Frequency Trimming for MEMS Resonator Oscillators

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***Abstract* — This paper presents various frequency trimming methodologies with the focus on silicon based micromechanical resonators. The techniques include mechanical trimming and pure electronic trimming. The experimental results showed the frequency accuracy have reached 2.6ppm for mechanical trimming and 1ppm for electronic trimming. Furthermore, the technique of digital electronic trimming resolved the temperature compensation issues for MEMS resonators at the same time.**

I. INTRODUCTION

Micro-Electro-Mechanical System (MEMS) resonators are now being developed for use in frequency-specific applications, such as reference oscillators and highly-selective band-pass filters. These applications require that the resonator possess a specific resonance frequency. For example, in the case of an oscillator that serves as part of a clock circuit, it is important that the resonator vibrates at a desired frequency. In the case of a filter, a resonator must likewise vibrate at a particular, targeted frequency to generate a pass-band to selectively pass or reject a signal as a function of frequency.

Frequency trimming is a common practice for mechanical resonators such as quartz crystals, bulk-acoustic-wave (BAW) resonators, and ceramic resonators. As summarized in Table I, the methods of trimming typically include two steps - coarse trimming and fine-tuning. Coarse trimming often starts with grinding, polishing, and plasma etching, which bring quartz resonators to the accuracy of several hundreds of ppm. Afterwards, a thin layer of metal is deposited on quartz surface in a batch mode. As the metal is deposited on the surface of quartz, the vibrating mass of the crystal and its frequency is changed. The accuracy of this method, however, is limited to few hundreds of ppm. Fine-tuning, on the other hand, is to add or remove metal from quartz surface at specific locations for individual resonators. At this time, frequencies are continuously monitored till the target frequency is achieved. Unfortunately, resonator frequency is sensitive to the metal film on the surface since a single atomic layer of may cause the frequency to shift tens of ppm. Moreover, packaging process afterwards also causes the frequency shift. If the applications require the frequency to be less than 10ppm, a bank of trimming capacitors is often implemented on oscillator circuit to pull the frequency of the resonator. As a result, further testing steps are required for individual packaged oscillators.

The performance of frequency synthesizers and phase-locked-loop (PLL) has been tremendously improved due to the advances in CMOS technologies. These advances contribute to higher frequency VCO's, frequency multipliers, and jitter attenuators. A PLL could now be programmed to translate low cost, fixed low-frequency resonators to the desired output frequency. This architecture provides a very wide tuning range for the oscillators because the frequency trimming is done through digital programming on non-volatile memory. As a result, the frequencies of the quartz crystal resonators do not need to be trimmed or pulled to high accuracy.

This paper discussed the frequency trimming techniques for silicon based micromechanical resonators, ranging from process definitions, later trimming, and electronic trimming. The experimental results showed the frequency accuracy have reached 2.6ppm for mechanical trimming and 1ppm for electronic trimming. As a result, with demonstrations of reliability [1] and manufacturability [2], silicon-based MEMS resonators have been marching out of research laboratories for high volume production, posing a potential replacement of some quartz-based timing and clock oscillators.

II. LASER TRIMMING

Metal deposition and laser-enhanced material removal have traditionally been used for trimming the resonant frequency for crystals. However, traditional ways of material deposition for quartz crystals, such as evaporation, have not been considered to be practical for MEMS resonators, since MEMS resonators are typically much smaller in size than their crystal counterparts. A typical resonator is less than 100μmx100μm in size with a mass on the order of 10^{-13}kg. Therefore, an atomic monolayer of gold would change the mass of a 2μm thick silicon resonator for 2000ppm. Therefore, it is difficult to either deposit on the MEMS resonators unless the deposition locations are carefully selected and masked. In contrast, laser techniques provide good accuracy of both deposition and material removal. So

TABLE I. COMPARISON OF FREQUENCY TRIMMING TECHNIQUES

Freq accuracy	Quartz	MEMS
10000ppm (1%)	Grinding/polishing*	Lithography/etching*
1000ppm	Grinding/polishing* Plasma etching*	• Mechanical Trimming – Laser – Metal deposition – Resonator array
100ppm	Plasma Etching* Metal deposition	Laser Trimming Electronic: bias voltage
10ppm	Selective metal dep Laser trimming Trim cap	Laser trimming Electronic: bias voltage
1ppm	Trim cap Synthesizer	Synthesizer

* Manufacturing Process

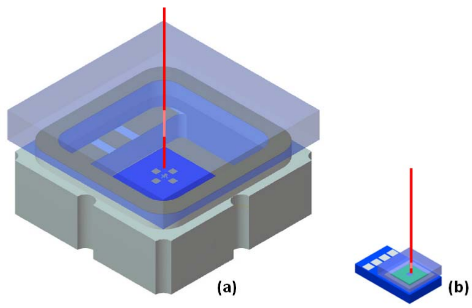

Figure 1 *Laser trimming through (a) 3x3 ceramic package, and (b) wafer level package*

mechanical trimming techniques discussed in this paper are divided into laser deposition and laser trimming.

As described in previous sections, the frequency of the resonators is determined by both material properties and geometry of the resonators – exactly the same as quartz crystal resonators. Typically, depending on the system requirements, the oscillator output frequency needs to be within ppm (e.g. from 1ppm to 100ppm) to the target frequency for system applications. However, since semiconductor processes are used for MEMS resonator fabrication, the process variation from the sum of film thickness, lithography, and etching made the frequency of the resonators prior to trimming vary between ±1% and ±5%, depending on the process control. Furthermore, it is known that the resonator packaging itself can affect the resonant frequency of a resonator. In other words, the resonant frequency of a resonator can differ before and after encapsulation in a package. If the trimming is conducted before the resonator is packaged, there is uncertainty as to how much frequency trimming is required.

Post-package pulsed-laser-deposition frequency trimming technologies have been demonstrated for MEMS resonators [3]. However, the resonator frequency still has not yet reached the accuracy of ppm level due to the difficulty of controlling the geometry and the amount of the materials deposited by laser. Furthermore, the quality factor of the resonator is often degraded with additional materials on the resonator as the resonator vibration lost its balance.

An alternative method to laser enhanced material deposition for frequency tuning is based on material removal. The first published effort for frequency trimming of MEMS resonators trimmed resonator from 2% initial frequency error to 21ppm [5]. However, the resonators were not packaged so that the resonator frequency would shift after the packaging.

Frequency accuracy smaller than 10 ppm are required for many oscillator applications. As shown in Figure 1, a packaged resonator is trimmed by directing femtosecond laser beam to the resonator through a transparent lid or cap of the resonator package. The energy removes (e.g., ablates, etc.) mass at the points of contact on the resonator. Removing mass from the resonator affects its resonance frequency in a predictable manner. The frequency trimmed is a function of (1) the amount of mass removed from the resonator and (2) the location(s) on the resonator at which the mass is removed.

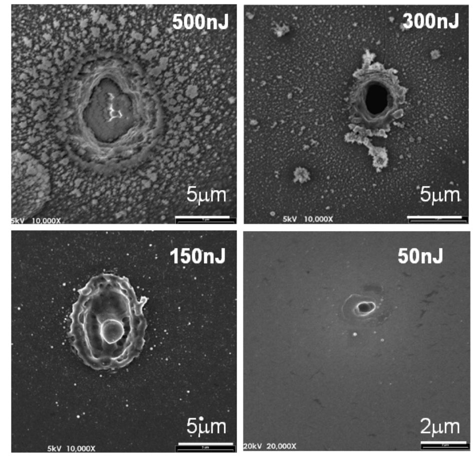

Figure 2 *Laser spot characterization on polysilicon*

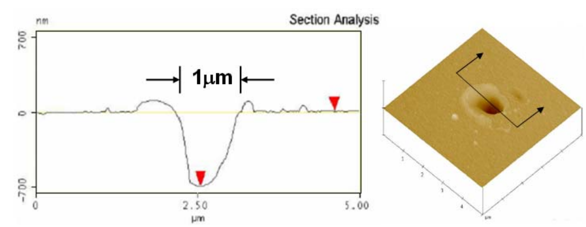

Figure 3 *AFM analysis of the divot formed by 50nJ laser*

The first task for laser trimming is to characterize the focus and the energy of the laser beam. All the parameters are characterized through the transparent lid of the package in order to match with the real situation. Figure 2 shows the SEM pictures of the polysilicon surface after laser trimming with the energy ranging from 500nJ down to 50nJ. As shown, 500nJ laser beam blasted the surface of polysilicon, leaving a lot of residues around. As the laser energy is brought down to 50nJ, the spot size becomes 1mm in diameter. Based on atomic force microscopy (AFM) measurement, one shot of femtosecond laser at 50nJ created a 1µm diameter and 0.7µm deep divot, as shown in Figure 3.

Once the frequency-trimming requirement is determined, the trimming is implemented by removing mass from selected locations on the resonator, since the change in frequency caused by removing mass is not only a function of the amount of mass, but also its location on the resonant element. As a result, a mass-trimming map is developed for identifying the potential mass-trimming sites on the resonator based on FEM and experimental verification. Each site can be classified as a "fine-tuning" site or a "coarse-tuning" site as a function of the magnitude of the change in resonance frequency that is caused by removing (a given amount of) mass at that site. Fine-tuning sites and coarse tuning sites tend to group in different regions on the resonator. Moreover, the trimming locations are usually located symmetrically on the resonator surface. This symmetric arrangement has the effect of changing the resonance frequency while the quality factor, Q, of the resonator remains substantially unaffected.

As shown in Figure 4(a), the MEMS resonator used in this experiment is 20µm wide and 31µm long resonator. The

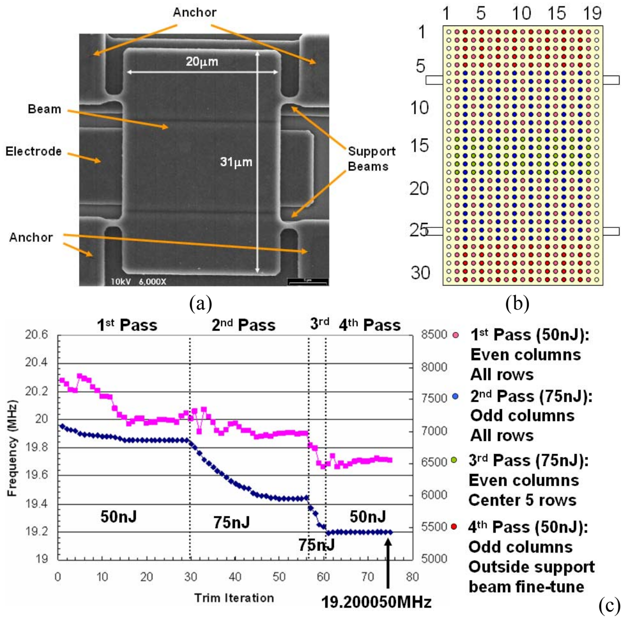

Figure 4 *(a) Resonator structure for laser trimming (b) Trimming map (c) Results of laser trimming MEMS resonator down to from 4% down to 2.5 ppm using three passes of coarse trimming followed by a single pass of fine trimming*

location for trimming is defined by the row and column numbers as shown in Figure 4(b). Each of the spots is 1µm apart. Figure 4(c) shows the resonator with a frequency 4% away from the target was trimmed to 2.6ppm away from the target after 4 passes of trimming. The 1st pass trimmed locations from with even columns of all rows and decreased the frequency about only 0.5%. The laser energy was increased from 50nJ to 75nJ for the 2nd pass, which trimmed odd columns and all rows. All columns and rows are trimmed. Therefore, additional trims at higher energy were overlapped on the even columns of the 5 rows from the beam center. The 3rd pass brought the frequency to target range. The 4th pass was for fine tuning on resonator frequency which eventually brought the resonator 2.6ppm away from the target frequency. Further trimming is conceptually possible, but not practical as the short term temperature fluctuations would induce a greater change obscuring the measurement since the TC_f of these devices is approximately –20 ppm/°C.

III. Electronic Frequency Compensation

An alternative to mechanical frequency trimming can be performed by electronic frequency compensation. For quartz based oscillators, fine trimming and temperature compensation can often be performed by an integrated, fusable capacitor table or varactor diodes that are used to load a crystal in a parallel feedback structure. However, the larege amount of trimming required, the large *TCf*, and the large motional impedance, typically 10's of kΩ, of most MEMS resonant elements make this method prohibitive.

Unlike the laser trimming, electronic frequency trimming has been explored to not only overcome the poor initial accuracy of the device, but also to improve the temperature coefficient of frequency by several orders of magnitude. Two methods have been investigated, namely polarization voltage (V_P) tuning and compensation through frequency synthesis.

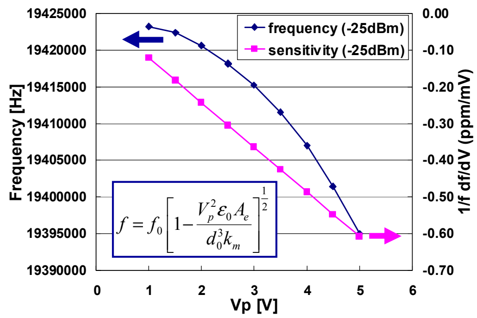

Figure 5 *Frequency pulling with V_P for the 19MHz resonators used in this experiment*

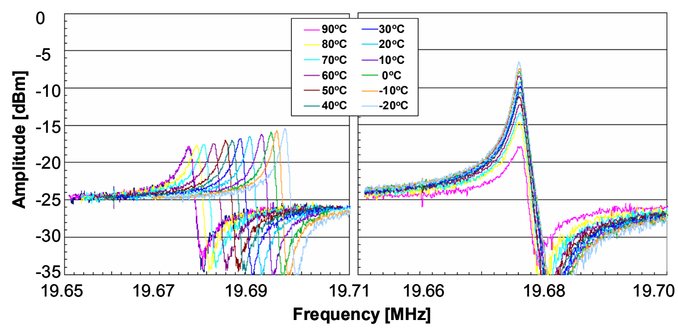

Figure 6 *Frequency responses of a non-tuned resonator (fixed Vp) and Frequency response of a resonator with Vp tuning set to null the temperature coefficient. Required range of Vp was approximately 2.5 to 9 V varied across temperature.*

A. *V_P Tuning of Resonantor Frequency*

The resonator frequency can be tuned by its bias voltage V_P through electrostatic spring softening phenomenon [4]. This method applies a variable voltage for the resonator bias effectively shifting the overall spring constant of the device. The frequency of the resonator is approximately:

$$f = f_0\left[1-\frac{V_p\varepsilon_0 A_e}{d_0^3 k_m}\right]^{1/2} \qquad (1)$$

where f_0 is the true mechanical resonance, V_P is the resonator bias, A_e is the effective area of the capacitive transducer, d_0 is the nominal gap between the transducer electrodes, and k_m is the mechanical spring constant. For the devices under consideration for this paper, the frequency can be pulled roughly 3000 ppm allowing enough range to effectively temperature compensate the frequency of a structure, but not allowing for the coarse trimming required for initial accuracies of as much as 5% error requiring this technique to be used in conjunction with laser trimming.

Other difficulties in using this method include requiring a large bias range, having to very accurately generate a square root function over a very large voltage range, and dealing with exaggerated device performance variations across temperature. Required range of V_P was approximately 2.5 to 9 V varied across temperature. While this method could control

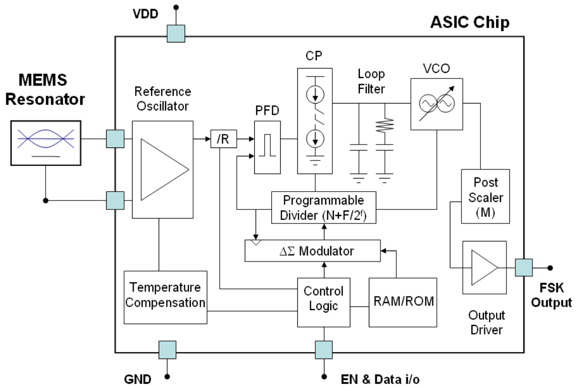

Figure 7 *Architecture of a MEMS-based, temperature compensated, programmable output clock source.*

the frequency vs. temperature, the motional resistance vs. temperature varies considerably greater compared to the fixed V_P case. This is clearly illustrated in Figure 6. As a result, the gain of the oscillator circuits needs to deal with large range of motional resistance, which is not a desired situation.

B. Frequency Trimming Through Frequency Synthesis

The last method explored involves setting the oscillator frequency through the use of a phase lock loop (PLL). PLL's are typically used to lock a high frequency voltage controlled oscillator (VCO) to a stable crystal reference oscillator where the VCO is often at a much higher frequency. This gives the VCO the accuracy and temperature stability of the reference oscillator as well as an improvement in VCO phase noise within the loop bandwidth of the PLL. A similar method was employed using a MEMS based reference oscillator.

As shown in Figure 7, digital electronic trimming was implemented using a high performance MEMS-based oscillator, a high resolution fractional-N synthesizer, a wide tuning range VCO, and necessary control and sensor infrastructure to perform the temperature compensation. The PLL gives frequency accuracy less than 1ppm for a given temperature, and approximately 2.6ppm over the full operating temperature range. As a result, typical initial frequency accuracy is around 1ppm at room temperature.

The other main advantage of this method is that a wide range of frequencies can be easily generated for an optimized resonator design, allowing standardization of the resonator process as well as optimization of the reference oscillator circuit. On the other hand, the impact of this method is that it inherently increases the phase noise of the entire system due to the PLL noise and VCO noise. However, for many clock and timing applications, jitter is only concerned between the band 1kHz and 25MHz away from the carrier frequency. So the increase in close-in phase noise is a negligible increase in jitter. For example, MEMS oscillators have shown an RMS period jitter of only 13 ps for a 33.0 MHz output frequency exceeding the typical jitter numbers of many other crystal based oscillator products commercially available (~25ps). On the contrary, quartz based oscillators can either adopt the same programming method where a new resonator is required for

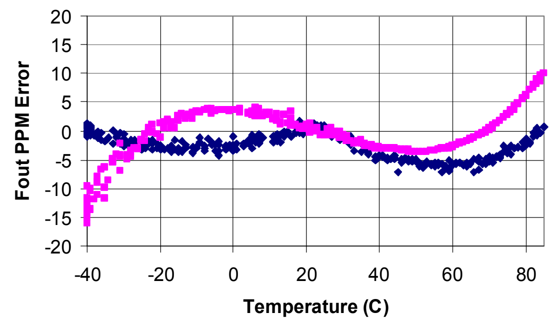

Figure 8 *Typical frequency stability vs. temperature of a MEMS oscillator product compared to an uncompensated quartz-based clock source (Epson SG8002).*

each frequency and the oscillator circuit must be designed to accommodate a wide range of resonator frequencies.

IV. Conclusions

Resonators with 5% of frequency deviation were trimmed by femtosecond laser after through the transparent package, achieving only 2.6ppm away from the target. The trimming energy and trimming map were characterized to reach this accuracy. The accuracy is limited by temperature control of the resonator during trimming. Moreover, the resonator Q generally degrades about 10% while the trim spots cover the width. However, laser trimming alone did not resolve temperature compensation issues.

Electronic trimming was discussed. Bias voltage can be used for frequency pulling and for temperature compensation. This trimming shows well match with laser trimming techniques. At the same time, digital synthesizer can also used for trimming. Theoretically and experimentally it shows frequency accuracy of 1ppm. Moreover, by implementing a temperature sensor and memories into the IC, synthesizer can react with temperature changes, resolving temperature compensation at the same time.

Acknowledgment

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