A SIMPLE PROCESS FOR THE FABRICATION OF PARALLEL-PLATE ELECTROSTATIC MEMS RESONATORS BY GOLD THERMOCOMPRESSION BONDING

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ABSTRACT

The present work introduces a simple and quick process for the fabrication of flexural MEMS resonators with electrostatic actuation and capacitive detection. Gold thermocompression is used to anchor the free-standing structure, to provide electrical connections and to seal the chip to protect the structure to be released during wet etching, in a single step. The additional advantage of this process is the ability to simply adjust the gap of the parallel-plate capacitor through the thickness of electroplated gold. Squeeze damping is reduced by fabricating devices with increasing gaps.

KEYWORDS

Micromechanical device, Cantilever, Parallel-plate capacitor, Resonant frequency, Q-factor, Packaging, Thermocompression.

INTRODUCTION

Electrostatic actuation and capacitive read-out implemented in MEMS resonators are known to provide a combination of low-power consumption and high-level of integration. Even if electrostatic MEMS architecture remains relatively simple, the difficulty in their implementation is to precisely define the micrometric gap between the moving structure and the fixed actuation/sensing electrode. Parallel-plate electrostatic MEMS are commonly fabricated following two different approaches: silicon surface micromachining using a sacrificial layer [1], or transfer methods, such as wafer bonding techniques [2] and micro-masonry [3,4].

Thermocompression bonding is a technique widely used for MEMS packaging [5], that has so far only been exploited once for the fabrication of a free-standing structure, an electrostatic relay [6]. This is surprising since this approach offers the advantage of providing mechanical anchoring and electrical connection in a single step. Besides, shear tests have demonstrated that thermocompression bonds exhibit strength similar to those obtained by silicon/glass anodic bonding [7].

Here, thermocompression bonding was used to fabricate a parallel-plate mechanical resonator where the novelty of our work is the use of the gold seal formed on the edge of each chip to protect the resonator during its release by wet etching the handle wafer (which differs from the dry etch approach used in [6]), and to conveniently control the gap size through the thickness of the electroplated gold joint.

We evaluated the electro-mechanical performances of the fabricated MEMS that behave as theoretically expected: we measure a quadratic dependance of the gap and capacitance with applied voltage, a non-linear response regime at resonance is obtained with high AC voltage and the spring softening effect is observed with increasing DC voltage. The quality factor of the MEMS cantilever drops with increasing pressure and a strong squeeze film air damping is observed at atmospheric pressure. This effect is reduced by increasing the parallel-plate capacitor gap through the fabrication of a thicker thermocompression joint.

DESIGN AND FABRICATION

The thermocompression-based process developed to fabricate electrostatic MEMS resonators uses standard microfabrication techniques to create a cantilever with its top electrode and a bottom electrode on a SOI and a fused silica substrate, respectively. Gold is deposited on both substrates at the location of the cantilever anchor to provide mechanical and electrical connections to the cantilever with its substrate upon chip bonding by gold-gold thermocompression. Moreover, gold is deposited on the chip perimeter to serve as a sealing joint to protect the cantilever so the handle SOI layer can be removed and the cantilever released by a simple wet etch step. This unique process, on top of being straightforward, also enables to control the parallel-plate gap by simply adjusting the thickness of the gold layer.

We designed various shapes of cantilever structures inspired from our previous work on gas sensors [8]. However, the most studied devices consisted of 500µm or 250µm long, 500µm wide and 5µm thick silicon cantilevers. Cantilevers with a similar surface area, thus capacitance, but slightly different shape, thus resonant frequency, were added onto each chip to be used as an electrical reference for static capacitance compensation during dynamic characterizations. Each chip integrates 4 different devices and two reference cantilevers (figure 1).

The fabrication process is illustrated in figure 2 and consists of three main steps: i) processing the resonator and its electrode, ii) processing the bottom electrode on the receiving substrate, and iii) thermocompression bonding followed by a wet etch to release the resonator. A joint that seals the top and bottom substrates around the chip is integrated with the aim to protect the cantilever during its release by wet etching.

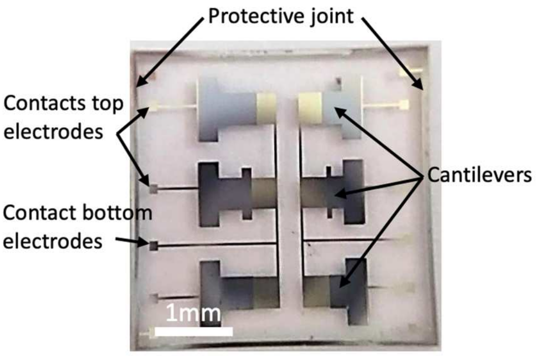

Figure 1: Optical image of a chip showing the various cantilever structures, the contacts for the top and bottom electrodes and the location of the gold joint used to protect the chip during wet etching.

The device process started with the 5µm thick dry etch of a 100mm SOI wafer (Si 5µm/SiO_2 1µm/Si bulk 400µm) to create the shape of the cantilevers using AZ ECI 3012 photoresist (figure 2.a-b). Then, a 200nm thick silicon oxide layer was thermally grown to avoid gold diffusion into the silicon cantilever during the thermocompression process (figure 2.c). Electrodes were created by sputtering a 50nm thick Cr seed layer and a 100nm thick Au layer, which were patterned by photolithography (AZ 4999 photoresist) and wet etching (figure 2.d). The bonding pads were then created by a lift-off step using AZ nLOF 2035 photoresist and 500nm thick Au layer deposition (figure 2.e). The wafer was finally annealed at 250°C for 20min to decrease the residual stress within the metal layers.

The substrate hosting the fixed bottom electrode was processed from a 100mm fused silica wafer to ensure the isolation of the contact electrodes. The use of a silicon substrate for the bottom electrode was prohibited since the last fabrication step consisted in releasing the cantilever by wet etching the silicon handle wafer. A first method to set the gap between the top and bottom electrodes was the use of a cavity within the fused silica substrate (figure 2.f). This cavity was created by dry etching the glass substrate patterned by photolithography (AZ 15nXT photoresist). Integration of the bottom electrodes and the bonding pads were then carried out in a similar way as for the top electrode and the metals layers were annealed (figure 2.g-h). A second method to set the gap was to directly use the thickness of the bonding pad by implementing thicker gold joints, thus conveniently avoiding the substrate etching step and enabling large gaps. To this aim, thicker bonding pads were achieved through the electrochemical deposition of gold into a dedicated AZ 40XT photoresist mold (figure 2.h). For this modified process, we also switched to the use of Borofloat 33 substrates that exhibit a coefficient of thermal expansion closer to the one of silicon in order to avoid bonding failure due to layer delamination or substrate cracking that was sometimes observed with fused silica.

After processing the device and substrate wafers, both were diced into chips and cleaned using oxygen plasma. Thermocompression bonding was then conducted after aligning both chips using a FC150 flip-chip bonder from SET (figure 2.i-j). The bonding process was performed by applying 40KgF at 350°C during 10min. Finally, the cantilevers were released by wet etching the device handle wafer and the buried silicon dioxide layer sequentially with TMAH and BHF (figure 2.k). To avoid stiction of the cantilever, sequential baths of ethanol-acetone-HFE7100-PF2 were used to rinse the device before drying it. Alternatively, supercritical CO_2 drying with a Tousimis 915B critical point dryer was also performed.

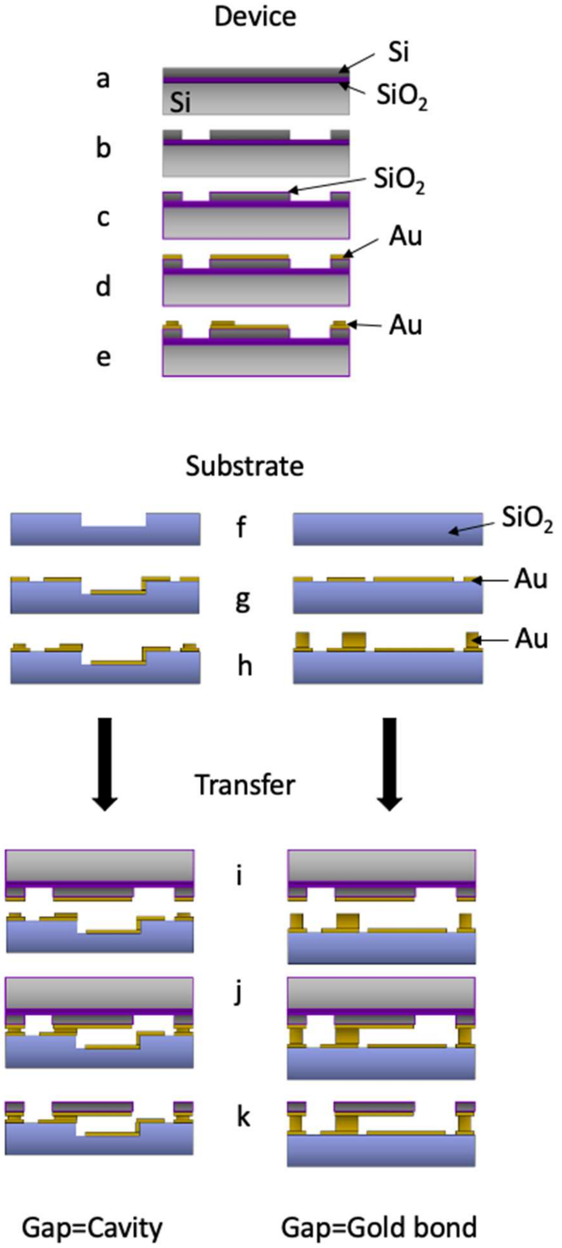

Figure 2: Thermocompression-based fabrication process of the MEMS resonator. The device is fabricated on a SOI wafer by silicon DRIE to form the cantilever and gold evaporation to create the top electrode (top). The bottom electrode and the electroplated gold joint are patterned onto a fused silica wafer that can be previously etched to create a cavity underneath the cantilever (middle, left) that defines the electrode gap. Alternatively, the gap can be set by the thickness of the gold bond, increased by electrochemical deposition of gold (middle, right). Fabrication of the device is finalized by gold-gold thermocompression to bond the 2 substrates and by wet etching the handle SOI layer to release the silicon cantilever (bottom).

It is interesting to note that to save TMAH etching time, the backside of the device wafer could be mechanically thinned down (from 400µm to 200µm) with a dicing saw, thus demonstrating the thermocompression bond strength. Also, before the release step by wet etching, the seal was checked for leaks by immersing the chip in ethanol: test failure resulted in the etch/damage of the cantilever (figure 3).

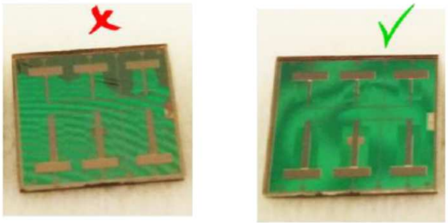

Figure 3: Optical picture of chips after immersion in an ethanol bath to test the joint sealing (Left: leaky device; Right: appropriate joint for subsequent wet etching).

RESULTS AND DISCUSSION

An example of a fabricated chip is shown in figure 1, where the protective joint at the periphery of the chip can clearly be seen. Figure 4 shows optical and SEM images of fabricated cantilevers where the gap of the parallel-plate capacitor, ranging from 3µm to 9µm, is set by a cavity etched in the silica substrate. The high-quality interface of the thermocompression bond can be seen on the SEM cross-section views. Figure 5 shows a SEM image of a device whose gap is defined by the thickness of the electroplated gold used for thermocompression. Structures with gaps up to 25µm were achieved with this process. Optical profilometry was used to image the surface of the fabricated cantilevers: as can be seen in figure 5, the cantilever surface is parallel to the substrate, indicating that the pressure is evenly distributed on the chip during the bonding process.

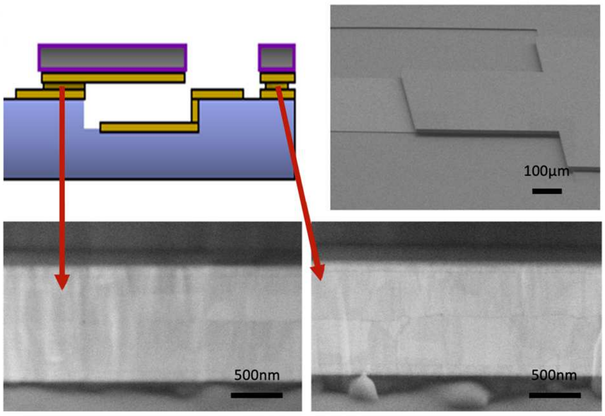

Figure 4: SEM images of a fabricated device with a cavity etched in the host glass substrate to create the gap; cross-section views of the gold bond.

The cantilevers were then characterized in static and dynamic modes. To this aim, we have used a home-made network analyzer to drive the excitation voltage and measure the gap capacitance using a charge amplifier. The deflection of the tip of the cantilever was additionally measured using a IFS2407-3 confocal microscope from micro-epsilon. Static characterizations are presented in figure 6: the value of the gap size, at the tip of the cantilever, and the corresponding capacitance measured onto a 500µm long, 500µm width, 5µm thick cantilever with a ~22µm gap size exhibit a quadratic behavior with applied voltage, as theoretically expected.

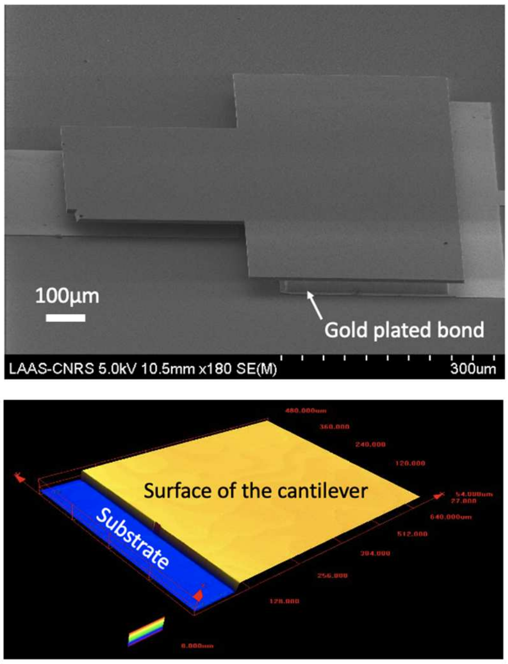

Figure 5: Top: SEM image of a cantilever with a large gap created by the electroplated gold. Bottom: Cantilever surface profile imaged with an optical profilometer.

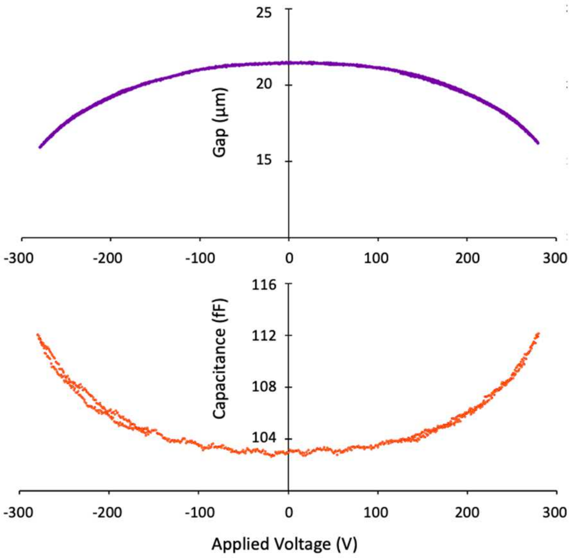

Figure 6: Static measurement of the cantilever gap and corresponding capacitance (after subtracting the static capacitance) as a function of applied DC voltage.

Last, we have studied the dynamic behavior of the cantilevers by driving them at resonance. The influence of the AC excitation and DC bias on resonant frequencies was studied and the expected non-linear response regime and the spring softening effect were observed with increasing AC and DC voltages, respectively (figure 7). The impact of environmental pressure on the quality (Q) factor of the mechanical resonators was studied using a Linkam vacuum chamber and a Cryoprober from SUSS MicroTec for medium and high vacuum measurements (figure 8). Q factors of up to 10^4 were obtained in high vacuum, indicating a limited dissipation due to the gold anchor. While devices with 3µm gap experienced critically damped vibrations because of squeeze damping in air [9], a Q factor of ~45 was obtained by increasing the gap to 25µm, thus demonstrating the interest of our fabrication technique for conveniently tunning the electrode gap.

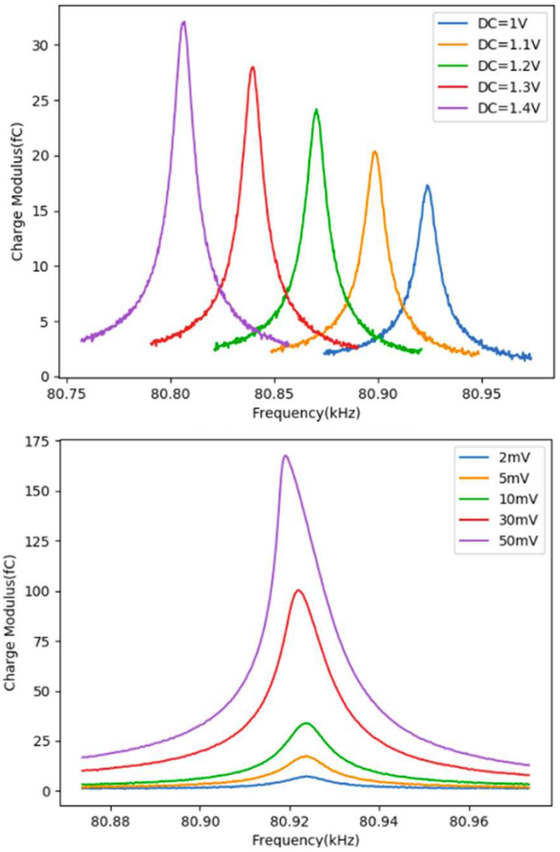

Figure 7: Characterization of a 3µm gap cantilever in high vacuum. Resonance frequency as a function of DC bias for V_{AC}=50mV (top) and AC signal for V_{DC}=1V (bottom).

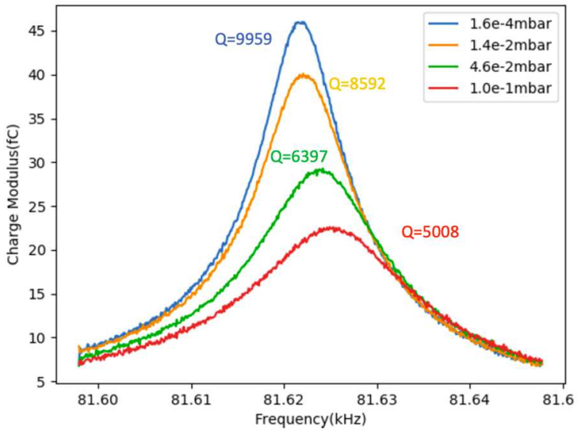

Figure 8: First mode resonance frequency spectrum of a 9µm gap device as a function of pressure (V_{AC}=90mV and V_{DC}=2.5V).

CONCLUSION

In this paper, we present a straightforward process based on gold thermocompression bonding for fabricating suspended electrostatic flexural MEMS structures. Anchor of the free-standing structure and electrical connections are provided in a single step. Additionally, the parallel-plate gap size is controlled by simply adjusting the thickness of the electroplated gold layer to reduce the squeeze damping of cantilever resonators. This process is foreseen to be applicable to other geometries and material devices, e.g. SiC.

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REFERENCES

[1] M. I. Haller, and B. T. Khuri-Yakub, "A surface micromachined electrostatic ultrasonic air transducer", *IEEE Trans. Ultrason. Ferroelectrics. Freq. Contr.*, vol. 43, pp. 1-6, 1996.

[2] A. S. Erguri, Y. Huang, X. Zhuang, O. Oralkan, G. G. Yarahoglu, and B. T. Khuri-Yakub, "Capacitive micromachined ultrasonic transducers: fabrication technology", *IEEE Trans. Ultrason. Ferroelectrics. Freq. Contr.*, vol. 52, pp. 2242-2258, 2005.

[3] A. Bhaswara, H. Keum, S. Rhee, B. Legrand, F. Mathieu, S. Kim, L. Nicu, and T. Leïchlé, "Fabrication of nanoplate resonating structures via micro-masonry", *J. Micromech. Microeng.*, vol. 24, 115012, 2014.

[4] A. Bhaswara, H. Keum, F. Mathieu, B. Legrand, S. Kim, L. Nicu, and T. Leïchlé, "A simple fabrication process based on micro-masonry for the realization of nanoplate resonators with integrated actuation and detection schemes", *Front. Mech. Eng.*, vol. 2, pp. 1-7, 2016.

[5] C. H. Tsau, S. M. Spearing and M. A. Schmidt, "Fabrication of wafer-level thermocompression bonds", *J. Microelectromech. Syst.*, vol. 11, pp. 641-647, 2002.

[6] F. Copt, Y. Civet, C. Koechli and Y. Perriard, "Design and manufacturing of an electrostatic MEMS relay for high power applications", *Sens. Actuators A: Phys.*, vol. 321, 112569, 2021.

[7] S. Charlot, P. Pons, M. Dilhan, I. Vallet, and S. Brida, "Hermetic Cavities Using Gold Wafer Level Thermocompression Bonding", in *Proceedings of Eurosensors 2017,* Paris, France, September 3–6, 2017, 1(4), 607.

[8] M. T. Boudjiet, J. Bertrand, F. Mathieu, L. Nicu, L. Mazenq, T. Leichle, M. Heinrich, C. Pellet, and I. Dufour, "Geometry optimization of uncoated silicon microcantilever-based gas density sensors", *Sens. Actuators B: Chem.*, vol. 208, pp. 600-607, 2015.

[9] M. Bao and H. Yang, "Squeeze film air damping in MEMS", *Sens. Actuators A: Phys.*, vol. 136, pp. 3-27, 2007.

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