CMEMS® Oscillator Architecture

Introduction

CMEMS® technology is an innovative CMOS+MEMS manufacturing process developed by Silicon Labs, a leading supplier of timing solutions. The term CMEMS is a contraction of the acronyms CMOS and MEMS (microelectromechanical systems). CMEMS technology offers many benefits over traditional oscillator approaches, ranging from scalability, customer-specific programmability and instantaneous samples at the customer site, to long-term reliability and performance. This white paper describes CMEMS process technology, existing hybrid oscillator architectures and the Si501/2/3/4 (Si50x) MEMS oscillator architecture.

A Brief Overview of Crystal Oscillators

The $3 billion (USD) per year frequency control market has been dominated by quartz crystals and quartz-based oscillators for many decades. Almost every type of electronic equipment relies in some manner on a tiny piece of machined quartz rock to generate at least one of many potential operating frequencies. Figure 1 shows a classic quartz-based oscillator and its components.

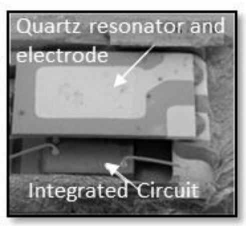

Figure 1. Crystal Oscillator Components

Over the last few decades, quartz manufacturing has reached new levels of sophistication, delivering smaller, thinner and higher-frequency solutions. While these manufacturing advances are important and certainly measurable, the overall process in terms of the required processing steps has not changed very much.

The manufacturing process starts with a blank piece of quartz that must be cut, lapped, polished, plated and further manipulated to achieve its required output frequency. Beyond this initial set of coarse steps, the process continues to refine the quartz crystal to achieve the required specifications. At each step, there are opportunities for the various components to suffer yield fallout. The complete system is not tested for yield and performance until final packaging, when the quartz crystal is hermetically sealed in a ceramic package with the silicon amplifier. Figure 2 provides a high-level overview of the enormously complex quartz crystal manufacturing process, which supports hundreds – if not thousands – of unique crystal shapes and cuts for specific frequencies for target systems.

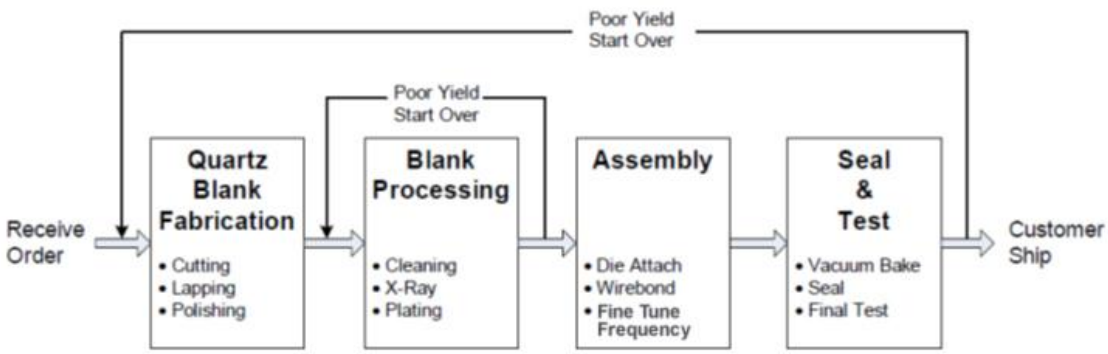

Figure 2. Crystal Oscillator Production Steps

In 2004, Silicon Labs introduced its family of crystal oscillators (XOs), which leverages innovative and proprietary mixed-signal expertise to generate almost any frequency from a single, crystal-based reference frequency. This revolutionary technology, called DSPLL®, achieves performance similar to that of the highest-performing crystal-based oscillators, but it obviates the requirement for unique crystals for different frequencies, thereby minimizing a very large part of the quartz manufacturing process, including unique cuts and plating. This approach shortens the time from receiving an order to delivering samples from many weeks to less than two. It also removes risk from the supply chain by using a single, high-volume crystal frequency. DSPLL-based XOs have been broadly adopted in the electronics industry and today represent a substantial business for Silicon Labs.

With CMEMS, Silicon Labs has again taken an important technological step forward in the frequency control market. CMEMS replaces the crystal resonating element in XOs with micromachined semiconductor resonators. CMEMS is a proven technology that enables high-performance MEMS to be constructed directly on standard, advanced-process-node CMOS wafers (<180 nm). Combined with Silicon Labs' mixed-signal expertise, CMEMS technology enables a single reference frequency to be used to generate almost any required frequency output that is as stable as mass-produced, high-volume quartz-based oscillators.

The Si50x CMEMS oscillator family is the first product offering to use CMEMS technology. It is optimized to support high-volume, low-cost applications where power and size are important, such as in the industrial, embedded and consumer electronics markets. Upcoming CMEMS products will be introduced to support other higher-performance markets as well as applications with unique requirements, such as ultra-low-power and multiple simultaneous frequencies.

Exploring MEMS and CMEMS in Frequency Control

Over the past decade, MEMS oscillators have finally begun to make inroads into the quartz-based frequency control market. Similar to quartz oscillator designs, these MEMS oscillators use a two-component, "hybrid" architecture that combines two physically-distinct components, the resonator and the amplifier, plus associated circuitry. Figure 3 shows a MEMS oscillator and an XO—two examples of this hybrid architecture.

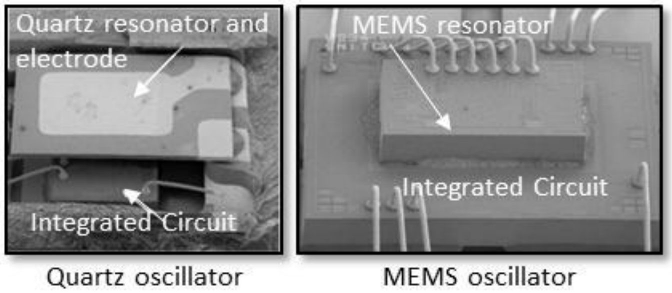

Figure 3. Comparison of Two-Component Oscillator Architectures

The similarities between these architectures are fairly obvious; each has two components, an oscillator base die and a resonator. Another less obvious similarity is that, just like crystals, the MEMS structures in the hybrid oscillator are manufactured in highly-specialized, boutique foundries. These boutique foundries focus on manufacturing with exotic materials and processes, including abrasive chemicals and extremely high-temperature. Unlike crystals, however, the economies of scale of these foundries are just beginning, leading to potential concerns for supply continuity.

Unlike standard XOs, MEMS-based devices use temperature compensation in the base die to offset the resonator's frequency deviation across temperature, also known as its temperature coefficient. Using two discrete components creates a meaningful thermal lag between the resonator and the CMOS temperature sensor and associated compensation circuitry in the base CMOS IC. As the CMOS ages, errors in the temperature sensor measurements combined with this thermal lag can lead to large errors in frequency compensation and, ultimately, in the frequency output. CMEMS technology addresses this weakness with its integrated design and resonator material composition and distribution, which are discussed later in this paper.

Another area for improvement within a hybrid MEMS + IC architecture is the complex packaging shown in Figure 3 and its inherent impacts on manufacturing complexity, cost, CMOS design and overall performance. First and most obvious is the difference and resulting cost in packaging. Crystal oscillators and other MEMS solutions require the resonator to be physically joined to the amplifier using epoxy and/or bond wires. For example, in the MEMS image, six bond wires are required to join the resonator to its base. This approach adds cost, failure points and complexity. Hybrid MEMS cost is also impacted by having discrete wafer foundries for the resonator and for the CMOS base, each with its own margin requirements and wafer processing steps. In summary, two-component architectures and the need for more complex packaging can create cost, reliability, supply and manufacturing challenges.

CMEMS Process Overview

The CMEMS wafer-level process is shown at a high-level in Figure 4. Starting with standard, passivated and planarized CMOS (Figure 4 [a]), polycrystalline silicon-germanium (Poly-SiGe) and pure germanium (Ge) are surface micro-machined to create integrated MEMS devices on top of the CMOS circuitry and interconnects (Figure 4 [b]). Silicon Labs' proprietary CMEMS process technology enables the use of these materials to create microstructures without destroying the underlying CMOS IC.

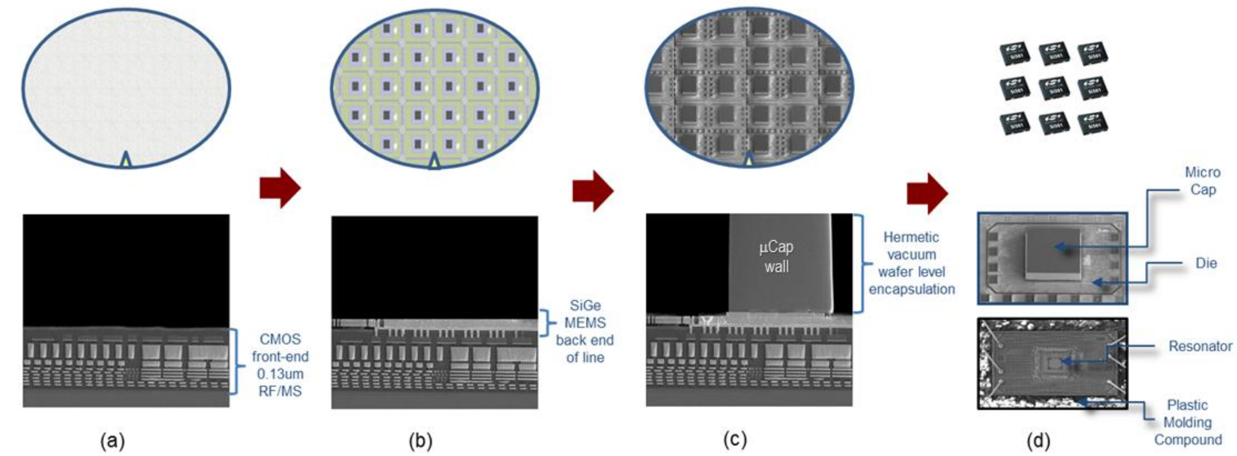

Figure 4. High-Level CMEMS Process Overview

Once the MEMS structure is grown on the CMOS wafer creating a full oscillator system, the CMEMS oscillators are encapsulated in a vacuum using eutectic wafer-level bonding (Figure 4 [c]). This technique creates an ultra-clean and very high-quality hermetic vacuum for the resonator. The wafers then contain full, working oscillator systems and can be probed in line for process and quality monitoring. This unique benefit of the CMEMS approach is a substantial step forward providing large-scale testing, cost and process improvements to MEMS-based oscillators.

Following wafer probe, the die is singulated and packaged in standard molded-compound, plastic packages available from a wide variety of Tier 1 suppliers (Figure 4 [d]). Again, this is an important CMEMS benefit since this packaging process is much simpler, more reliable and more cost-efficient than the multichip modules or hermetically-sealed ceramic packages required for hybrid offerings.

Si50x CMEMS Oscillator Architecture Overview

Silicon Labs' CMEMS-based oscillator architecture offers a more elegant approach than the hybrid architecture used to date. The CMEMS die is shown in Figure 5.

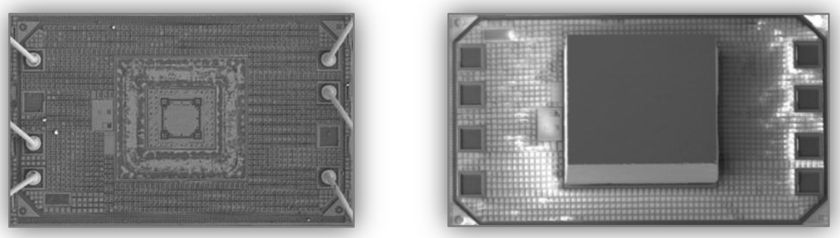

Figure 5. CMEMS Devices without Wafer Cap (Left) and with Wafer Cap (Right)

The Si50x MEMS oscillator family reuses much of the DSPLL technology employed in Silicon Labs' crystal-based oscillator family but has been redesigned to consume less power with a lower cost basis. It is intended to meet the needs of the high-volume industrial, embedded and consumer markets, while the existing Silicon Labs crystal-based oscillator family serves the communications and networking markets.

The Si50x resonator structure is a square plate with slits of silicon dioxide (SiO_2) as shown in Figure 6. There are several key innovations in the proprietary CMEMS resonator structure including its topology, anchor placement, spring structures and material composition. The plate is designed to avoid sensitivities to parasitic modes by modeling the effects of material variation and distribution, shape and structural dimensions.

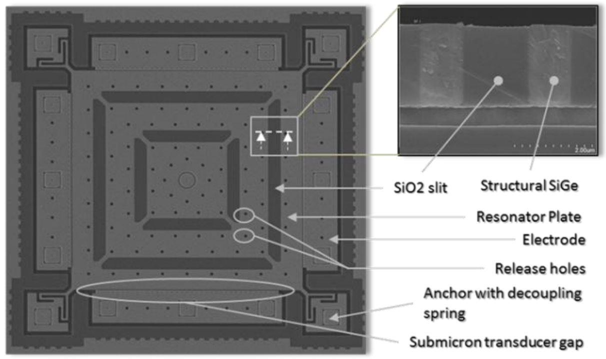

Figure 6. Si50x CMEMS Resonator Image

The resonator's SiO2 slits are a key component of Silicon Labs' CMEMS intellectual property (IP) in material composition and MEMS structure design. Other MEMS resonators are fabricated from single crystal silicon or similar uniform materials. As such, they are inherently tied to the temperature coefficient of that individual material, which is typically in the -30ppm/°C to -40 ppm/°C range. This temperature coefficient acts as a large gain factor for translating noise, strain, and aging into the clock synthesis circuit and, thus, potentially into relatively large frequency errors and noise at the output. As previously discussed, when the MEMS resonator is physically separated from the CMOS base, the CMOS temperature sensor's measurement error is magnified, and its accuracy for determining the resonator's temperature is compromised, especially over time as the materials and circuits age. As a result, oscillator frequency accuracy may degrade over time if the compensation circuits are not well-designed with this temperature coefficient frequency drift in mind.

In contrast, the CMEMS resonator is fabricated from two materials, poly-SiGe and SiO2. As illustrated in Figure 7, SiO2 has an offsetting temperature coefficient to SiGe. The balance and design of these material temperature coefficients in the Si50x resonator produce a resonator temperature coefficient in single-digit ppms/°C, as shown in Figure 8. This composite material compensation provides passive compensation of the resonator, allowing the supporting CMOS system to more accurately compensate for remaining frequency drift over the full operating product life, using smaller, simpler, lower-power and more cost-effective circuits.

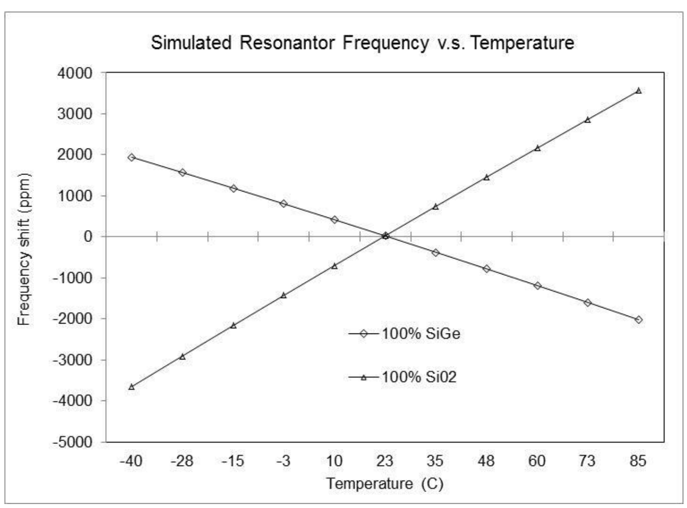

Figure 7. Simulated SiO2 and SiGe Uncompensated Temperature Coefficient Curves Show ± 30-40 ppm/°C

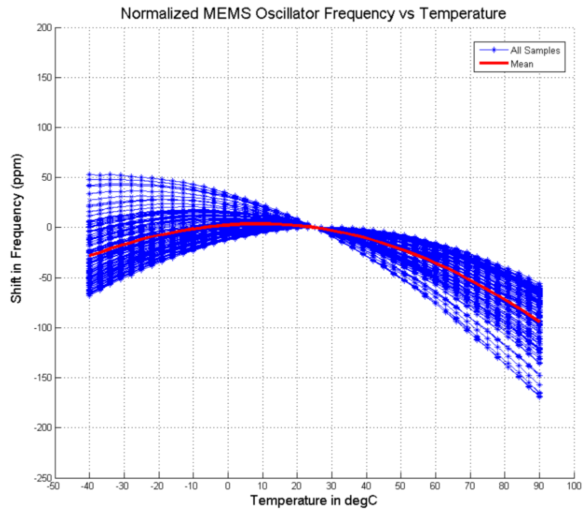

Figure 8. Passively-Compensated SiGe + SiO2 Resonator Curve (Red Line) Shows ~1 ppm/°C Temperature Coefficient

For example, the reduced resonator temperature coefficient means that random measurement fluctuations (noise) from the temperature sensor are scaled by a smaller factor as they drive the frequency-locked loop (FLL) to produce the desired output clock than if the resonator had a larger temperature coefficient. Thus, a lower power (higher noise) temperature sensor can be used for the same performance level compared to what would be needed for an uncompensated resonator. In addition, because the temperature coefficient of the passively compensated resonator is less than 5 percent of the uncompensated resonator (~-1 ppm vs. ~-30 ppm), any age-induced thermometer error will have much less impact on the oscillator system performance.

The Si50x MEMS oscillator family uses the passively compensated resonator as its reference frequency. It employs a cost-optimized, power-efficient digital FLL architecture to produce the device's system and output clocks, as shown in Figure 9. The FLL uses the MEMS reference frequency along with a divided signal from an on-chip, digitally-controlled VCO to drive a frequency comparator that generates frequency error values and feeds them to the FLL's digital loop filter. The loop filter accumulates and further processes the frequency error values along with digital temperature compensation information, generating a digital code that drives through a DAC to the VCO, producing the target output frequency.

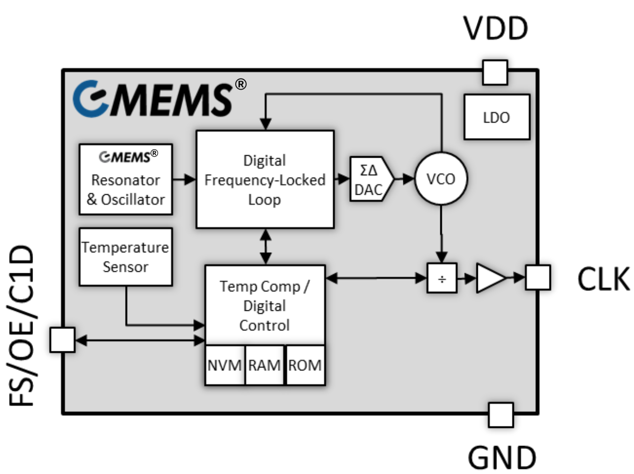

Figure 9. Si50x CMEMS Oscillator Architecture and Block Diagram

The device also uses temperature compensation information to offset any temperature drift of the MEMS oscillator. To produce the digital temperature compensation information for the FLL, the oscillator uses a high-resolution, low-noise temperature sensor and temperature compensation algorithm. Each device is calibrated for temperature and MEMS-resonant frequency pairs at final test, and the values are stored in on-chip memory. As the temperature changes, the compensation circuitry uses this calibration information to drive a device-specific high-order polynomial to the FLL. Single-chip integration through CMEMS technology allows this frequency control system to be very fast and accurate since the whole system is in close, sub-micron proximity and, therefore, very tightly thermally-coupled.

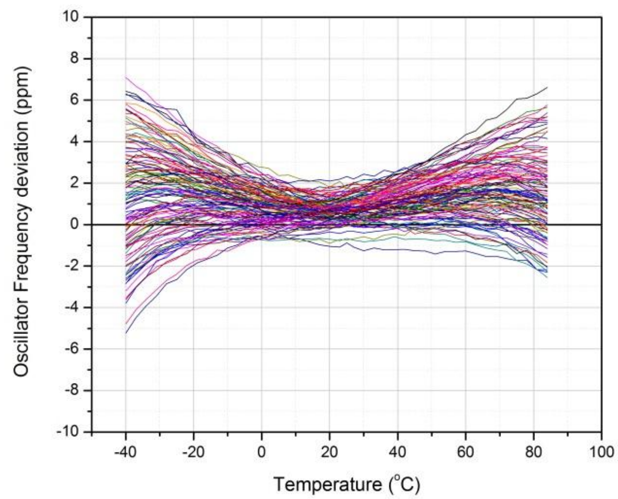

Figure 10. Si50x CMEMS Frequency Stability Across Temperature

The complete FLL process occurs many thousands of times per second, providing excellent frequency accuracy and stability across temperature as shown in Figure 10. The oscillator also supports a low-power version of this loop that reduces the FLL sampling cycle to a longer period and provides lower bias current to the VCO, which reduces power consumption by more than half for applications that can tolerate relaxed jitter specifications.

Si50x Oscillator Stress Test Performance

Devices using the CMEMS process provide more stable oscillator performance across time, temperature and various stresses than other previously available technologies. These benefits will reduce field failures, improve system reliability over time and help make systems more robust to external influences.

Using classic “torture tests,” including exposure to freeze spray and heat gun effects, helps to quickly quantify the CMEMS benefits in relation to alternative options. As discussed earlier and demonstrated in Figure 11 and Figure 12, two-component solutions are subject to thermal lag, making it difficult for the system to compensate for changes in the thermal environment and resulting in large deviations in the operating frequency. On the other hand, the monolithic CMEMS solution shows very little change. This provides greater stability in uncontrolled or unpredictable environments. Note that the two plots show a close-up, very high-resolution *y*-axis to reveal the changes to the Si50x CMEMS oscillator since they are unobservable on the higher-value *y*-axis shown for the classic quartz oscillator and MEMS oscillator plots.

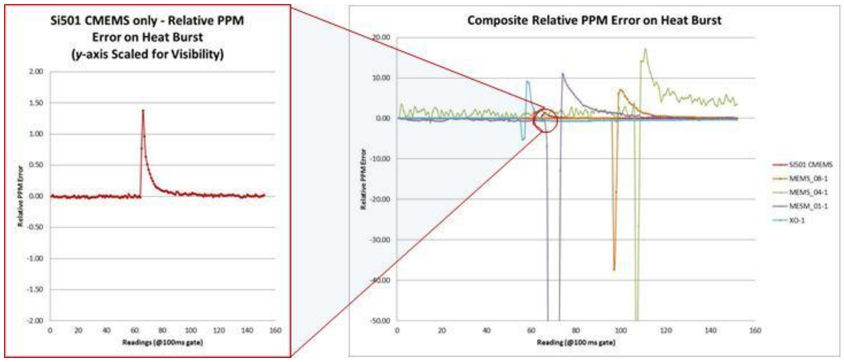

Figure 11. Thermal Shock Testing Results of Crystal, MEMS and CMEMS Oscillators

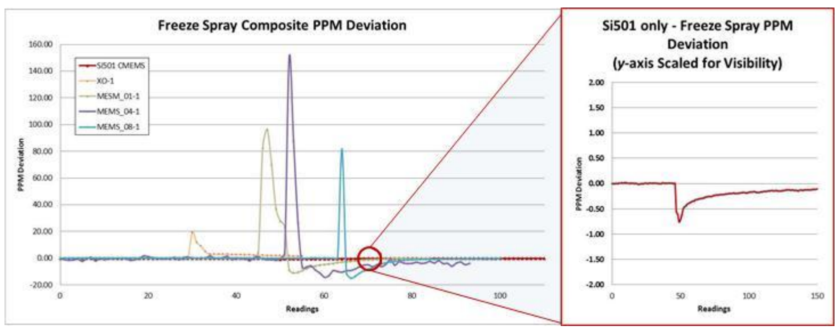

Figure 12. Comparative Cold-Spray Results of Crystal, MEMS and CMEMS Oscillators

CMEMS long-term aging performance is also superior when compared with existing hybrid technologies. Figure 13 provides a comparison of several quartz and MEMS oscillators compared with an Si50x CMEMS oscillator. In this plot, the quartz oscillators were aged at 70 °C according to MIL-0-5530B while all MEMS and CMEMS devices were aged at 125 °C and then extrapolated to the same duration. Again, the CMEMS device is substantially improved over existing MEMS technology approaches, providing greater stability over time to systems that adopt CMEMS technology.

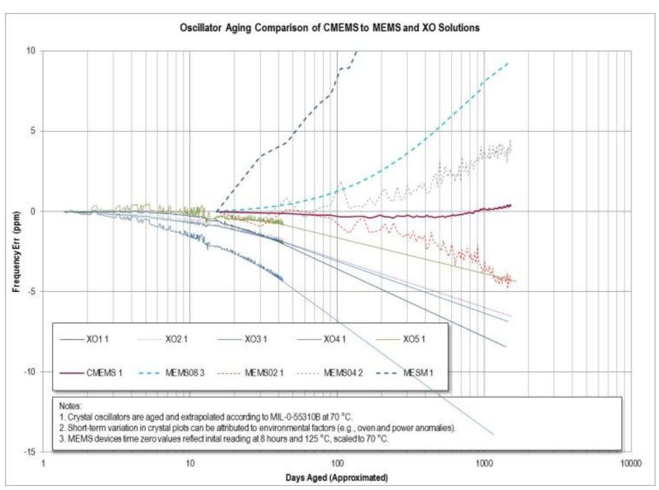

Figure 13. Comparative Aging Results of Crystal, MEMS and CMEMS Oscillators

Si50x CMEMS Oscillator Family

The Si50x CMEMS oscillator family includes four programmable devices designed for the industrial, embedded and consumer electronics markets, as shown in Table 1. Each device is customizable from the web or in the field. Web-configured samples are delivered within two weeks. Devices can also be programmed at the customer's offices using the Field Programmer Board shown in Figure 14. This flexible programmability allows the Si50x family to quickly meet the needs of unique customers.

Table 1. Si50x CMEMS Oscillator Family Overview

Device	Functionality	Control	Freq Range	Frequency Stability	Temp Range	Package Sizes
Si501	Single frequency	OE	32 kHz to 100 MHz	+/- 20 ppm +/- 30 ppm +/- 50 ppm Frequency stability includes initial frequency tolerance, operating temperature range, rated power supply voltage change, load change, 10-yr aging, shock and vibration.	All devices support both extended commercial (-20 to 70 °C) and industrial (-40 to 85 °C) temperatures as ordering options.	2 x 2.5 mm 2.5 x 3.2 mm 3.2 x 5 mm Packages are drop-in compatible to industry-standard 4-pin footprints.
Si502	Dual frequency	FS/OE				
Si503	Quad frequency	FS				
Si504	Programmable for any supported frequency and configuration option.	Device supports a proprietary single-wire C1 interface. Example code provided.				

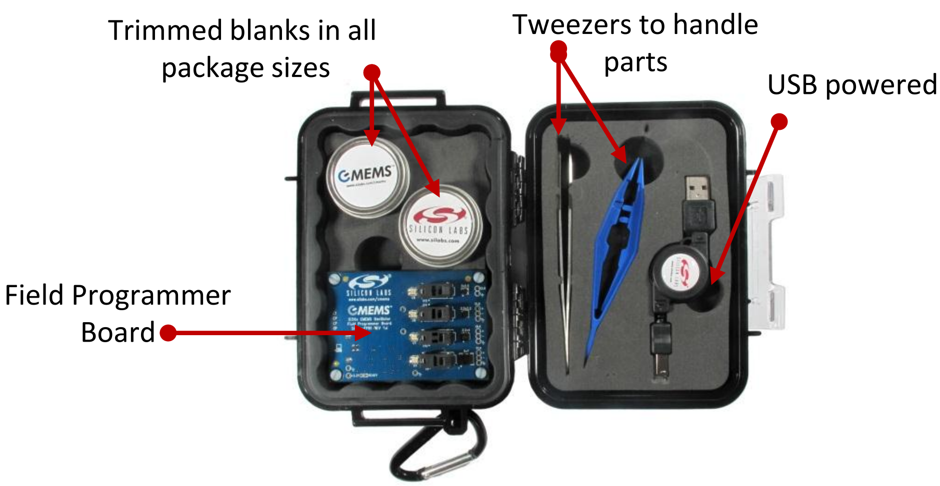

Figure 14. Si50x Field Programmer Board

As shown in Figure 15, the Si50x price/performance level complements Silicon Labs' existing high-performance crystal oscillator family used globally in many complex frequency control applications. The Si50x family addresses the cost and performance requirements of high-volume industrial, embedded and consumer markets, while Silicon Labs' crystal oscillators provide higher performance capabilities to address more demanding applications, such as communications and network infrastructure.

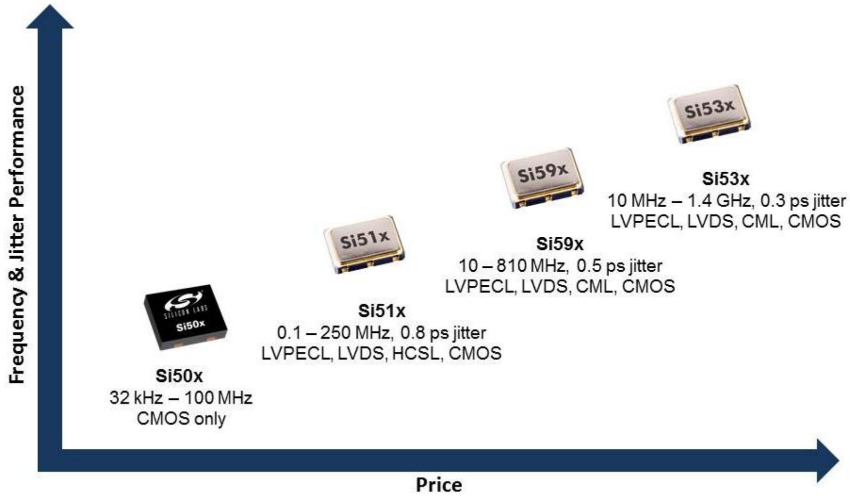

Figure 15. Price/Performance Comparison of
Si50x CMEMS Oscillator vs. Si51x, Si59x, and Si53x/5x/7x XOs

Conclusion

With the introduction of the Si50x MEMS oscillator family, Silicon Labs continues its history of providing innovative, disruptive frequency control products for the timing market. CMEMS oscillators provide superior manufacturability, faster lead times and competitive performance compared to traditional quartz and MEMS oscillator offerings. The Si50x family is the first CMEMS-based offering targeting the cost-sensitive, high-volume industrial, embedded and consumer markets. Possibilities for additional CMEMS-based products are virtually unlimited, providing opportunities to address new and emerging markets with higher performance solutions, a wide range of frequencies and power budgets and higher levels of single-chip integration. Find out more about Silicon Labs' new Si50x MEMS oscillator family at www.silabs.com/cmems.

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