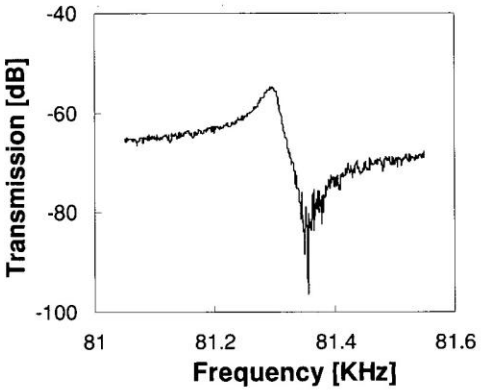

Figure 6. The transmission spectrum of glass encapsulate μ-resonator with 90 minutes wait time in vacuum environment (Q=2500).

factors of un-packaged resonators as a function of pressure are measured as shown in Figure 7. It is observed in Figure 7 that a quality factor of 2300 of the comb resonator corresponds to a vacuum level of about 25 mtorr. This result is consistent with the data shown in Figure 6 where the pressure in the package after bonding is approximately 25mtorr. Furthermore, the un-packaged resonators have a maximum Q of about 3850 at a very low pressure of 1 mtorr which can be improved to higher than 8000 by means of local annealing **[11]**. Therefore, the low Q result of the vacuum encapsulated resonator is not believed to be due to air damping. More testing on the resonators with higher Q was conducted to verify this speculation. Figure 8 shows a vacuum encapsulated un-annealed μ-resonator (~57kHz) after 120 minutes of wait time. The measured Q-factor after packaging is 9600. Based on the measurement of Q vs. pressure of a high Q unpackaged μ-resonator as shown in Figure 7, it is demonstrated that the pressure inside the packaging is comparable to the vacuum level of packaging chamber. Figure 9 shows long-term measurement of the Q-factor of the un-annealed, vacuum packaged μ-resonators. It is found that both vacuum packages provide stable operation vacuum environments for μ-resonators with 2500 and 9600 of Q-factors respectively. No degradation of Q-factors is found after 20 and 7 weeks in both packages.

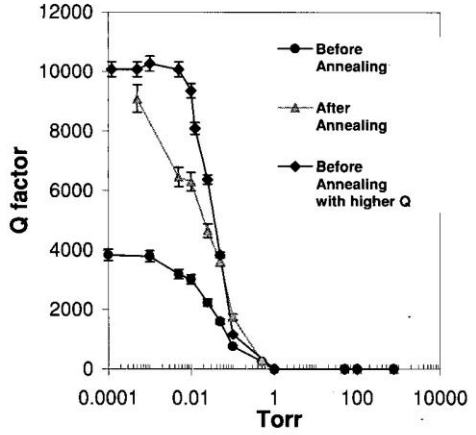

Figure 7. The relationship of Q factor vs. pressure of unpackaged μ-resonators.

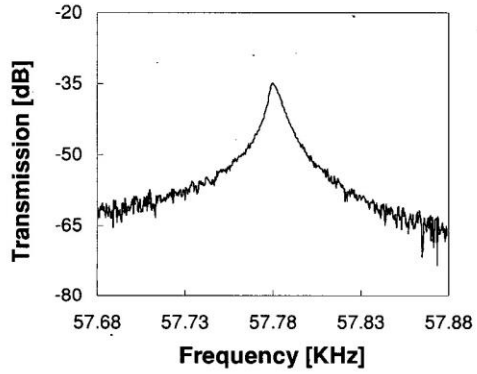

Figure 8. The transmission spectrum of glass encapsulated μ-resonator with 120 minutes wait time in vacuum environment (Q=9600).

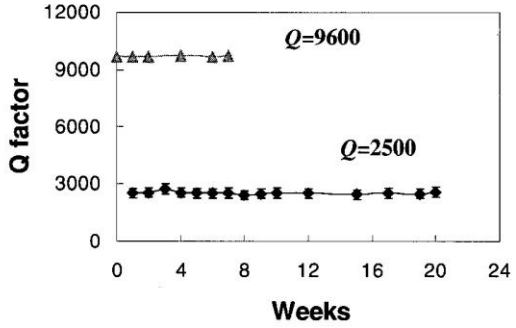

Figure 9. Long-term measurement of encapsulated μ-resonators. No degradation of Q factors are found after 20 weeks and 7 weeks.

Since the performance of high Q μ- resonator is very sensitive to environmental pressure as shown in Figure 7, the leakage rate can be further investigated using the high Q μ-resonator. This demonstrates that both aluminum and Pyrex glass are suitable materials for vacuum packaging applications. This bonding based post-process encapsulation technology will be quite useful in high vacuum packaging applications.

CONCLUSION

We have successfully encapsulated folded-beam comb drive μ-resonators in vacuum based on localized aluminum/silicon-to-glass bonding. With 3.4 watts of heating power, ~0.2MPa applied contact pressure, and 90 minutes of waiting time in 25 mtorr of vacuum before bonding, vacuum encapsulation can be achieved. The effects of outgassing and gas resident time on the sealed micro cavity have been discussed. The use of a metal coating as a diffusion barrier as well as a wait period before bonding to achieve high vacuum inside the package are proposed. This micropackaging method accomplishes post-process MEMS packaging which requires controllability of the cavity pressure, low temperature processing at the wafer-level, excellent bonding strength, low fabrication cost and high reliability.

Acknowledgements

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