MEMS Resonators: Getting the Packaging Right

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Biography:
Aaron Partridge received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from Stanford University, Stanford, CA, in 1996, 1999, and 2003, respectively. He is currently CTO of SiTime Corp. From 2001 through 2004 he was Project Manager at Robert Bosch Research and Technology Center (RTC), Palo Alto, CA, where he coordinated the MEMS resonator research. In 1987, he co-founded Atomis, Inc., a manufacturer of STM, AFM, and Ballistic Emission Electron Microscopes (BEEM), were he was Chief Scientist through 1991 when Atomis was sold to Surface Interface Inc. Atomis equipment has been installed at AT&T Bell Laboratories, CERN, NIST, GM, and various universities. Dr. Partridge has authored and co-authored over 30 scientific papers and holds 8 patents.

Abstract:
Microelectromechanical Systems (MEMS) resonators have been investigated for over forty years but have never delivered the high performance and low cost required of commercial oscillators. Packaging technology has been one of the primary limitations. MEMS resonators must be enclosed in very clean environments because even small amounts of surface contamination can significantly change resonator frequency. In addition, since the packaging can dominate the product cost and the applications are often cost sensitive, the packaging should be inexpensive. These requirements have now been met by SiTime's MEMS-First^{TM} wafer-level encapsulation and packaging technology. SiTime builds encapsulated MEMS resonators in epitaxially sealed epipoly (epitaxially grown polysilicon) chambers buried under the wafer surface. The encapsulated resonator wafers are diced and molded into standard plastic IC packages with drive electronics. This encapsulation and packaging technology is inexpensive and extremely clean. The resulting silicon MEMS oscillators show performance levels similar to quartz and are expected to be suitable for a range of commercial applications.

Introduction:
Two of the earliest MEMS papers, published by Nathanson in 1965 and 1967, described resonant structures [1, 2]. However, MEMS timing references are only now about to be commercially introduced. Among the toughest problems to be surmounted in the intervening forty years was the development of an economical and sufficiently clean hermetic packaging system. This packaging must (1) provide an exceptionally clean internal environment, (2) provide a robust mechanical cover over the MEMS structure, (3) be small and preferably CMOS integrable to leverage MEMS strengths, and (4) be low-cost. The SiTime encapsulation and packaging technology described here provides all of these features.

Packaging cleanliness requires special attention for reference resonators. Unpackaged resonators can have drift on the order of a hundred ppm per day [3]. Quartz resonators dominate the timing reference market and are generally packaged in metal or ceramic vacuum enclosures. Similar enclosures might be made to work with MEMS resonators [4], but resonators packaged this way have yet to show the required stability. Anodically bonded covers have been found to give clean enough environments for some resonator types in some applications [5], but are not yet universally sufficiently clean. Getters have been investigated to provide a clean encapsulated environment [6] and have yielded high quality vacuums, but the added cost and complexity of getters is significant and integration problems exist.

The resonator packaging should leverage MEMS strengths, namely small size, potential CMOS integrability, and low costs derived from integrated circuit manufacturing technologies. Otherwise new MEMS resonators would have difficulty competing against the mature quartz technologies. Therefore SiTime has looked beyond metal or ceramic vacuum chip packages that are presently used with quartz for its MEMS frequency references.

When durable covers are needed in MEMS the most common solutions include wafer bonding of bulk micromachined silicon or glass cover wafers. Wafer bonding techniques are in mass production, for instance in the Bosch airbag and yaw rate sensors [7]. Technologies include for example, frit glass, solder, and compression bonding [8-10]. While these covers provide mechanical protection, only exceptional cases have been shown to provide clean enough environments for timing references [5]. Bonded covers incur significant system costs, usually greatly exceeding the cost of the resonator. They require fabrication, require wafer-to-wafer alignment of the cover to the active wafer, double the thickness of the MEMS components, and use significant die area for sealing rings and bondpad access. The seal rings and bondpad routing can consume as much as eighty to ninety percent of the die area, and thus can account for over eighty to ninety percent of the cost of the packaged MEMS resonator.

Film encapsulation techniques are an alternative to bonded covers. These are usually based on thin layers, for example LPCVD nitride or polysilicon [11-13], or based on plated metal [14]. These techniques do not burden the encapsulated part with large seal rings and restrictive bondpad layouts, but they are not generally intended to withstand the full pressure of plastic molding or are not intrinsically clean enough for frequency references. The progenitor of the SiTime encapsulation, built with epitaxial polysilicon but sealed with oxide [15-17], was designed for packaging durability in accelerometer applications but was not optimized to be intrinsically clean. Our tests of resonators in these oxide-sealed packages showed tens of ppm of frequency histeresis over temperature. Epitaxially encapsulated and sealed resonators have been used in resonant pressure sensors [18-21] with great success. In this case the resonators were electrochemically defined and packaged in a purely single-crystal process.

SiTime's encapsulation does not require sealing rings or restrictive bondpad routing, and the electrical connections may be brought to the surface of the die wherever appropriate, enabling efficient use of die area. This can reduce the die area to a tenth of that needed for bonded covers. The encapsulation is mechanically strong, and is able to survive hundreds of atmosphere of pressure [15-17] in the transfer plastic molding process used for chip packaging. The encapsulation also provides a vacuum environment that is exceptionally clean and stable and is suitable for reference oscillators [22]. The stability data for encapsulated MEMS resonators presented here is similar to quartz resonators. Finally, the production process is highly economical.

Fabrication Process:

The Fabrication of a SiTime resonator is shown in Figure 1. (1) A 10-20um Silicon On Insulator (SOI) substrate is patterned with a DRIE etch into a resonant structure. (2) An oxide is deposited and patterned to cover selected parts of the resonator while providing electrical contracts to drive and sense electrodes. (3) A 1.5um epi silicon layer is deposited and patterned with vents to access to the oxide. (4) The oxide over and under the structures to be mechanically freed is removed through the vents. (5) The resonator chamber is sealed in an epi environment with SiTime's EpiSeal process, giving an extremely clean enclosure. (6) The wafer surface is Chemical Mechanical Polish (CMP) planarized and patterned with contact isolation trenches, yielding a 10-20um thick mechanically durable epipoly encapsulation. (7) Insulation oxide, metal interconnections, and a scratch mask are deposited and patterned or CMOS is fabricated.

The first and second silicon depositions grow polycrystalline silicon on the oxide and single crystal silicon where the oxide has been removed. After CMP, the field areas are thus smooth single crystal silicon and can support fully integrated CMOS electronics. The vacuum in the enclosed cavity has a pressure of approximately 10mT [22] and is thought to be virtually free from water and other high vapor-pressure contaminants.

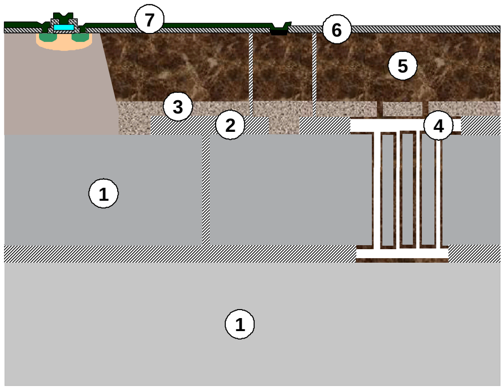

Figure 1. Fabrication cross section.

Figure 2 shows a Scanning Electron Micrograph (SEM) of a completed resonator structure prior to contact and metallization that has been sectioned to show the wafer surface and the cross section through the encapsulation and resonator. Part of a resonator element is protruding from the section edge.

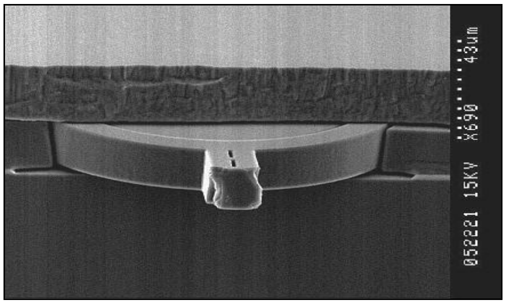

Figure 2. Scanning Electron Micrograph (SEM) of a cleaved wafer showing the resonator and encapsulation.

The encapsulated resonators are diced and packaged in standard transfer molded chip packages. Figure 3 shows a design schematic for a 2.5 x 2.0 x 0.85mm plastic package with the MEMS resonator mounted on a CMOS driver IC. This packaging method is highly economical and leverages QFN/MLF technology. This is exceptionally small for an oscillator and further size reductions are possible.

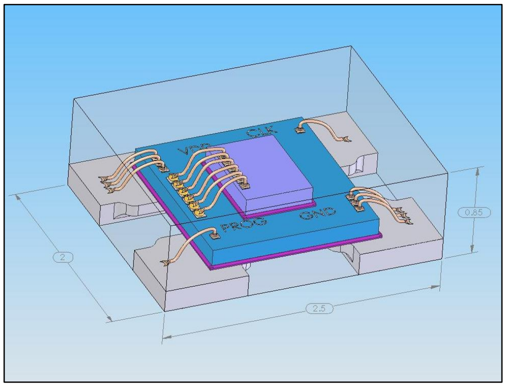

Figure 3. Packaging schematic of a MEMS resonator mounted on top of a CMOS driver IC enclosed in plastic.

Measurement Results:

This paper reports resonator measurement results for (1) initial frequency stability, (2) long term frequency stability, (3) long term package hermeticity, (4) temperature cycle durability, and (5) temperature ramp stability.

Figure 4 shows the initial frequency stability of a temperature compensated encapsulated MEMS resonator. The data collection commenced within minutes of the resonator startup at 50C and without any initial burn-in. This data shows that the resonator drifted less than 50ppb over the first two weeks of its operation.

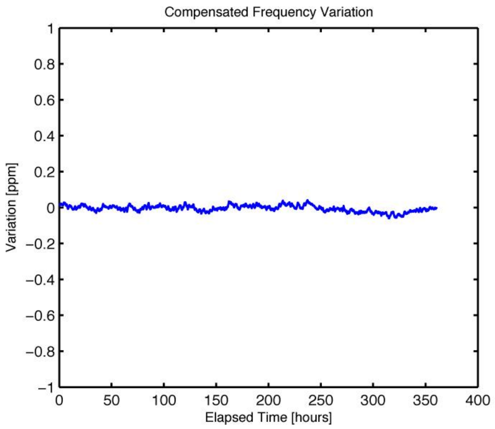

Figure 4. Initial frequency stability over two weeks at 50C.

Figure 5 shows the long term frequency stability of four resonators at 25C over 8000 hours. The total measured drift of approximately 2ppm was within by the 3ppm specified stability of the measurement equipment.

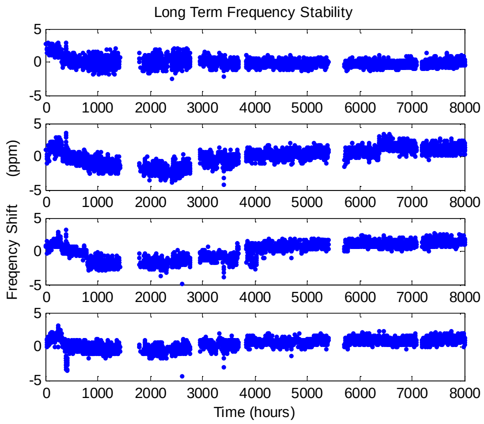

Figure 5. Long term frequency stability of four resonators at 25C.

Figure 6 shows the frequency stability of two resonators as they are temperature cycled. The data was taken at 30C in the upward and downward legs of cycles from -50C to +80C. This data represents approximately 600 cycles, and within the specified measurement limits of approximately 3ppm shows no frequency shift. This and the data from Figure 5 are described in further detail in [23].

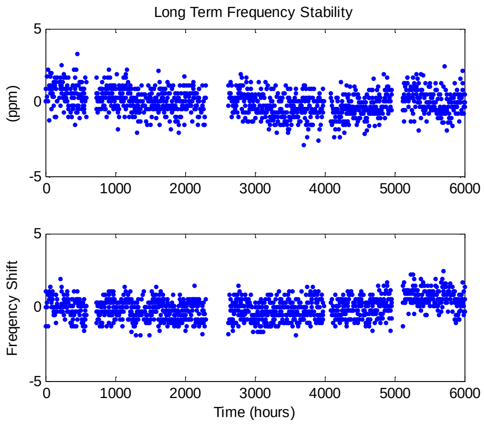

Figure 6. Frequency stability of two resonators measured at 30C while under temperature cycles from -50C to +80C.

Figure 7 shows the compensated frequency stability of a resonator as it is swept twice from -40C to +85C and back to -40C. The total frequency error over this temperature range is less than 100ppb under a measurement noise floor of 200ppb, and a specified measurement error of 30ppb. The histeresis is less than about 50ppb. This data is collected from a resonator in a plastic molded package.

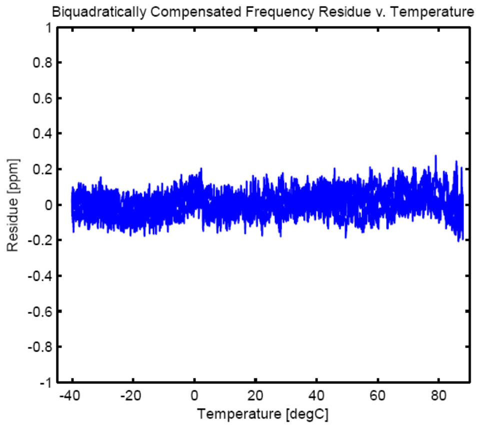

Figure 7. Frequency stability of a resonator as it is ramped twice through -40C to +80C and back.

These results are comparable to the performance of quartz. Figures 4-7 show stability data better than any previously published for MEMS resonators. They are limited by the measurement equipment and thus do not yet demonstrate the full potential of the resonator and encapsulation technology. These measurements are performed with high quality laboratory equipment; they represent the potential of the technology and not the specifications of production oscillators.

Conclusions:

MEMS resonators have been investigated for over forty years but are only now nearing commercial introduction. One of the most significant hurdles has been developing an economical and sufficiently clean hermetic packaging system. This paper has shown a suitable manufacturing process and shown measurement data that is comparable to that of the legacy quartz technology. The measurements are the most stable ever shown for MEMS resonators. The resulting silicon MEMS oscillators are expected to be suitable for a range of commercial applications.

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