

CMEMS[®] Technology: Leveraging High-Volume CMOS Manufacturing for MEMS-Based Frequency Control

Over the last five years, microelectromechanical systems (MEMS) solutions have steadily eroded the 100-year-old monopoly held by quartz crystal solutions for frequency control and timing products. MEMS technologies, originally designed around the promise of smaller form factors, have enabled significant additional advantages related to lead time, supply stability, product reliability, device size, and price and performance tradeoffs—advantages that promise to secure a meaningful share of the quartz-based frequency control market for MEMS oscillators.

Relying on legacy technology, quartz-based frequency-control designs have had to cope with a number of inherent limitations. These include the need for highly specialized and complex manufacturing flows, exotic ceramic-based packaging (see Figure 1) requiring hermetic sealing of cavities along with off-chip matching capacitors, and a given sensitivity to environmental factors, such as thermal stress and shock and vibration in particular, potentially leading to field failures.

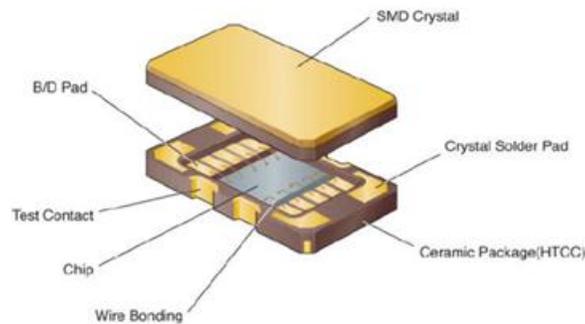


Figure 1. Diagram of a Typical Quartz-Based Oscillator Assembly with Ceramic Packaging

These limitations are now largely alleviated by MEMS technologies, which enable small device sizes and leverage standard semiconductor manufacturing techniques. Until recently, however, their integration into frequency-control and clock products has still been done in the same fashion as quartz-based products and other MEMS products—through the assembly of the MEMS resonator chip with a separate IC into a multichip module (see Figure 2). While such an approach can use more standard packaging techniques than quartz-based oscillators, it still relies on boutique MEMS foundries outside of mainstream, high-volume CMOS foundries. As such, two-chip MEMS solutions represent only an intermediate step toward CMOS+MEMS integration, making them more sensitive to MEMS resonator characteristics and thus sub-optimal from a system performance and system cost standpoint.

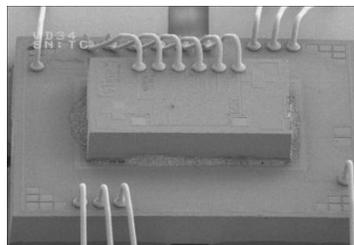


Figure 2. Micrograph of a Multi-Chip MEMS-Based Oscillator

With the introduction of CMEMS[®] technology, Silicon Labs has made a quantum leap in the integration of frequency-control products by processing the resonator directly on top of an advanced mixed-signal IC to enable a fully monolithic solution that allows true, MEMS+CMOS co-design. CMEMS technology brings significant benefits to the frequency control industry, including smaller size, better performance, lower cost and greater scalability.

CMEMS: Monolithic Integration of CMOS and MEMS

The term CMEMS comes from the contraction of two acronyms: CMOS+MEMS. CMEMS technology enables the modular post-processing of MEMS devices directly on top of CMOS circuitry, which is unique compared to any other approach to MEMS integration. CMEMS is the first technology [1] of its kind to allow direct post-processing of high-quality MEMS layers on top of advanced RF/mixed-signal CMOS technology (0.18 μm and below), thereby leveraging the scalability of state-of-the-art CMOS manufacturing as a modular back-end-of-line option attached to the same manufacturing line used to fabricate advanced CMOS wafers (see Figure 3).

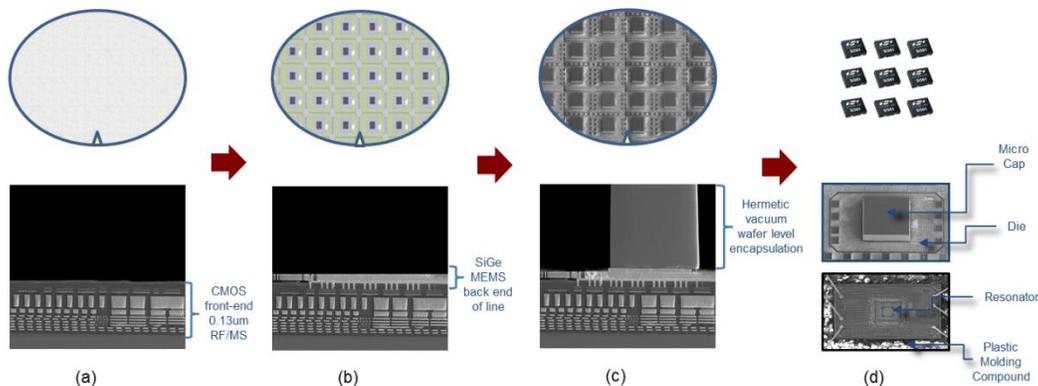


Figure 3: Basic Sequence of the CMEMS Manufacturing Flow

(a) Starting material in the form of a passivated and planar CMOS wafer on top of which (b) polycrystalline SiGe is surface-micromachined into integrated MEMS devices, which are (c) encapsulated in a vacuum using wafer-level bonding. The fully finished wafer continues to probing, (d) die singulation and standard small-size packaging assembly, just like a standard CMOS product.

CMEMS technology relies on the use of polycrystalline silicon-germanium (poly-SiGe) as the MEMS structural material [2]. This material is considered CMOS-friendly in the sense that its thermal budget is compatible with the CMOS backend. Poly-SiGe can be deposited around 400 °C. In other words, it will not melt the existing CMOS and backend materials when directly deposited on top of mainstream CMOS technology. It also allows the use of pure germanium (Ge), which dissolves in hydrogen peroxide (H_2O_2), as a sacrificial material. H_2O_2 is commonly used in CMOS backend processing and is friendlier than hydrofluoric acid or other etchants commonly used for some MEMS processes. Those two main features make the process integration of MEMS surface micromachining compatible with advanced CMOS technology.

Process compatibility is only one part of the problem. Material quality is also absolutely critical. Generally, material quality and deposition temperature tend to go in opposite directions for MEMS applications. While metals like aluminum and copper are compatible with CMOS processing, this aspect disqualifies them from being used as structural materials. On the other hand, SiGe stands out in this key aspect. Above 400 °C and under certain conditions, SiGe is a polycrystalline material as deposited. It has properties similar to polysilicon, a widely used material in MEMS. These properties include high fracture strength and low thermoelastic losses (i.e., high Q), and SiGe does not exhibit creep or hysteresis when cycled through stress. These properties are absolutely critical for fabricating high-performance MEMS devices, in particular for the long-term stability required in frequency control.

In addition to the material advantages of SiGe, CMEMS technology offers several other key features that make it robust and optimal for system integration:

- A combination of plug and damascene contact modules with specific barrier layers ensures low ohmic contact resistance between the top metal and the SiGe MEMS layers; this technique minimizes contact size and access parasitics.
- A spacer module allows high aspect ratio electrode gaps to be defined for in-plane electrostatic transducers with relatively high efficiency.
- Flexibility around the structural thickness (2-4 μm) allows surface micromachining of thin and compact structures, enabling both in- and out-of-plane modes of operation.
- A silicon dioxide slit module embedded in the structure enables mechanical compensation of thermal drift along with electrical isolation.
- Eutectic seal wafer-to-wafer bonding allows ultra-clean vacuum hermetic encapsulation of the MEMS device.

Building the MEMS structures on top of existing CMOS wafers involves several challenges. First, thermal compatibility does not mean that the materials and devices behave identically when taken through the thermal cycles of the manufacturing flow. Stress and coefficient of thermal expansion (CTE) mismatch are quite significant. SiGe is compressive with a CTE of single digit ppm/ $^{\circ}\text{C}$ as opposed to the metal stack underneath, which is usually tensile, having a CTE in the 10-20 ppm/ $^{\circ}\text{C}$ range. As such, making this manufacturing technology a reality requires expert knowledge of all materials involved in the flow and technical expertise in designing them to coexist.

Substrate outgassing is also a concern. MEMS resonators require a clean, stable vacuum environment to operate. However, thermal cycles tend to liberate loose molecules that can diffuse out of the substrate into the cavity and change the resonator's properties. Accordingly, one must attend carefully to the physico-chemistry of the backend materials during deposition to achieve a vacuum encapsulation whose absolute level and stability are adequate for both the short-term stability (quality factor) and long-term stability (aging) of the device.

Finally, yield loss stacking can also occur when the complexity of any given manufacturing flow is increased. Fortunately, CMOS fabrication lines are among the most highly-controlled manufacturing environments in the world. Thanks to the robustness of the CMEMS process integration and device design, the overall effect of yield compounding is minimal, and the final yield numbers remain similar to those of CMOS—in the upper 90 percent range.

The current generation of CMEMS manufacturing allows integration of 0.2 μm space: 0.5 μm line feature size MEMS devices on top of 0.13 μm RF/MS CMOS with eight metal layers. A complete and mature product/process design kit (PDK) allows relatively predictable design and manufacture of new devices and systems in this technology. CMEMS is now running in production at a top-tier CMOS foundry with a large capacity (>1,000 wpm). This capacity consolidates CMOS, MEMS, vacuum encapsulation, wafer acceptance and chip probe on the same line and offers tremendous benefits in terms of scalability and quality assurance. CMEMS technology is modular; the same manufacturing capability has been demonstrated in both 0.18 and 0.13 μm . CMEMS can also be considered a platform technology in that different types of devices (resonators, inertial sensors, etc.) can be manufactured reliably within the same flow. These two properties make the so-called law of “one process, one MEMS” irrelevant and are critical for the scalability of CMEMS technology and the paradigm shift that CMEMS represents for the frequency-control industry.

Why is monolithic integration now important to frequency control, and how does it suggest an irreversible trend for new functionalities and technologies in the timing industry?

First, the market needs monolithic integration. With consumer embedded systems becoming increasingly pervasive, the market has consolidated more functions into system-on-chip (SoC) devices. Take, for example, a smart phone motherboard. A tear-down reveals that anything that can be manufactured in CMOS has been consolidated into single-chip devices already. What remains unconsolidated are non-

CMOS components, such as quartz oscillators or more exotic technologies used for power amplifiers (PAs) or duplexers. CMOS integration needs to be even tighter and more inclusive, pushing the limits of interconnect density for existing solutions and moving toward 2D and 3D integration. In this context, CMEMS is breaking new ground by embedding MEMS devices directly on top of CMOS. This breakthrough is similar to how the CMOS industry began integrating metal options for integrated passives a few years ago.

Form factor is also a strong driver of CMEMS technology. Whether one looks at oscillators, inertial devices or quartz devices, they all tend to come in relatively bulky packages with stacks of passive and active devices. This prevents their integration into anything thinner than 1 mm without significant added cost, so they end up consuming relatively large amounts of PCB space. Likewise, because these components are off chip, they remain separate on the PCB, adding an extra layer of complexity to system design and jeopardizing performance by exposing critical signals to surrounding electromagnetic interference (EMI). From a usage point of view, a self-contained monolithic solution enabled by CMEMS technology is much easier and safer to integrate within an overall system solution.

As for **performance**, monolithic integration inherently offers more flexibility in MEMS system design optimization. For example, in the case of oscillators (see Figure 4), the critical gain needed in the feedback amplifier is largely influenced by the parasitic capacitance present between the active part and the resonator. This is represented by the parameter, p . The higher the p parameter, the lower the gain (g_{crit}) needed to generate a stable oscillation, and lower gain results in lower power consumption (I_0) for the same output level (V_0). This power consumption is also largely determined by losses in the resonating element. For micro-scale devices, insertion loss (represented by the motional resistance, R_x) is usually higher and SNR is usually lower, which could imply a detrimental effect on power; however, this drawback is far outweighed by the benefit of extremely low parasitic, and, as a result, the system becomes easier to optimize for low power.

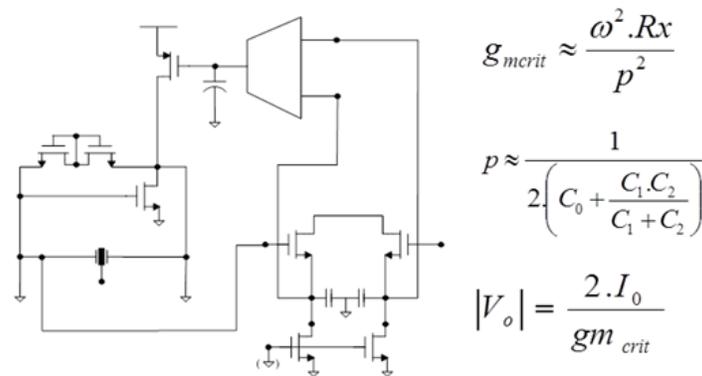


Figure 4. Basic Circuit Schematic of a Resonator-Based Pierce Oscillator with Equations of Critical Gain (g_{crit}), Parasitic Load (p) and Output Voltage Amplitude (V_o) [5]

Sensors offer another example of performance optimized through MEMS integration. In the case of accelerometer readout circuits, variable capacitances are modulated differentially, and any displacement of the MEMS proof mass due to acceleration induces a signal on the common node. Parasitic capacitances between the sensor and the readout circuit dominate the available signal and reduce the effective sensitivity in terms of volts per G. In this context, with the smallest possible parasitics and tightly controlled on-chip matching, monolithic CMOS+MEMS co-designs allow optimum power/sensitivity trade-offs while using smaller devices. Smaller devices mean that more components can be combined into arrays, further improving sensitivity and resolution. If the devices are small, they also have lower masses, effectively increasing immunity to shock and vibration. Additionally, by enabling fewer materials, fewer interfaces and a tighter scale, monolithic integration is inherently more reliable.

Reduced cost may be the biggest motivation behind CMOS+MEMS monolithic integration. CMEMS technology allows the foundry to leverage a fabless model in which the manufacturing line is shared across hundreds of products powered by a robust MEMS product design kit. Ultimately, cost savings are derived from process optimization, integration trends and reduced time-to-market thanks to IP reuse across multiple designs. Incorporating MEMS into the CMOS manufacturing line enables chip manufacturers to leverage a huge investment base that is distributed across many different CMOS-based products. This also provides access to fully amortized, high-performance equipment, such as advanced lithography and deposition and etch tools, and it supports the semiconductor industry's trend toward higher density and larger (8 to 12 inch) wafers.

Co-integration also brings the manufacturing flow into a single line by putting all parts of the subsystem on the same substrate. This enables wafer-level chip-scale packaging—a substantial cost saver for subsystems historically made with incompatible technologies, such as oscillators and sensors. More importantly, co-integration reduces test costs tremendously. CMEMS provides the ability to test the MEMS system as a complete, operational system, instead of as piecemeal components from various foundries, and to calibrate and compensate the system at the wafer level. The two costly manufacturing steps of packaging and testing are historically among the biggest challenges for MEMS oscillators and sensors because they rely on two incompatible, separate devices, i.e., a mechanical MEMS device and a CMOS circuit.

Frequency Control Product Challenges and the Benefits of CMEMS

While CMEMS technology can be applied to many types of MEMS products, it was first aimed at revolutionizing the 100-year-old monopoly of quartz technology for frequency control products. Starting from crudely cut pieces of quartz, manufacturers have been continuously refining their processes to make quartz-based oscillators more stable, more accurate and available in ever smaller packages. As a result, quartz-based oscillators have improved over the years and show aging and short-term stability on the order of parts per billion. They are inherently stable over temperature, making them the standard for frequency control.

Quartz devices, however, come with a number of limitations. Their boutique-style, highly-specialized manufacturing flow (with several weeks to months of lead time) not only makes the supply chain more difficult to manage but also limits the frequency range achievable by a reference oscillator. With data rates increasing in computing, communications and networking equipment, this limitation puts more pressure on clock synthesizers to deliver clean clock signals at higher frequencies. MEMS-based solutions, and in particular CMEMS technology applied to factory-programmable oscillators, enable shorter lead time (less than two weeks) and infinite programmability of output frequencies from the low kHz to high GHz.

Quartz devices are also plagued by reliability concerns and field failures. Their assembly configuration and meso-scale size make them sensitive to vibration and shocks. MEMS devices, on the other hand, are small and compact and can sustain much higher levels of stress. For these reasons, MEMS-based oscillators are capable of going through reliability qualification flows very similar to those used for CMOS-only products. In general, CMOS qualification tests are far more stringent than those used to qualify quartz-based products.

In addition, the fact that quartz resonators are off-chip makes them more sensitive to board design and EMI. They also suffer from activity dips due to parasitic resonance, capacitive load shifting from device to device, and other sensitivities over temperature and environmental conditions. These issues make system integration of quartz resonators much less predictable than using a CMEMS integrated clock, which can lead to severe consequences for time-to-market.

The size reduction roadmap for quartz resonators is also nearing an end with the cost of further miniaturization in the quartz crystal industry increasing sharply and only a handful of crystal suppliers able to manufacture the smallest quartz devices. Therefore, it appears that the future of miniaturization and integration has reached a point of diminishing returns and limited further development.

In contrast, while MEMS resonator technology has addressed the fundamental limitations of quartz crystals, it initially entered the competitive frequency control market with numerous shortcomings. First, MEMS devices are smaller than quartz crystals, so they cannot pack as much energy into an oscillation cycle. This means that, for the same frequency as a quartz counterpart, transduction efficiency is much less, and, as a result, the signal-to-noise ratio is much worse. Second, classic MEMS materials, such as single-crystal silicon, polysilicon or even poly-SiGe, drift significantly with temperature. They become softer as temperatures rise, and this can translate into a frequency temperature coefficient as large as -30 ppm/°C. This large coefficient affects overall stability.

Because MEMS devices are so small, they cannot be physically trimmed as easily as their quartz counterparts, which impacts initial accuracy. Initial MEMS resonator research was mainly driven by universities, and, as a result, aging and reliability data were unproven compared to the decades of research and data associated with quartz. MEMS-based sensors have been around for a while, but offset specifications for other existing MEMS products have always been in the realm of percent, not ppm or ppb. Figure 5 shows a typical center-frequency distribution of 48 MHz resonators right out of the fab. The 6-sigma range corresponds to about ± 0.2 percent, which is far from the 10-20 ppm usually required for frequency control. Tolerances around physical dimensions, material properties and environmental factors like package stress contribute to the overall distribution.

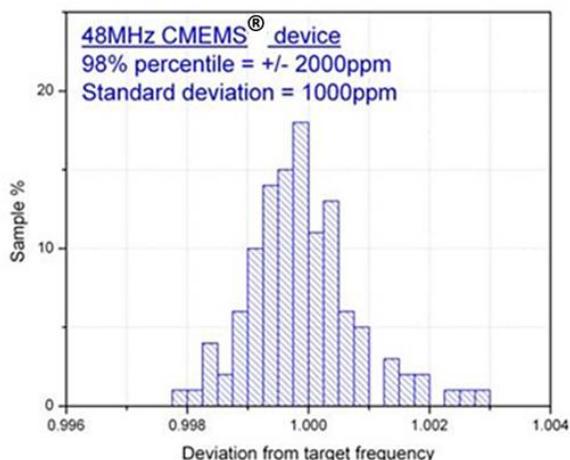


Figure 5. Cross-Wafer + Cross-Lot Distribution of a Typical Resonator Frequency with CMEMS

To address trimming and initial room temperature accuracy, a “MEMS-stabilized VCO” can be built, resulting in a device with a separate oscillator locked to the MEMS reference through a complementary circuit (see Figure 6). The control loop forces a predetermined ratio between the MEMS oscillator and the VCO so that the output frequency of the VCO is corrected if there is any inaccuracy present in the MEMS reference. Such an approach also allows the programmability of the output frequency, something that quartz oscillators lack since they are pure frequency references (unless additional circuitry is added). By adding a temperature sensor to the system, the trim values affecting the MEMS-to-VCO frequency ratio can be varied over temperature to compensate for the MEMS oscillator temperature drift. Various implementations of the same concept can be used with more or less complexity, but, in the end, the MEMS reference is untouched, and the output clock signal derived from it is made accurate and stable by compensation.

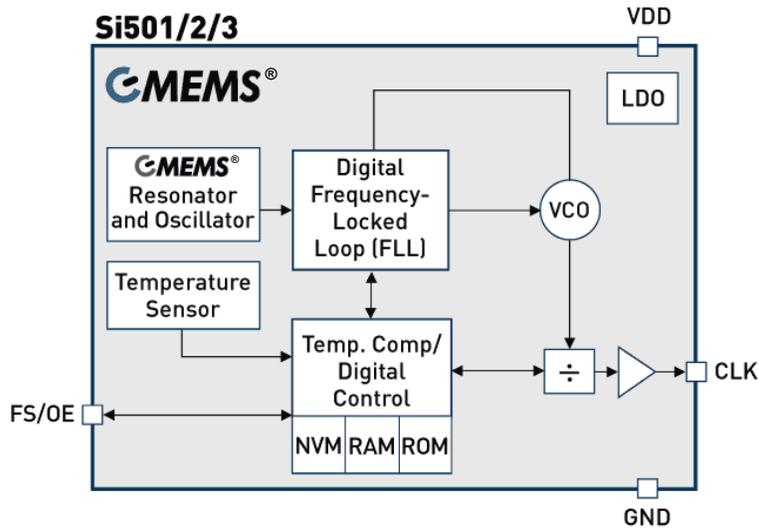


Figure 6. Example of CMEMS Programmable Oscillator

Because of the inherently large temperature drift of MEMS resonators, the quartz industry quickly identified a significant weakness in early MEMS solutions: the open loop transfer function from temperature sensor to frequency output is extremely steep [3]. This means that, due to fast transient temperature variations or simply quantization noise in the temperature sensor, any subtle change in the temperature sensor response can be transferred directly to and amplified into the output frequency, leading to significant short-term stability concerns.

While optimization of the temperature sensor and its noise characteristic dramatically improves short-term stability, CMEMS technology addresses this issue by tackling the problem at its root, namely the mechanical stability of the MEMS resonator, and by compensating the device mechanically to achieve stability over temperatures similar to quartz resonators [4]. With TC_E of SiGe (Young's modulus temperature coefficient) on the same order as other MEMS structural materials like single-crystal silicon (~ -60 to -80 ppm/ $^{\circ}$ C), the solution is to alloy the structural material with another material that has the opposite behavior over temperature. Fortunately, silicon dioxide (SiO_2) is one of the materials available in a CMOS manufacturing environment, and, over a certain temperature range, it becomes harder as temperature increases. This increase in hardness counteracts SiGe, which gets softer. Specifically, the CMEMS approach involves putting compensating material where it matters most—at the maximum stress point and in the form of small slits of oxide. Figure 7 shows an example of a Lamé mode resonator, which has a contraction and expansion mode with respect to its electrode. In this topology, patterned slits of oxide are embedded in the structural layer to compensate for the specific stress tensor experienced in this mode.

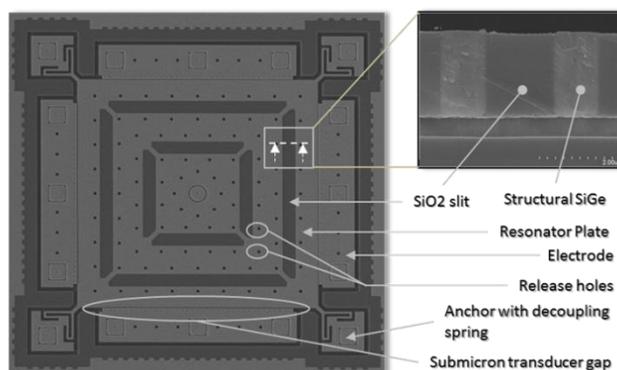


Figure 7. Top and Cross-Section Views of a Plate Resonator, Mechanically Compensated for Temperature Stability

As shown in Figure 8, the net result is a compensation of the first-order coefficient that is very close to zero (from about -30 ppm/°C for native SiGe) into a second-order characteristic where the frequency is stable across temperature—nearing the behavior of an AT-cut quartz crystal. Of course, manufacturing tolerances will influence the first-order coefficient distribution, which generally lies between ± 1 ppm/°C. However, a very significant advantage of this technique, when compared to quartz rock cutting or any other exotic approach, is that it can be applied to any mode shape—in-plane or out-of-plane, any frequency, and, more generally, any mechanical device.

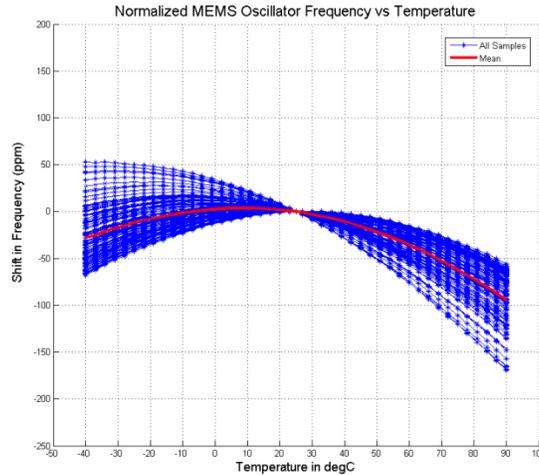


Figure 8. Native Frequency-Temperature Characteristic of the Plate Resonator Shown in Figure 7

With a simple change of the mask pattern defining the oxide slit, thermal drift can be eliminated. This feature, along with the careful design of the temperature sensor (designed to reach the best noise/power tradeoff), allows CMEMS-based oscillators to exhibit short-term stability in the range of a few ppb, which is orders of magnitude lower than first-generation MEMS oscillators. Temperature calibration then completes the process by further compensating the device’s temperature stability at the system level (see Figure 9).

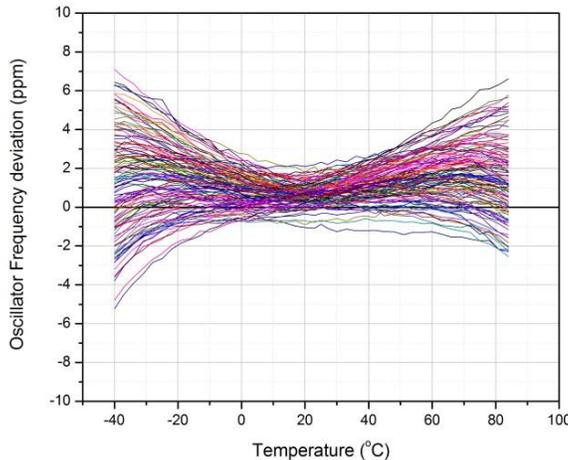


Figure 9. Temperature Characteristic of Fully Calibrated and Compensated CMEMS Oscillators (Sample Size ~ 100). Solder Shift is Included on This Plot

By leveraging this capability along with monolithic integration, CMEMS technology offers significant performance gains in terms of thermal slew as compared to both other traditional MEMS solutions, and

more importantly, over quartz-based solutions. Indeed, when a linear control system relies on a temperature sensor, system integration and thermal transport become very relevant. Let's use the example of a two-chip stacked die assembly, with the CMOS circuit at the bottom and the MEMS die sitting on top. A simple model of thermal transfer would need to account for the CMOS chip, wire bonds and die attach epoxy, the MEMS chip and the whole package. This means thermal lead or lag can happen between the resonator and the temperature sensor, which is supposed to compensate for thermal excursion. With a slope of $-30 \text{ ppm}/^\circ\text{C}$, even a $0.1 \text{ }^\circ\text{C}$ delta becomes significant and creates a stability problem. This issue becomes magnified when the device is exposed to fast thermal transients.

This analysis, which is valid for MEMS-based oscillators, also holds true for quartz oscillators, which have even larger thermal lag within their ceramic packaging. However, quartz oscillators benefit from much smaller resonator temperature sensitivity, which makes this issue less visible than one would expect. With CMEMS-based solutions, combining the low sensitivity of mechanically-compensated devices with an ultra-short thermal path and small thermal time constant enabled by monolithic integration enables the design of oscillators that are far more resistant to thermal slew compared to any other existing solution. This benefit is best illustrated by running a freeze spray/heat gun experiment and comparing all three architectures (CMEMS, two-chip MEMS and quartz) when exposed to the same stimuli. As shown in Figure 10, the CMEMS oscillator remains stable with large thermal slew while the other solutions clearly show temperature-slew sensitivity, sometimes to the point of the part being out of specification. Package strain sensitivity might also contribute to this behavior, but in the end, the experiment clearly shows the superiority of CMEMS technology. Such a property is very important when considering a system designed around the high-power/low-duty cycle SoCs used in tightly-integrated embedded devices.

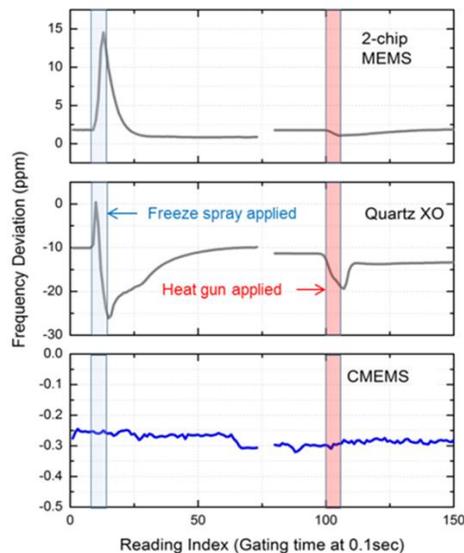


Figure 10. Comparison of Frequency Response of Three Oscillator Solutions to Fast Thermal Transients. The Y-Axis Scale in Each Plot Changes to Accommodate the Frequency Deviation Scale.

The importance of mechanical temperature compensation goes beyond the basic temperature stability of the output frequency. Indeed, the MEMS-based system is basically controlled by three references: the frequency reference (MEMS oscillator), the temperature reference (temperature sensor) and the voltage reference (bandgap/LDO). As such, the sensitivity of the scale factor or the sensitivity of the offset to external stimuli will be transferred directly into the frequency accuracy at the output. Environmental effects, such as strain applied to the package through solder reflow or as part of temperature cycles, can affect the offset of the temperature sensor. The corresponding temperature error will then turn into a frequency error compared to the factory-calibrated frequency offset. In the case of CMEMS, however, the low-temperature sensitivity of the resonator allows the system to be decoupled from this effect. This

property, along with careful design of the mechanical structure for package assembly and solder reflow strain rejection, results in much improved solder reflow sensitivity, as shown in Figure 11.

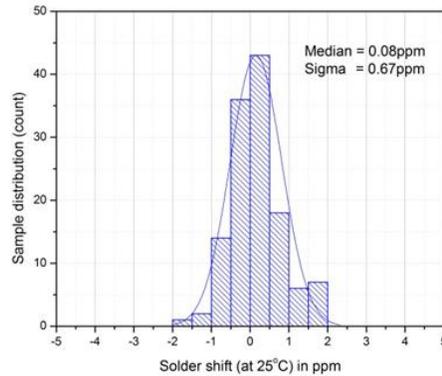


Figure 11. Typical Distribution of Room Temperature Solder Shift for Group of 128 CMEMS Parts

The stability of reference offsets over time also has important implications for aging. Because of the large temperature dependence of classic MEMS devices, the frequency-aging characteristics are no longer dictated by the resonator only, but by all of the elements used to control the output oscillator. For example, package strain influences the temperature sensor offset, and, if this strain varies over time due to package relaxation or if the voltage reference in the temperature sensor changes over time because of dopant recombination, their effects will manifest as frequency aging with the circuit compensation tracking their resulting offset variations. Such effects are magnified when the temperature coefficient is large, as illustrated in Figure 12, which shows the effect in a two-chip MEMS device. Aging at 70 °C shows stellar behavior for the first 1,000 hours, demonstrating what is believed to be the mechanical resonator aging characteristic—very typical of a mechanical softening in the first tens of hours of operation. This continues until a slower process, believed to be related to temperature sensor offset variations, takes over and not only changes the direction of aging, but also increases its magnitude. By running the same experiment at a higher temperature (125 °C), the temperature sensor offset shift is accelerated and the true aging characteristic of the part can be measured and considered for lifetime extrapolation.

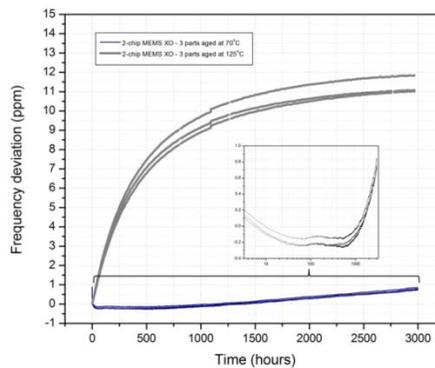


Figure 12. Aging Characteristic of a Two-Chip MEMS-Based Oscillator with Close-Up View of Low-Temperature Aging

The same experiment was conducted extensively on a large population of CMEMS oscillators, and they performed extremely well, as shown in Figure 13, which presents typical CMEMS results using soldered down parts for the initial 3,000 hours.

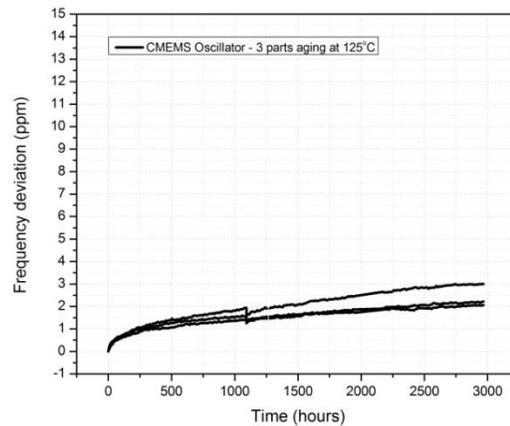


Figure 13. CMEMS Oscillator Aging Characteristics at 125 °C Showing Best-in-Class Aging Stability

These results show the importance of understanding the mechanisms behind aging to define empirical models around the failures in time (FIT) rate. Clearly, guaranteeing aging at 25 °C has never been considered a good indication of lifetime for this class of product, nor is a single run of 1,000 hours. Aging data across multiple lots, elevated temperatures and longer durations is required to begin to understand device lifetime behavior. These results also demonstrate that today's conventional wisdom, which maintains that high temperature (>1000 °C) MEMS processing and resonator sealing are "must-haves" for high stability and low aging, is not only erroneous but is now superseded by CMEMS technology. CMEMS technology, with its clean, chemical-free and relatively low temperature processing, enables even better performance. However, clean vacuum encapsulation technology is a condition that is necessary but not sufficient for best-in-class aging characteristics of reference oscillators. Indeed, in contrast to alternative solutions (such as two-chip approaches or piezoelectric materials, which are prone to thermally induced creep), CMEMS enables superior long-term performance through the use of its polycrystalline material as well as optimized system co-design and manufacturing to decouple system performance from reference offset variations.

Based on these demonstrated results, CMEMS technology's outstanding control and robustness around temperature stability, solder shift and aging allows CMEMS solutions to specify frequency stability inclusive of all effects over the lifetime of the device. This key characteristic, also known as total accuracy, is not available from quartz or other MEMS-based oscillators.

A Paradigm Shift in the Frequency Control Industry and Beyond

CMEMS technology is poised to create a positive disruption in the frequency-control industry by combining all the advantages of MEMS-based solutions while retaining and even improving many of the best characteristics of quartz solutions. These beneficial characteristics include:

- Streamlined wafer level manufacturing in an advanced CMOS line
- Streamlined standard packaging
- Programmability and short lead times
- Reliability meeting IC industry standards
- Low aging characteristics
- Low strain sensitivity (initial accuracy post solder reflow)
- Good temperature stability (mechanical compensation)
- Immunity to fast thermal transients
- Extended frequency range for low-noise references
- Immunity to EMI

Because the system construction is completed at the wafer level, wafer-level chip-scale packaging opens the possibility of extending the packaging and form-factor roadmaps beyond the standard oscillator footprints, thereby potentially achieving unprecedented device sizes, both in terms of area ($< 1 \text{ mm}^2$) and thickness ($< 0.5 \text{ mm}$). Dual-chip and quartz-based solutions do not have this potential, at least not in a practical, scalable and cost-competitive fashion. Furthermore, by continuously improving CMEMS device designs, modeling, and packaging techniques, finished products can be delivered in wafer form. This will enable new business models for frequency-control products: the sale of wafer-calibrated frequency references for system-in-package integration. In other words, CMEMS technology enables guaranteed specification die sales of reference oscillators. In the long run, this new model could mean the disappearance of discrete frequency-control devices from system boards since these timing devices become integrated into each single SoC as a companion chip or, in some cases, as direct post-processing of the timing functionality.

Beyond timing applications, CMEMS technology also presents the characteristics of a platform technology. Its modular construction relies on high-quality structural materials, and its process integration enables designers to build sensors and actuators in addition to timing devices, thereby allowing the MEMS industry to integrate more on-chip functionalities with improved performance alongside critical computing and communication capabilities. With advanced CMEMS and CMOS technology available, designers can leverage digital circuitry to optimize a wide range of mixed-signal designs and use these designs as a base technology to deliver self-contained nodes capable of sensing, analyzing and communicating with their environment.

Initially leveraging this advanced technology with a strong presence in the timing market, Silicon Labs will introduce a series of CMEMS-based frequency control products beginning with the Si50x CMEMS oscillator family. Additional CMEMS product lines will follow to address various segments of the electronics market—from low-frequency to high-frequency, from embedded consumer products to high-performance communications and networking applications—and, eventually, to serve the entire market with fully-integrated frequency-control products that are smaller, more economical, more reliable, and easier to manufacture and incorporate into system designs than incumbent quartz solutions. Find out more about CMEMS technology and the Si50x CMEMS oscillator family at www.silabs.com/cmems.

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