

MEMS Oscillators with Improved Resilience for Harsh Automotive Environments

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ABSTRACT

Oscillators are key components in automotive electronics systems. For example, a typical automotive camera module may have three or more oscillators, providing the clocks for microcontrollers, Ethernet controllers, and video chipsets. These oscillators have historically been built around a quartz crystal resonator connected to an analog sustaining circuit driving the crystal to vibrate at its resonant frequency. However, quartz-based devices suffer from poor performance and reliability in harsh automotive environments. SiTime has developed timing solutions based on silicon micro-electromechanical systems (MEMS) technology that exhibit better electromagnetic noise rejection and better performance under shock and vibration. In this paper, we first discuss the design and manufacturing of the MEMS-based device, with emphasis on the specific design aspects that improve reliability and resilience in harsh automotive environments. These aspects include the SOI-based MEMS fabrication process, the oscillator and state-of-the-art temperature compensation architecture, and the manufacturing and packaging process. We then describe the test methods used to evaluate the resilience of the device, including electromagnetic susceptibility (EMS), and performance during shock and vibration. The results show that the MEMS-based oscillator performs better than all quartz oscillators that were tested, with up to 50x better EMS, up to 24x better performance during shock, and up to 100x and 20x better performance during sinusoidal and random vibration, respectively.

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INTRODUCTION

Resonating quartz crystals have been used as time and frequency references for almost a century. Quartz crystals were first used as frequency references for radios in the early 1920s, and the first quartz crystal clock was developed in 1928 at Bell Telephone Laboratories [1,2]. Until the last decade, quartz crystal oscillators were the de facto standard frequency references, and billions of quartz crystal timing products were used each year in a wide range of applications including military, industrial, consumer, and automotive [3]. Examples of these quartz-based products are shown in Figure 1.

In the last decade, micro-electromechanical systems (MEMS) oscillators began replacing quartz oscillators in many applications, including high-reliability automotive applications [4]. A key requirement for oscillators used in automotive applications is resilience and reliability in a variety of harsh environmental conditions. In this paper, we present measured data demonstrating that the resilience of the MEMS oscillators greatly exceeds that of quartz crystal oscillators during shock, vibration, and electromagnetic interference (EMI) that can occur in an automotive application. As an additional benefit, the MEMS-based resonator die does not require special vacuum packaging, which enables smaller size and a wider range of package options.

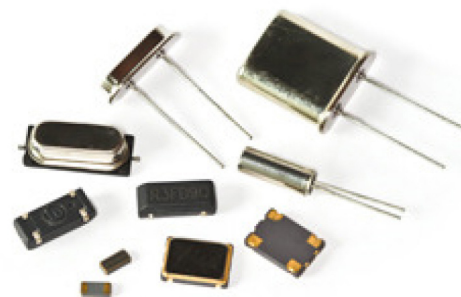


Figure 1. Traditional vacuum-packaged quartz crystal timing products [5].

MEMS OSCILLATOR OVERVIEW

The primary goal of a timing reference is to produce an accurate and low noise clock signal that does not degrade over time and temperature, or due to environmental factors such as stress, shock, vibration, and electromagnetic noise. This section describes the design and implementation of the MEMS-based oscillator to achieve this goal.

MEMS Resonator

The key building block of the MEMS-based oscillator is the MEMS resonator, which is fabricated and encapsulated at the silicon wafer level using the MEMS First™ process [6,7]. The MEMS structure is designed to mechanically resonate at a specific frequency that is stable over time and temperature, and is not affected by external

forces applied to the MEMS die. The resonator is a passive mechanical structure that requires an active oscillator circuit to induce mechanical vibration. Figure 2 shows a detailed cross-sectional diagram of the MEMS resonator fabrication process. First, photolithography is used to pattern the resonator, and a deep reactive ion etch (DRIE) process is used to define the resonator structure in the device layer of a silicon-on-insulator (SOI) wafer (step 1). A silicon dioxide layer is deposited and electrical contacts are defined (step 2). A thin epitaxial polysilicon layer is then deposited at 1100°C and small “vent” holes are etched above the resonating structure (step 3). The resonating structure is released using a hydrofluoric (HF) acid vapor to etch the silicon dioxide around the resonator (step 4). The vent holes are sealed using a thick epitaxial polysilicon layer (step 5). This critical step provides a clean, low-pressure enclosure for the MEMS structure and protection from the external environment. The hermetic vacuum encapsulation is critical to achieving long-term frequency stability [8]. The rough polysilicon layer is polished and a thin silicon dioxide passivation layer is deposited. Finally, electrical contacts are created, and metal traces are defined on the surface to connect the contacts to the electrical pads (step 6).

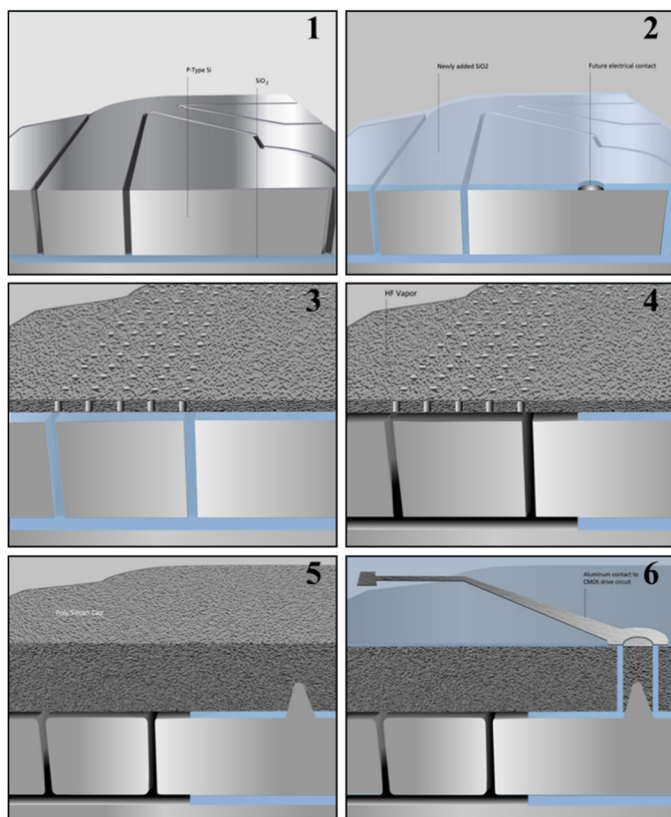


Figure 2. Cross-sectional diagram of the MEMS resonator fabrication process [7].

For automotive applications, there are several advantages of the MEMS oscillator in comparison to a traditional quartz resonator or oscillator. Due to its small size, the mass of the MEMS resonator is much less than that of a quartz crystal, making it less susceptible to the effects of shock and vibration. The MEMS resonator is centrally anchored, making it more immune to externally applied stress. In addition, the MEMS resonator is vacuum encapsulated inside the die, such that it does not require external vacuum packaging that increases the size of the product and may leak over time.

Figure 3 shows a comparison between a MEMS resonator and a quartz resonator. The quartz resonator is sealed in a 3.2 mm × 2.5 mm ceramic cavity vacuum package. Note the sealed cover was removed for the image. The quartz crystal is approximately 1.5 mm × 2.5 mm and is soldered to the package. The MEMS resonator is encapsulated inside a tiny 0.4 mm × 0.4 mm silicon die that does not require an additional sealed vacuum package. The resonator itself is much smaller than the quartz crystal and is centrally anchored, making it robust against stress, shock, and vibration.

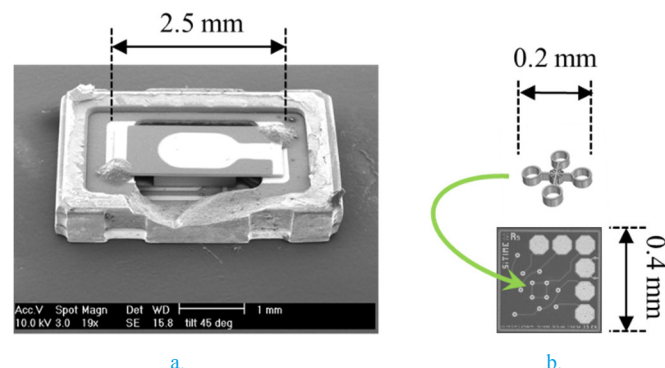


Figure 3. Comparison of a quartz resonator (a) and MEMS resonator (b).

Programmable Oscillator Architecture

The MEMS resonator is combined with a programmable oscillator IC as illustrated in Figure 4. The MEMS oscillator's patented architecture has been described previously [9] and for clarity is summarized here. The IC includes the active sustaining amplifier which drives the MEMS resonator and forms the oscillator circuit. The resonator uses differential drive and sense circuits that inherently reject any electromagnetically-coupled common-mode noise. The architecture also includes a temperature sensor and temperature compensation logic that controls a fractional-N phase-locked loop (PLL). The PLL serves two purposes. First, it is used to synthesize a large range of unique frequencies from the MEMS reference frequency. Second, it is used to compensate for small frequency offsets of the resonator due to fabrication tolerances and temperature. The two die are stacked, assembled, and molded in a plastic DFN package, a plastic SOT-23 package, or assembled into a chip scale package (CSP). An optical image of an assembled DFN package with the outer plastic compound removed is shown in Figure 5.

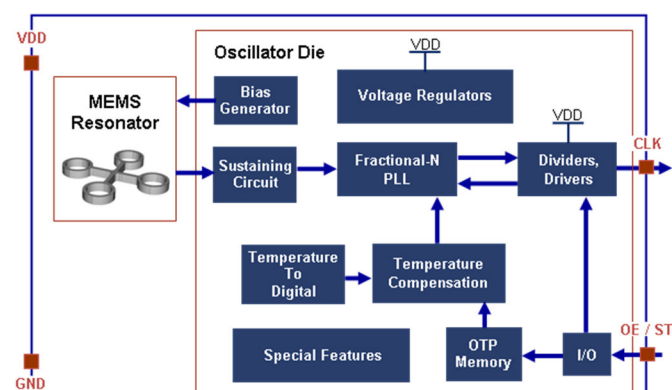


Figure 4. Programmable MEMS oscillator system architecture.

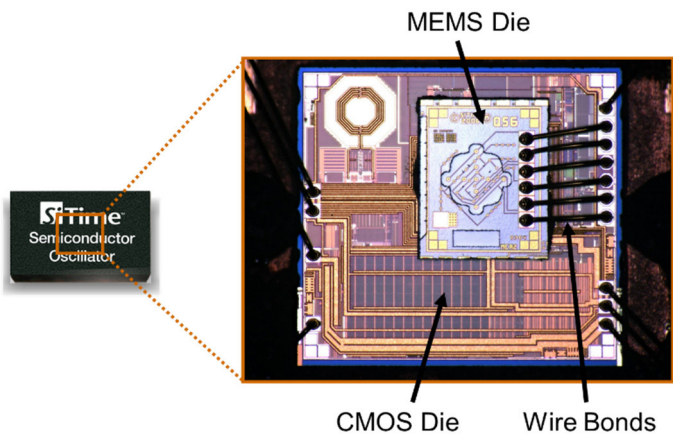


Figure 5. Optical image of a MEMS oscillator with plastic mold compound removed.

RESILIENCE TEST METHODS AND RESULTS

In this section, we describe the experimental methods used to compare the resilience of the MEMS oscillator to several commercially available quartz oscillators. We performed the following tests: electromagnetic susceptibility (EMS), performance during shock, and performance during sinusoidal and random vibration. The tests and performance metrics are summarized in Table 1.

Table 1. Summary of resilience tests and performance metrics.

Reliability or resilience test	Performance metric
Electromagnetic susceptibility	Average phase noise spur (dB)
Performance during shock	Peak frequency deviation (ppm)
Performance during sinusoidal vibration	Frequency deviation per g (ppb/g)
Performance during random vibration	Induced integrated phase jitter (ps rms)

Table 2 summarizes the oscillators that were compared in the study. Six different commercially available oscillators from common vendors were chosen. In addition to our MEMS oscillator, we included both 3rd overtone and surface acoustic wave (SAW) quartz-based oscillators. All oscillators were 3.3 V devices in 7.0 mm × 5.0 mm packages with 156.25 MHz differential LVPECL outputs.

Table 2. Summary of the MEMS and quartz oscillators tested in this study.

Label	Technology	Output
MEMS	MEMS + PLL	156.25 MHz (LVPECL)
Quartz1	Quartz, SAW	156.25 MHz (LVPECL)
Quartz2	Quartz, 3 rd Overtone	156.25 MHz (LVPECL)
Quartz3	Quartz, 3 rd Overtone	156.25 MHz (LVPECL)
Quartz4	Quartz, SAW	156.25 MHz (LVPECL)
Quartz5	Quartz, 3 rd Overtone + PLL	156.25 MHz (LVPECL)

Electromagnetic Susceptibility (EMS)

For oscillators, phase noise is defined as the frequency domain representation of rapid fluctuations in the phase of the clock signal. Increased phase noise can lead to performance issues such as bit errors or corruption of video frames. It is known that radiated EMI

adversely impacts the phase noise performance of quartz oscillators [10,11]. In this study, we measured the increase in oscillator phase noise due to exposure to radiated EMI. We followed electromagnetic compatibility standard IEC EN610004.3 [12] which specifies test conditions for evaluating the response of electronic components to EMI. The test was conducted in an anechoic chamber using the setup shown in Figure 6. The setup included a phase noise analyzer (PNA) to capture the phase noise of the device under test (DUT). The DUT was positioned so that it was aligned with the axis of the antenna as shown in Figure 7. The signal generator created an electromagnetic field with strength of 3V/m and scanned the frequency range from 80 MHz to 1 GHz in steps of 1%.

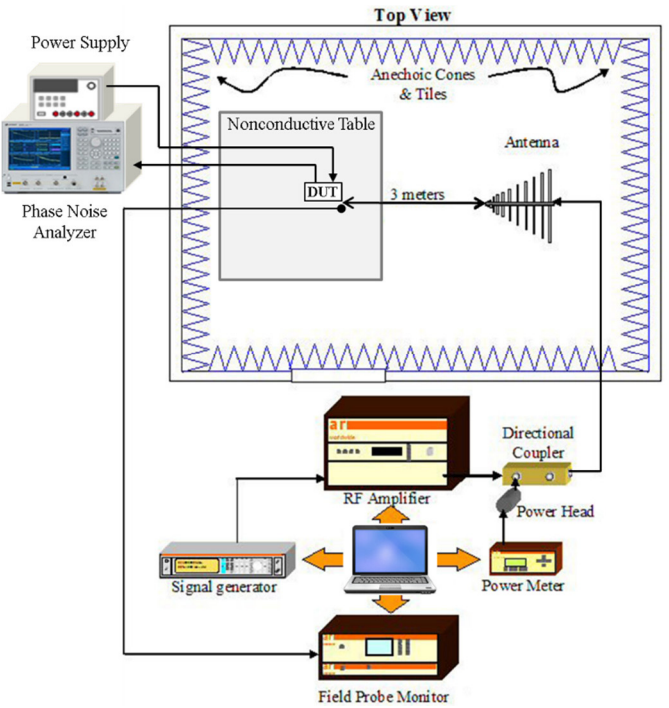


Figure 6. Experimental setup for testing EMS.

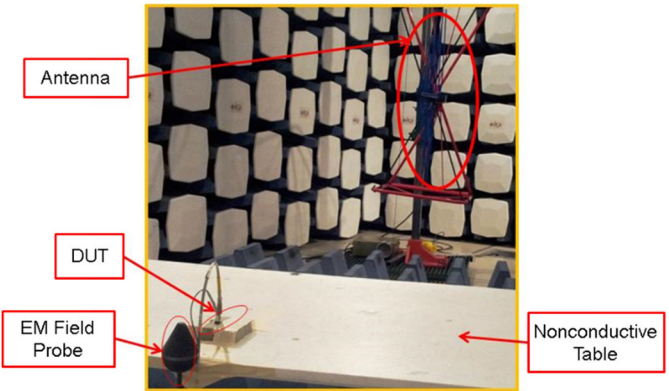


Figure 7. Photo showing the antenna and testing table inside the anechoic chamber.

Exposure to radiated EMI at a single frequency causes a sharp peak in the phase noise spectrum referred to as a phase noise “spur.” An example phase noise spectrum including a spur is shown in Figure 8.