ETCH-HOLE FREE, LARGE GAP WAFER SCALE ENCAPSULATION PROCESS FOR MICROELECTROMECHANICAL RESONATORS

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ABSTRACT

We present a fabrication process for wafer-level encapsulated MEMS devices that allows for large masses without etch-holes with small and large transduction gaps. This combination of features allows for large masses with combdrive transduction with reduced thermoelastic dissipation. The omission of wafer bonding in this process reduces the footprint of an encapsulated device and creates a hermetically sealed cavity free of particles and organics. We present the performance of a bulk mode resonator (Q = 1.7M) and a flexural mode resonator (Q = 11k, 68k) that utilizes the small and large transduction gap capability. These devices exemplify the ability of this fabrication process to create single die containing high-Q silicon-based timing references and inertial sensors.

KEYWORDS

Resonant MEMS; Wafer-Level Encapsulation; Thin Film Encapsulation; High Quality Factor Resonator; MEM Timing Reference.

INTRODUCTION

Many products in the electronics industry contain a timing reference and inertial sensors, including smart devices, wearables, Internet-of-Things (IOT), small electronics, etc. Many of these applications could benefit from a single chip containing a timing reference and inertial sensors to reduce manufacturing cost and to decrease the footprint of the sensors. However, the different design requirements for timing references and inertial sensors result in the need for different fabrication processes, which results in different encapsulation methods.

In the past, timing references in smart devices and other small electronics used quartz oscillators. However, quartz-based timing references are very large and are not CMOS compatible and thus are expensive to batch fabricate [1]. Microelectromechanical (MEM) timing references have a smaller footprint and are compatible with CMOS fabrication processes. MEM timing references need to contain high-Q resonators with extremely low frequency drift. This requires an ultra-clean and low-pressure cavity. This leads to the need of these resonators to be hermetically packaged at the wafer level, which is demonstrated by the fact that the only commercially successful MEM timing products are manufactured using wafer-scale pre-release encapsulation [2].

MEM inertial sensors need to be encapsulated and have large and small transduction gaps. Most modern MEM inertial sensors are encapsulated using a wafer-bonded post-release package that allows for capping structures with large transduction gaps [3][4]. However, this method has significant drawbacks for resonant MEM inertial sensors. Generally, it is impossible to eliminate adsorbed water and other organic molecules from the surfaces of a released MEM resonator prior to wafer bonding or sealing, which can reduce device yield and cause drift and aging [5]. Even for sensors that can tolerate this drift and contamination, such as gyroscopes, these wafer bonding processes require that significant area is allocated to sealing rings, which increases minimum device size [6].

In-process thin film encapsulation solves many of the issues that plague wafer bonding [7-10]. Epitaxial silicon thin-film encapsulation builds an in-process capping layer in an ultra-clean epitaxial reactor at a high temperature, which allows sealing of MEM resonators inside an ultra-clean cavity without any residual molecular contamination [11]. This creates a low pressure, particle-free, and oxide-free environment that enables the resonators to be extremely stable over time [12]. This process also creates silicon-based resonators with smooth sidewalls, which ensures repeatable mechanical properties and prevents crack formation, or fatigue [13]. Additionally, no sealing rings are required, so device footprint is minimized.

While hermetic epitaxial wafer-scale encapsulation results in clean, stable resonators, the added complexity of the processing makes it harder to include other desired features. Inertial sensors for high dynamic range applications require large transduction gaps and high-frequency timing resonators rely on large, etch hole free masses, both of which are hard to achieve with epitaxial wafer-scale encapsulation.

We propose a hybrid process, described in Figure 1, that combines previous work of an etch-hole free variant of epitaxial encapsulation [14] with a large gap variant of epitaxial encapsulation by using sacrificial oxide posts [15]. Removing etch-holes in bulk-mode resonators with large masses reduces thermoelastic dissipation (TED), thereby increasing the Q of the resonator [16]. This new combination of processes supports a much broader range of resonator designs by allowing for large and small transduction gaps, etch-hole free large resonant masses, top electrodes, and low-pressure encapsulation without wafer bonding.

FABRICATION PROCESS

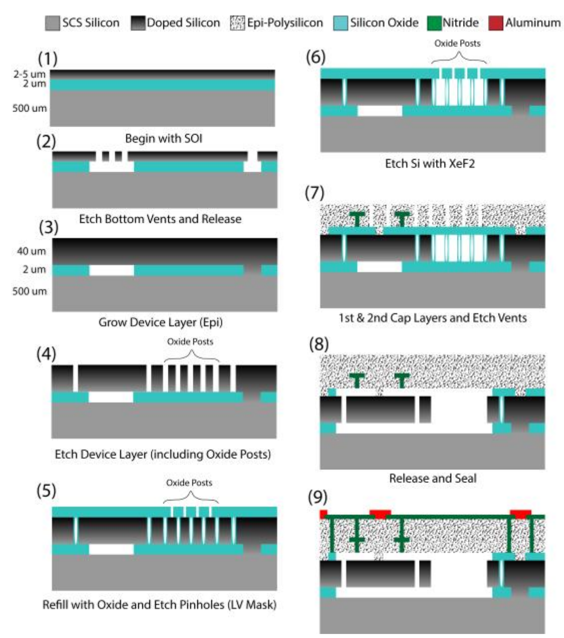

Figure 1: The process flow of this fabrication process a) starts with an SOI wafer. b) Vents are etched with DRIE and then areas beneath large masses are released with vapor phase HF. c) Immediately following, the device layer is grown with doped epitaxial silicon growth, d) and then devices and oxide posts (in large gap areas) are patterned with DRIE. e) LPCVD oxide (using TEOS) refills device trenches and trenches defining oxide posts. Vents are etched through the top oxide layer in large gap areas between the oxide posts. f) XeF_2 removes silicon from the large gap areas through the vents. g) More LPCVD oxide refills the vents and builds up the top oxide layer. Vias to the device layer are etched, then the first and second cap layers are deposited using epitaxial silicon. Vents for device release are etched with DRIE. h) The devices are released with vapor phase HF and sealed in a low pressure, high temperature epitaxial reactor. i) Finally, contacts to the device layer are patterned and isolated from the rest of the cap with nitride. Aluminum contact are patterned with aluminum etchant.

This process starts with an SOI wafer with a 2-5 μm device layer and 3 μm box oxide, illustrated in Figure 1a. Vents are etched with deep-reactive ion etching (DRIE) in areas where large masses are desired. Through these vent holes, vapor phase HF etches the oxide beneath large masses to release them, Figure 1b. Immediately following, the device layer is grown with doped epitaxial silicon growth, sealing the vent holes as well. The devices are patterned using DRIE with 20:1, 40:1, and 60:1 trench depth to width ratios. Trenches where oxide posts are desired, in large gap areas, are also patterned during this step, as seen in Figure 1d. Next, oxide is deposited in a low-pressure chemical vapor deposition (LPCVD) process using Tetraethylorthosilicate (TEOS) to conformally refill device trenches and the trenches defining the oxide posts. The oxide refill results in keyholes in the trenches because the trenches are sealed at the top before enough oxide deposits on the side walls of the high aspect ratio trenches. Vents are etched through the top oxide layer in large gap areas between the oxide posts using a fluorine-based magnetically-enhanced reactive ion etch (MERIE), as seen in Figure 1e. Vapor phase XeF_2 isotropically etches silicon from the large gap areas through the vents (Figure 1f). Figure 2 illustrates a cross-section of a cavity created by a XeF_2 etch of silicon in the device layer where a large transduction gap is desired, leaving oxide posts to support the top layer of oxide. The keyholes in the oxide posts formed by the conformal LPCVD oxide are visible.

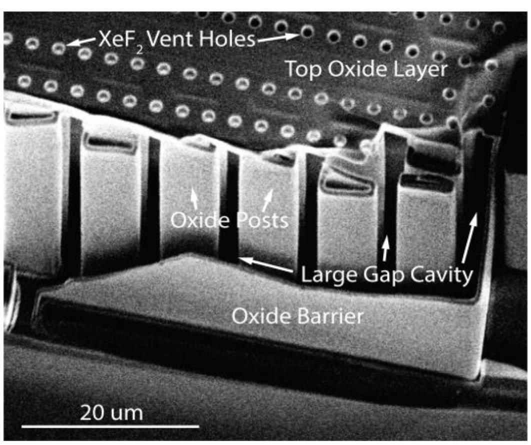

Figure 2: SEM of large gap cavity after XeF_2 etch.

More LPCVD oxide refills the vents and increases the thickness of the top oxide layer to 3 μm. Vias to the device layer are etched with fluorine-based MERIE, then the first and second cap layers are deposited using epitaxial silicon. Top electrodes are defined with DRIE and are isolated with nitride above devices intended to be released. Vents for device release are etched in the cap layers with DRIE, as illustrated in Figure 1g. The devices are released with vapor phase HF and sealed in a low pressure, high temperature epitaxial reactor with a third and final capping layer (Figure 1h). Finally, contacts to the device layer are patterned and isolated from the rest of the cap with a LPCVD low-stress nitride. Aluminum contact are patterned with aluminum etchant. Figure 1i depicts the cross-section of the final device.

Through this process, large gaps of up to 50 μm wide and 40 μm deep were created. Figure 3a illustrates the top view of a 50 μm by 450 μm trench. Additionally, resonators with large masses were successfully encapsulated without etch holes, as depicted in the SEM in Figure 3b.

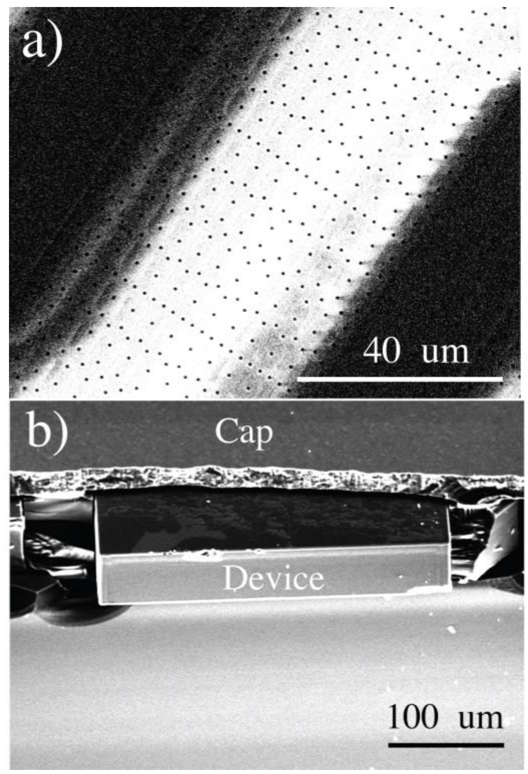

Figure 3: SEM images of a) the top view of a large gap cavity 50 μm wide and 450 μm long after the XeF_2 etch, and b) a cross-section of an encapsulated etch-hole free square bulk-mode resonator from this process.

DEVICE RESULTS

Figure 4 shows the frequency responses and mode shapes of a bulk-mode resonator consisting of a 400μm wide etch-hole free square plate and a large displacement beam resonator with 11.5 μm transduction gaps, both of which were recently fabricated in the first complete run of this process. Figure 3b depicts a cross-section of the square bulk-mode resonator with no etch-holes. The absence of etch-holes allows this square bulk-mode resonator to have a quality factor of 1.7M because the TED induced in the bulk mass in the isochoric Lamé mode shape, depicted in Figure 4a, is negligible without the strain gradients caused by the etch-holes.

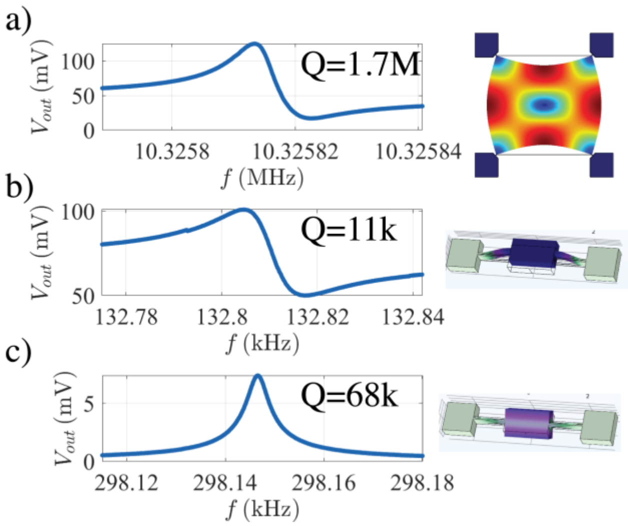

Figure 4: Mode shapes and frequency responses of a) the Lamé mode of a square bulk-mode resonator fabricated without etch-holes with a Q of 1.7M, which is achievable due to low TED contribution without etch-holes, b) an in-plane flexural mode of a large displacement resonator made possible with the large gap process, and c) a torsional mode of the same large displacement resonator.

The simple flexural mode resonator represents a device that can be used as a displacement-based or resonant accelerometer. The in-plane mode represents the ability to design a displacement-based accelerometer with a large mass, no etch-holes, and large transduction gaps to support high dynamic range. The Q for such a device could be designed or tuned to a lower Q to serve as a displacement-based accelerometer [17-19]. Disc resonant gyroscopes were also created in this process.

This work demonstrates co-fabrication of high-Q resonators for application in timing references as well as large displacement resonators for applications in accelerometers and gyroscopes to be fabricated on the same chip for the first time.

CONCLUSION

We presented a fabrication process to create hermetically sealed resonant MEMS where high-Q timing references and inertial sensors can be fabricated on the same die without wafer bonding. This high temperature epitaxial encapsulation process allows for small and large transduction gaps (tested up to 50 µm wide) and etch-hole free large masses. This process increases the design space for future resonant and non-resonant MEMS.

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