A Review of the Recent Development of MEMS and Crystal Oscillators and Their Impacts on the Frequency Control Products Industry

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Abstract- Due to their high Q and temperature-stable properties, quartz crystal oscillators are important clock sources in consumer, commercial, industrial, and military products for many years. The demand for quartz crystals and crystal oscillators has been increasing steadily between 4 and 10% annually since the "dotcom" market collapse in 2000~2001. The total market for 2008 is expected to exceed $4.1B. The quartz crystal and crystal oscillator industry has made major progresses in miniaturization, performance enhancement, and cost reduction in the past ten years. The unique fabrication and encapsulation requirements though render quartz crystals and crystal oscillators difficult or close to impossible to be integrated onto the silicon-based IC platforms. The recent strong marketing push of the all silicon MEMS resonators and oscillators seemed to re-ignite the interest in displacing the quartz crystal technology and to open up again the prospect in clock source integration. Based on a 2006 review paper,[1] the author expands on the subject by reviewing the development of the all silicon MEMS oscillators and crystal oscillators in the past few years and commenting on what challenges they face in the highly competitive frequency control products industry. Since information on the technical development of the all silicon MEMS oscillators and crystal oscillators is abundantly and readily available, this paper addresses more on the *market and business aspects.* This paper also touches on the recent development of piezoelectric-activated silicon MEMS resonators and oscillators and all silicon oscillators (with no moving parts).

Keywords- frequency control products, MEMS oscillator, crystal oscillator

1. Introduction

Due to their high Q and temperature stable properties, quartz crystal oscillators are important clock sources in consumer, commercial, industrial, and military products for many years. The demand for quartz crystals and crystal oscillators has been increasing steadily between 4 and 10% annually since the "dotcom" market collapse in 2000~2001. The total market for 2008 is expected to exceed $4.1B. Quartz crystals and crystal oscillators (piezoelectric frequency control components in general) can be found in almost all portable and stationary electronic equipment around us. One good portable example is handset. In the earlier days, a typical GSM handset had four different sets of piezoelectric frequency control components- RF SAW filter (~900 MHz to 2 GHz using piezoelectric lithium tantalate or lithium niobate) for transmission and receiving filtering between the antenna and the transceiver chipset; IF SAW filter (~50 to 400 MHz using mainly quartz) if superheterodyne down conversion is used; TCXO (temperature-compensated crystal oscillator, 13/26 MHz using quartz crystal) as clock reference in the transceiver synthesizer for channelization; and tuning fork (32.768 KHz using quartz crystal) for standby clocking in the baseband section (2^{15} = 32768).

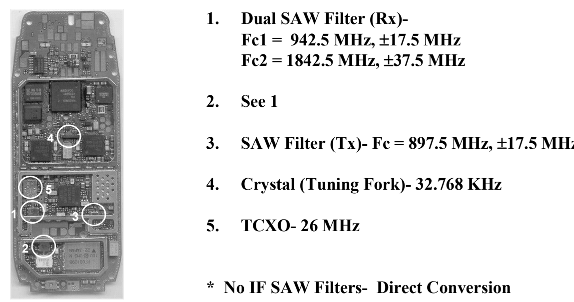


Fig. 1 Piezoelectric Components in a Typical Dual-Band GSM Handset (GSM900 and DCS1800)

Later on, the successful development of direct conversion technology obsoleted the IF SAW filter in many GSM handsets (Fig. 1). A few years ago GSM transceiver chipsets with on-chip digitally-compensated crystal oscillator (DCXO) circuit began to appear.[2] TCXO is no longer needed to pair with these transceiver chipsets. However, an off-chip quartz crystal is still needed (Fig. 2).

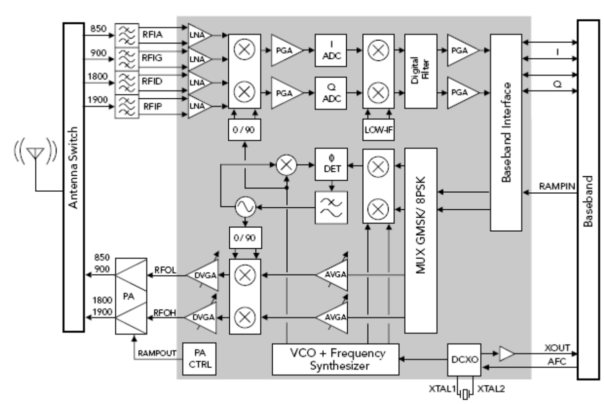


Fig. 2 GSM Transceiver Chipset with On-chip DCXO[2]

Through years of efforts, these off-chip piezoelectric frequency control components have become very small and they provide excellent frequency generating and filtering functions to support the demanding requirements from the handset designers. The unique fabrication and encapsulation requirements of these components though render them close to impossible to be integrated onto the mature silicon-based IC platforms. As the handset market continues to grow, developing MEMS-based RF components such as switches, filters, resonators, oscillators, VCO, etc. in the RF section of handsets seems to be the logical route toward integration (Fig. 3).

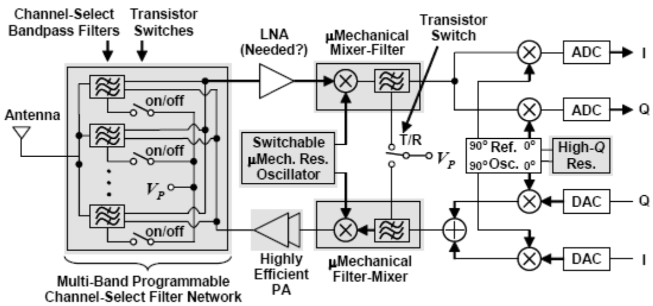


Fig. 3 Proposed RF MEMS Replacing Devices (Shaded) in TxRx Section of Handsets[3]

Based on the earlier MEMS works funded by DARPA, Discera was established in 2001 with the mission "to become a global leader in CMOS MEMS resonator technology and to offer a broad portfolio of patented PureSilicon™ resonators whose breakthrough technology is proven reliable and used to create the industry's most advanced and economical Frequency Control and RF Circuits. Discera is the trend setter in today's multi-billion dollar timing industry, displacing quartz crystal solutions with systems-on-a-chip alternatives."[4] Seven years later, while there seems to be some potential successes in implementing MEMS switches, quartz crystal, SAW, and FBAR (film bulk acoustic resonator) components still dominate the RF section of handsets. Quartz tuning fork is still "the solution" in providing reliable standby clocking in the baseband section of handsets. Nowadays handsets don't seem to get smaller as they are quite small already. In fact some handsets are becoming bigger so to accommodate more functions desired by consumers- DSC, DVC, MP3, GPS, Internet access, Bluetooth, DTV, etc. Opposite to the earlier thought that less and less piezoelectric frequency control components would be needed as time progressed, handsets nowadays have many more off-chip of them- quartz tuning fork, quartz crystal, crystal oscillator (XO), VCXO (voltage-controlled crystal oscillator), TCXO, and RF SAW/FBAR filter/duplexer.

Based on the IP licensed through Bosch, SiTime was established in 2004 with the mission "to become a fabless integrated circuit company developing silicon timing, clock, and RF chips, which incorporate MEMS timing reference devices inside standard silicon electronic chips, eliminating the need for quartz crystals."[5] The first product (1~125 MHz) introduced in 2006 was the SiT8002 series programmable MEMS oscillator and the SiT1 series fixed frequency MEMS oscillator. These all silicon MEMS oscillators were available in 7x5, 5x3.2, 3.2 and 2.5x2mm^2- clearly targeting at the pin-to-pin compatible quartz crystal oscillator market. The intense marketing of such MEMS oscillators prompted Discera to divert from its earlier efforts in replacing components in the RF section of handsets to offer a smaller yet similar family of pin-to-pin compatible MEMS oscillators.

The recent strong marketing push of the all silicon MEMS resonators and oscillators seemed to re-ignite the interest in displacing the quartz crystal technology and to open up again the prospect in clock source integration. Based on a 2006 review paper,[1] the author expands on the subject by reviewing the development of the all silicon MEMS oscillators and crystal oscillators in the past few years and commenting on what challenges they face in the highly competitive frequency control products industry. Since information on the technical development of the all silicon MEMS oscillators and crystal oscillators is abundantly and readily available, this paper addresses more on the *market and business aspects.* This paper also touches on the recent development of piezoelectric-activated silicon MEMS resonators and oscillators and all silicon oscillators (with no moving parts).

2. Current status of the quartz crystal and crystal oscillator industry

This year marks the 90th anniversary of the birth of the first quartz oscillator.[6] Due to its high Q, unchallenged frequency-temperature stability, low cost, technical maturity, and wide commercial availability, quartz crystal continues to be the choice, and often the only choice, in providing stable frequency sources in the ever expanding digital world.

Crystal-based (<MHz ~ 200 MHz)	*SAW-based (<50 MHz ~ 2.5 GHz)*
Passives-	
Tuning Fork and AT-Cut Crystal	**SAWR**
MCF	**SAWF**
Oscillators-	
CXO (=XO=SPXO)	**CSO**
PCXO (Programmable)	**PCSO**
VCXO (Voltage-Controlled)	**VCSO**
TCXO (Temperature-Compensated)	**TCSO**
OCXO (Oven-Controlled)	**OCSO**
Timing Modules-	
CDR (Clock Data Recovery)	**CDR (Clock Data Recovery)**
CS (Clock Smoother)	**CS (Clock Smoother)**
FX (Frequency Translator)	**FX (Frequency Translator)**
STM (Synchronous Timing Module)	**STM (Synchronous Timing Module)**

Table 1 Crystal- and SAW-based Products

Powered by the fierce growth in the wired and wireless market, quartz crystal and its high frequency version SAW device are being used widely ranging from a simple passive quartz crystal for an electronic toy to a complex synchronous timing module

(STM) for the backbone clocking of the most sophisticated telecom networks as shown in Table 1. As said above, the demand for quartz crystals and crystal oscillators has been increasing steadily between 4 to 10% annually since the "dotcom" market collapse in the 2000~2001. The frequency control products industry landscape has also changed tremendously since the collapse. The author noted the following.

2.1 Explosion of the small size quartz crystal and crystal oscillator market

The tremendous growth of electronic equipment for the entertainment, gaming and portable markets in the past few years propels the demand of smaller and smaller quartz crystals and crystal oscillators to an unprecedented level. Though unthinkable a few years ago, AT-cut quartz crystal as small as 2.0x1.6mm^2 is now being shipped in volume (Fig. 4). Plastic-molded with metal tubular encapsulated 32.768 KHz quartz tuning forks have been available for many years. Recently quartz tuning forks using the traditional AT-cut crystal packaging methods became available in real small sizes- 4.1x1.5, 3.2x1.5 and 2.0x1.2mm^2 (Fig. 5). The thrust now is to push the thickness of such quartz tuning forks to 0.4mm or lower for low profile applications. Applications which need even smaller quartz crystals (1.6x1.0 and 1.0x0.8mm^2) are expected to appear in the next couple of years and quartz crystal manufacturers are getting ready for them.

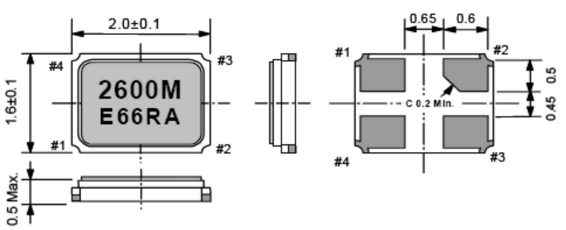


Fig. 4 2.0x1.6mm^2 24~54 MHz Quartz Crystal[7]

Smaller than 5x3.2mm^2 quartz crystals in general need to be sealed in vacuum to sustain impedance integrity. Low MHz small size quartz crystal blanks also need to be beveled (contoured) to sustain efficient energy trapping. Using photolithographic methods to process small size quartz crystal[8] and low MHz frequency quartz crystal[9] are being implemented by several crystal oscillator companies. This though can become a major technical barrier in further miniaturizing quartz crystal for many companies which have been using the conventional lapping method to process quartz crystals. The technical difficulties in quartz crystal plating, mounting, and packaging shall also be as challenging as processing the small size raw quartz crystal blanks.

As for the crystal oscillators, shipping of 2.5x2mm^2 CMOS fixed frequency crystal oscillators (Fig. 6) is in full swing and the yet smaller 2x1.6mm^2 version is available.[10] 2.5V supply voltage is typical nowadays with 1.8V or lower supply voltage market starts to emerge.

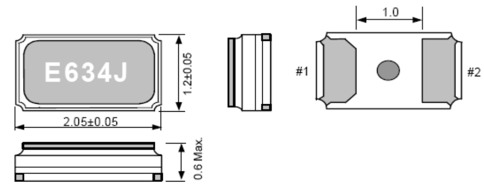


Fig. 5 2.0x1.2mm^2 32.768 KHz Quartz Tuning Fork[7]

The programmable version (PCXO) of the above crystal oscillators is available in 7x5, 5x3.2 and 3.2x2mm^2. These oscillators have on-chip phase lock loop (PLL) which allows programming to almost any frequency within a working frequency range (e.g. 2 to 200 MHz) based on a single low frequency quartz crystal (e.g. 25 MHz). These oscillators are attractive to designers as they can be quickly programmed to the frequencies desired for development purposes. These crystal oscillators do suffer from higher jitter which is inherent to all PLL-based oscillators. Crystal oscillators with differential LVPECL/LVDS output are also available in 14x9, 7x5, and 5x3.2mm^2 platforms. The frequency stability over temperature of the above quartz crystals, crystal oscillators and programmable crystal oscillators is usually specified at less than ±100, 50, and 25 dependent on the temperature range of operation. *Hence, AT-cut quartz crystal is the only known resonant element which can provide such stability without any compensations.*

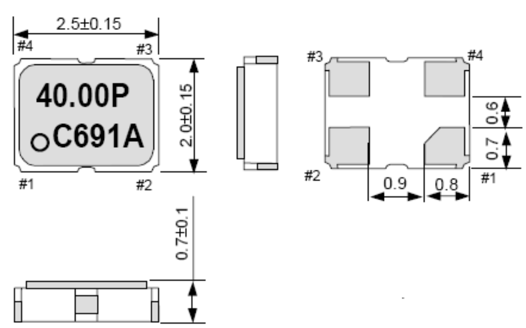


Fig. 6 2.5x2.0mm^2 2~48 MHz CMOS Crystal Oscillator[7]

To provide even better frequency stability, TCXO is available. AT-cut quartz crystal's frequency-temperature stability is cubic. The TCXO oscillator circuit has voltage-frequency pulling function to analogously or digitally compensate the cubic frequency-temperature to the sub-10 ppm over temperature with remarkable frequency change rate over temperature (Fig. 7). For nowadays handset applications, a frequency stability of better than ±2.5 ppm TCXO is usually needed to provide the accurate reference clock for frequency synthesizing. For GPS equipment, TCXO of less than ±0.5 ppm is needed. The smallest TCXO available is 2x1.6mm^2 (Fig. 8).

Overall, in the past decade, quartz crystal and crystal oscillator manufacturers have done the what once thought was impossible- shrinking the sizes of quartz crystal, XO, PCXO, VCXO, and TCXO to where we are and most important of all, without sacrificing performance and cost.[10,11] More and more quartz crystal devices are shipped yearly. The average selling prices of the mature products continue to drop.

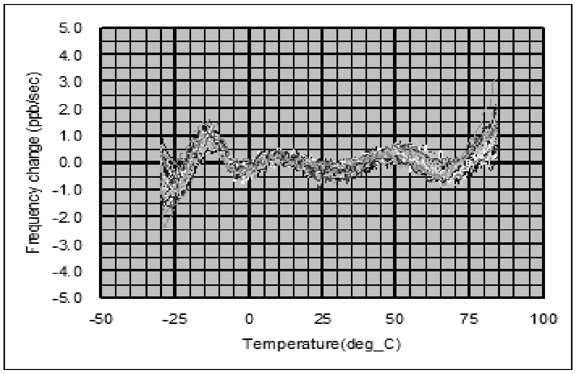


Fig. 7 Frequency Change Rate over Temperature (ramped at 2°C/minute) of 16 MHz TCXO (80 units)

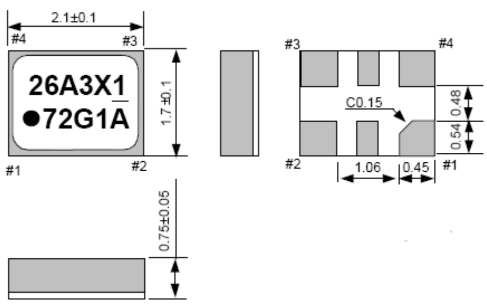


Fig. 8 2.0x1.6mm^2 12~52 MHz TCXO[7]

2.2 Strong growth in high frequency fixed frequency oscillators for the networking and storage market

For many years the fixed frequency crystal oscillator market needs mainly CMOS output (single-end) and less than 70 MHz products. Lower than 70 MHz 3rd OT quartz crystal was considered easy to processs. The thrust was to reduce the size and to lower the supply voltage of crystal oscillators. The recent strong growth in the networking and storage market boosted the demand for differential output (LVPECL and LVDS) oscillators up to 160 MHz. Products are now available in 7x5 and 5x3.2mm^2 platforms from many suppliers. There are three groups of solutions with different performances. The first group consists of the pairing of either a HFF (high frequency fundamental) quartz crystal, a 3rd overtone (OT) quartz crystal, or a fundamental SAW resonator with a traditional feedback loop oscillator IC. The second group pairs a low frequency quartz crystal (20 to 35 MHz) with a simple divider PLL IC. The third group consists of the pairing of a 3rd OT quartz crystal with a higher level PLL IC- e.g. a 3rd OT quartz crystal with an AFM™ (analog frequency multiplier, e.g. x2) IC[12], a 3rd OT quartz crystal with a fully programmable DSPLL oscillator IC[13], etc. The above solutions offer less than 1 ps rms phase jitter (12 KHz to 20 MHz). Except for the SAW solution, the above solutions offer typical AT-cut quartz crystal's cubic frequency-temperature property and ±100, 50 and 25 ppm options are available. Fixed frequency SAW oscillators with quadratic frequency-temperature property are now available from several suppliers. Couple of suppliers offer improved frequency-temperature SAW oscillators.[14-16] When the <160 MHz crystal oscillator market expands, the average selling prices will drop. The author expects in the near future only the 3rd OT quartz crystal and SAW resonator solutions from the first group will be able to compete. The >160 MHz crystal oscillator market is still evolving. If that market materializes tomorrow, the HFF and 3rd OT quartz crystal solutions in the first group will not be able to compete as these quartz crystals will be too expensive to be produced.

2.3 General offering of oscillator IC die

In the past, only a handful of US, European and Japanese crystal oscillator suppliers had accesses to proprietary oscillator ICs. These companies dominated the frequency control products market. Others could only participate in the low-end CMOS oscillator segment or they simply stayed with manufacturing only quartz crystal. Nowadays oscillator IC die for many low- to mid-end XO, PCXO, VCXO and TCXO are available from quite a few IC suppliers (NPC, JRC, Interchip, IDT, Phaselink, AKM, Panasonic, MAS, Glacier, KME, Pericom, Silicon Clocks, EM Microelectronics, et al.). These IC suppliers are willing to work with the crystal oscillator companies to come up with smaller and thinner value-added oscillator IC die for different applications. Many more crystal oscillator companies, especially those from Taiwan, China and Korea, can now compete in more segments of the frequency control products market.

2.4. Timing products companies offering crystal oscillators

As said earlier, the total quartz crystal and crystal oscillator market for 2008 is expected to exceed $4.1B. The participants in this market are usually categorized as "crystal oscillator suppliers" and some of them also offer some SAW-based products like filter, resonator, and oscillator (the $4.1B doesn't include revenues from suppliers like EPCOS which produce SAW products and not crystal products). There is another group of suppliers which provides products for clock buffering, clock generation, clock distribution, etc.[17] The participants are usually categorized as "timing products suppliers." The timing products market is expected to reach $1.8B in 2008. In almost all situations, users will still need to acquire quartz crystals or crystal oscillators from the "crystal oscillator suppliers" to pair with the timing products they purchase. In the past, crystal oscillator suppliers and timing products suppliers supported their own customers and they seldom crossed paths. Things began to change in 2004. IDT (ICS then) became the first "timing products supplier" to offer 7x5mm^2 PLL-based crystal oscillator (with quartz crystal inside).[18] Since then, a few more IC companies (Silabs, Maxim, ON Semi, et al.) began to offer 7x5 and 5x3.2mm^2 XO/VCXO for the networking and storage market as discussed in Sec. 2.2 and the high-end telecom market which is discussed in Sec. 2.6 (Fig. 9).

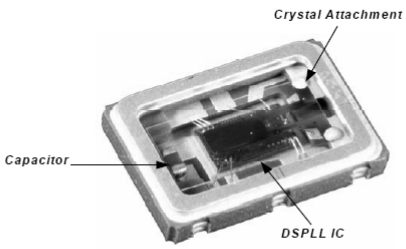


Fig. 9 Silabs' Si5XX Series 7x5mm^2 XO/VCXO[19]

These products compete head-on with those from some of the established crystal oscillator suppliers. One US timing products supplier even secured its own quartz crystal capability by acquiring couple of Asian crystal oscillator suppliers. The notion of capturing even just 10% of the $4.1B crystal and quartz crystal and crystal oscillator market is enticing to many. Such participation (or intrusion considered by some) from the timing products suppliers was received by the crystal oscillator suppliers with mixed reactions. On one side it proves the crystal oscillator market is viable as it attracts more players. On the other side it tends to drive down the average selling prices.

2.5 Oscillator performance improvements coming from the circuitry

Many years ago TCXO became the first crystal oscillator which achieved sub-10 ppm stability over temperature using compensation network along with the oscillator circuitry. Later on by making use of the fractional-N PLL circuitry, PCXO became a successful product. The above represented the earliest examples of improving the performance of crystal oscillators through circuitry. Recently, tighter ppm XO ("mildly" temperature-compensated with less than ±15 ppm over wide temperature range of operation[20] and post-seal cap array trimmed to achieve tighter set tolerance at room temperature) became available from some crystal oscillator suppliers. As said earlier, the first PLL-based crystal oscillator with less than 1 ps rms phase jitter (12 KHz to 20 MHz) appeared in 2004. The first fully programmable DSPLL-based CXO/VCXO appeared a year later. Some of these products started out to challenge the VCSO and HFF-based VCXO from the incumbent telecom crystal oscillator suppliers. The above temperature compensation and clock generation schemes played a key role in the recent development of all silicon MEMS oscillator and all silicon clock which are discussed in the second half of this paper. Indeed, the oscillator circuitry improvements happened in the past few years will continue. The author believes the impact on the future of the quartz crystal and crystal oscillator industry will be coming not only from the variants of the resonant element (MEMS resonator, FBAR, RLC, ceramic resonator, etc.) but also from the oscillator circuitry improvements.

2.6 Slow recovery of the telecom market

Many US and European crystal oscillator suppliers suffered 50 to 80% drop in revenues in a short two years during the "dotcom" market collapse as their business strategies were to service mainly the telecom giants with their mid- to high-end quartz crystals and crystal oscillators (HFF inverted mesa crystal, XO, VCXO/VCSO, TCXO, OCXO, and timing module). Several suppliers disappeared during the downturn. The telecom quartz crystal and crystal oscillator market is showing signs of recovery but no one for sure when the market will return at least to the 1999's level. In the meantime, many more crystal oscillator suppliers, who have grown in folds in the markets discussed in Sec. 2.1, are investing in developing mid- to high-end crystals and crystal oscillators to prepare for the telecom market return. Suppliers who suffered during the downturn will be glad to see the market return but they will find more competitors out there and the telecom customers will demand lower prices.

2.7 DIP-type AT-cut quartz crystal

As said above, even though small size 32.768 KHz quartz tuning forks (4.1x1.5, 3.2x1.5 and 2.0x1.2mm^2) are now available, the plastic-molded versions (with metal tubular encapsulated quartz tuning forks) are still selling well as many customers either don't need or don't want to pay premium for the smaller parts. As the market for small size quartz crystal (5x3.2mm^2 and smaller) continues to grow, the demand for its less expensive and bulkier counterpart DIP-type AT-cut quartz crystal (average selling price in the cents) also rises. These quartz crystals are produced in very high volume in China as the Chinese quartz crystal suppliers can source all the raw materials (metal base, metal lid, and quartz crystal) within China. Even the Taiwanese quartz crystal suppliers can't produce them with profits in Taiwan.

3. All silicon MEMS oscillator

Suggesting to use MEMS techniques to build the resonators for oscillator applications is not something new.[21] Quartz crystal resonator's vibration is based on piezoelectric excitation. They resonators come in simple planar round or rectangular shapes with top and bottom electrodes.

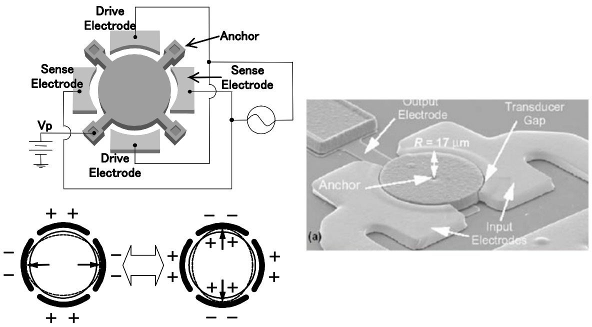
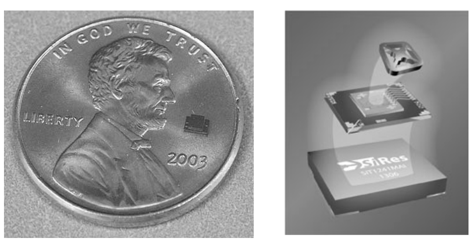


Fig. 10 Electrostatic Dynamics of Disc-Like MEMS Resonator[22,23]

All silicon MEMS resonator's vibration is based on electrostatic dynamics and it is usually micromachined from silicon. All silicon MEMS resonators come in different complicate shapes like comb, beam web, disc, etc. surrounded by driving and sensing electrodes with "transducer gaps" typical less than 1 µm (Fig. 10).[22,23] All silicon MEMS resonators can be very small and so they are rugged. Integration, though will be difficult, is possible.



(a) (b)

Fig. 11 (a) Discera's 3x3mm^2 MEMS Oscillator[4] and (b) SiTime's MEMS Oscillator[5]

In 2003, Discera offered its first 19.2 MHz all silicon MEMS oscillator for multiband wireless transceiver application (Fig. 11a). The resonator was a 30µmx8µm^2 MEMS beam. In 2004, Discera also demonstrated the first integrated 1.6 GHz tunable oscillator, likely for the VCO (usually discrete RLC-based) of the local oscillator in wireless transceiver applications. Discera's earliest effort in replacing components in the RF section of handsets was clear. However, as of today, no detailed specifications of the above two oscillators are available in the public domain and it's difficult to assess their acceptability in the commercial market. In 2006 SiTime introduced its first families of MEMS oscillators (Fig. 11b)- the SiT8002 series programmable MEMS oscillator and the SiT1 series fixed frequency MEMS oscillator (programmed from SiT8002). These all silicon MEMS oscillators were available in 7x5, 5x3.2, 3.2 and 2.5x2mm^2- clearly targeting at the pin-to-pin compatible quartz crystal oscillator market. The "turmoil" created in the quartz crystal and crystal oscillator industry by the intense marketing of such all silicon MEMS oscillators surpassed the earlier announcements of the offering of crystal oscillators by couple of timing products suppliers as said in Sec. 2.4.

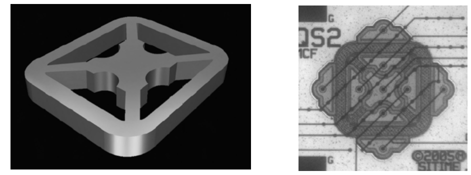


Fig. 12 MEMS Resonator based on 4-Beam Structure[5]

The key success over previous MEMS efforts, according to SiTime, was that "the clean and high vacuum sealing technology developed was able to minimize contamination and to support low aging of the MEMS resonator."[24,25] The SiT8002 and SiT1 series oscillators started out with a packaged 4-beam MEMS resonator (Fig. 12) wirebonded onto a leadframe-supported oscillator IC, and the whole assembly was then plastic-molded.

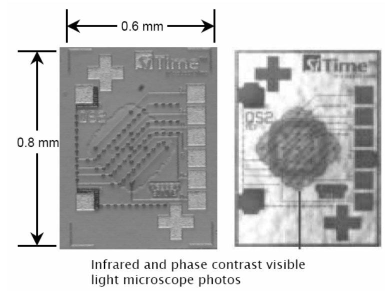


Fig. 13 Packaged 0.8x0.6x0.15mm^3 MEMS Resonators[5]

Little information was available on the MEMS resonator until SiTime announced the offering of it as a SiT0100 part (Fig. 13). The MEMS resonator (0.8x0.6x0.15mm^3) operates at ~5 MHz with 6-pad connection which is different from the familiar 2-pad connection of a quartz crystal resonator (all silicon MEMS resonators need a biased voltage). The know-how in driving the MEMS resonator, the equivalent parameters, the programming methodology of the oscillator, etc. are only available under a non-disclosure fees-associated agreement. No commercial available oscllator ICs are known to be available in pairing with the MEMS resonator.

The SiT8002 series MEMS oscillators[26] have a 5 MHz all silicon MEMS resonator inside and the oscillator output frequency is programmed via a fractional-N PLL- similar to the PCXO mentioned in Section 2.1 (Fig. 14). As said earlier, AT-cut quartz crystal is the only known resonant element which can provide less than 100 ppm stability over temperature without any compensations. All silicon MEMS resonator exhibits an inherent -20~-30 ppm/°C frequency-temperature stability. To achieve the frequency stability claimed by the MEMS oscillator suppliers, temperature compensation is needed- similar to the TCXOs mentioned in Section 2.1 (a simpler linear compensation).

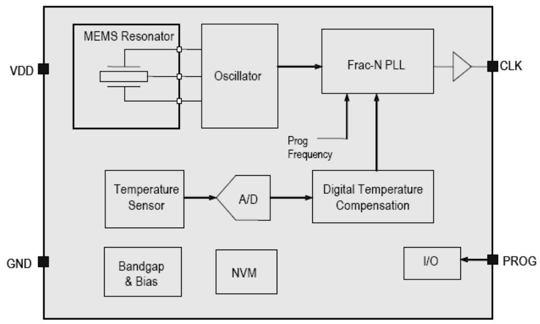


Fig. 14 SiT8002 System Architecture (0.18μm CMOS)[5]

In summary, the current generation of all silicon MEMS oscillators needs to be-

programmed to frequency (like PCXO) and
programmed to compensate frequency stability (like TCXO).

A PCXO needs to go through the following steps after encapsulation- test, program, and test (all done at room temperature). A TCXO needs to go through the following elaborate and costly steps after encapsulation-frequency-temperature test (over the temperature range of operation), compensation, and verification test (over the temperature range of operation). Since the all silicon MEMS resonator exhibits a more linear like frequency-temperature stability, compensation at couple of temperature points near to the room temperature might be adequate to achieve ±50~100 ppm stability. To attain better stability, compensation over a wider temperature is likely needed. Anyhow, extra programming and compensation steps before final test add cost. Study is on-going to temperature-compensate the all silicon MEMS resonator with the deposition of silicon dioxide. Some successes have been recorded.[27] However, the lossy silicon dioxide tends to de-Q the MEMS resonator quickly.

As said in the Introduction Sec.- the strong marketing push of the all silicon MEMS resonators and oscillators seemed to re-ignite the interest in displacing the quartz crystal technology and to open up again the prospect in clock source integration and as said above- the “turmoil” created in the quartz crystal and crystal oscillator industry by the recent intense marketing of such MEMS oscillators surpassed the earlier announcements of offering of crystal oscillators by couple of timing products suppliers. The first formal qualitative review from the quartz crystal and crystal oscillator industry on the all silicon MEMS resonator and oscillator appeared in Dec. 2006 by a Taiwanese supplier.[1] The second qualitative review appeared in June 2007 by a Japanese supplier.[28] The first detailed quantitative comparison (Figs. 15 & 16) of all silicon MEMS oscillators and crystal oscillators (7x5 and 5x3.2mm^2) appeared in May 2008 by a US supplier.[29]

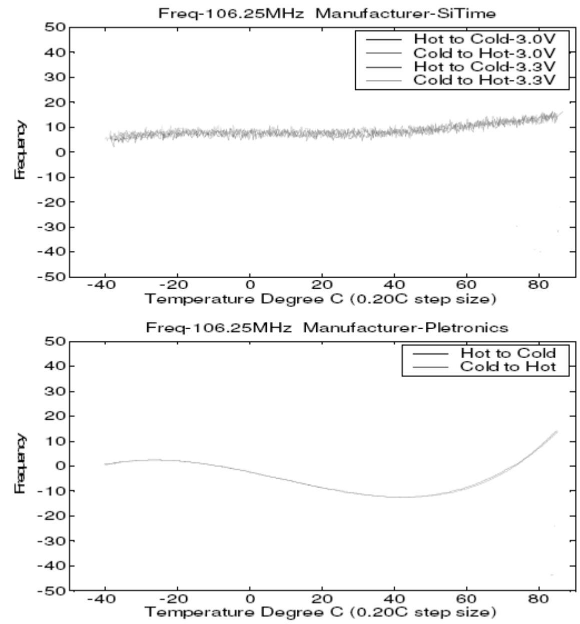


Fig. 15 Frequency Change vs Temperature of 106.25 MHz All Silicon MEMS Oscillator and Crystal oscillator[29]

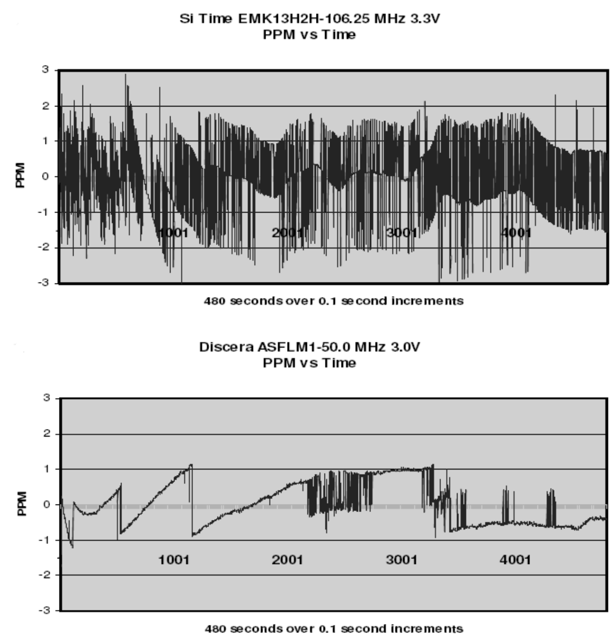


Fig. 16 Short Term Frequency Stability of 106.25 and 50 MHz All Silicon MEMS Oscillators[29]

Based on the data in [29] and discussions among the crystal oscillator suppliers, the following can be observed-

Digital temperature compensation can easily bring the stability to ±10 ppm or even lower. However, perturbation (frequency pulsation) of a few ppm is observed. This resulted in poor *short term stability with excessive phase noise and jitter.*

Current consumption is lower for one supplier and higher for the other one when compared with similar crystal oscillators.

Startup time is longer when compared with similar crystal oscillators. One supplier's startup time is long and it exceeds the typical spec of 10 ms.

Aging (long term stability) is comparable with crystal oscillators.

Many applications serviced by crystal oscillators now need smooth frequency transition over temperature and time (Fig. 7). The current generation of all silicon MEMS oscillators doesn't seem to be able to provide that and in general they don't perform to specifications. All silicon MEMS oscillator though can indeed be very rugged, small, and thin (down to 0.25mm recently). The author expects them to find initial applications in some niche markets.

4. Piezoelectric-activated silicon MEMS oscillator

In the past few years, intense studies of piezoelectric-activated silicon MEMS resonators and oscillators have been observed (Fig. 17). The bulk of the motion of this sort of resonators is from the silicon. However, the motion is induced through the excitation of piezoelectric thinfilms (e.g. AlN, ZnO, etc.) deposited on the silicon.[30~32] The configuration is like a hybrid version of quartz crystal (piezoelectric excitation) and all silicon MEMS resonator (silicon vibration).

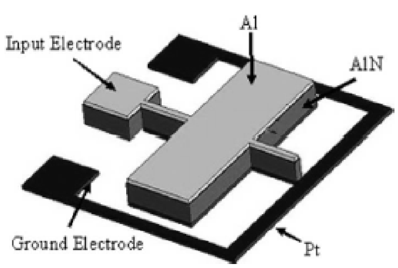


Fig. 17 Schematic Representation of One-Port AlN Contour-Mode Rectangular Plate Resonator[30]

Some studies claimed high vacuum sealing might not be needed to maintain modest Q for this sort of hybrid silicon MEMS resonators (all silicon MEMS resonators must be sealed in high vacuum). FBAR (also coined BAWR nowadays by some), with its small size, photolithographic patterning process, silicon etching process, and sacrificial layer removal step, can be considered a MEMS component. Piezoelectric-activated silicon MEMS resonator is similar to FBAR in some aspects. The bulk of the motion in FBAR is from the AlN thinfilm. FBAR filter and duplexer are the only new piezoelectric frequency control components which penetrate successfully in the handset applications in the last few years.[33] One optimistic view in pushing the development of the piezoelectric-activated silicon MEMS resonators came from the successful development of FBAR filter/duplexer. Some think all silicon MEMS resonator technology may not seem to be ready and a hybrid version like the piezoelectric-activated silicon MEMS resonator may stand a better chance to succeed.

5 Quartz plus MEMS- QMEMS

Unknown to many, quite a few quartz crystal (and SAW) components are being manufactured with some MEMS processing steps- double-side photolithography, non-planar metallization, etch through, sacrificial layer deposition and removal, Au etch protection, etc. These products include quartz tuning fork, quartz gyro-sensor, bi-mesa type quartz crystals (Fig. 18)[34], Lamé mode quartz crystal[9], etc. In fact, the non-planar metallization schemes for quartz tuning fork, the resistant to etching due to the hardness of quartz crystal, the different etch rates of the highly anisotropic quartz crystal, etc. make the processing of these miniaturized quartz crystal products more technical challenging when compared with many silicon-based MEMS processes. Epson-Toyocom Corporation coined the term "QMEMS" couple of years ago in recognizing the importance of linking the quartz and MEMS technologies for the next generations of quartz crystal devices.[8]

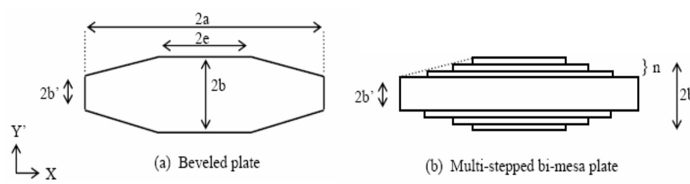
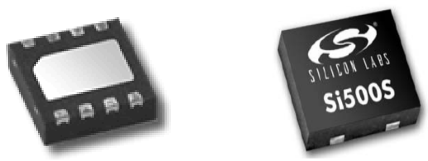


Fig. 18 (a) Beveled Quartz Crystal and (b) Bi-Mesa Quartz Crystal[34]

6. All silicon oscillators

All silicon oscillators (a.k.a. CMOS oscillators, silicon clocks) are integrated circuits without using ceramic resonators, quartz crystals or other off-chip components for operation. The frequency stability of these oscillators is usually from 5,000 to 15,000 ppm (0.5 to 1.5%) and so their applications are somewhat limited. All silicon oscillators have RLC resonant elements which can be integrated onto many silicon-based IC platforms. These oscillators are good alternatives to crystal oscillators in applications where size and cost are important but absolute frequency accuracy is not. One key advantage is their ruggedness (especially suitable for high shock and vibration applications) as they have no discrete mechanical resonant elements (no moving parts). Their biggest disadvantage is clearly their poor frequency stability. In 2005 Mobius Microsystems, a proponent of all silicon oscillator technology, announced the offering of the "all-silicon

Copernicus Clock with 2,500 ppm (0.25%) frequency stability over process, voltage, and temperature."[35] Recently, using on-chip temperature-compensation, Mobius Microsystems claimed its CMOS Harmonic Oscillator (CHO) could achieve close to ±100 ppm stability (CMOS output only) which would find applications in some segments of the consumer, storage, computer peripherals, and automotive markets (Fig. 19a).[36]



(a) (b)

Fig. 19 (a) Mobius Microsystems' 3x3mm^2 CHO[37] and (b) Silabs' 4x3.2mm^2 Si500S Silicon Oscillators[38]

Silabs, an IC company which began to offer crystal oscillators in 2005 as discussed in Sec. 2.4, recently announced the offering of their all silicon oscillators (CMOS and differential outputs, likely temperature-compensated also) with 100~150 ppm stability (Fig. 19b). The 4x3.2mm^2 pin layout of the Si500S DFN package seems to be able to drop straight onto the current 5x3.2mm^2 crystal oscillator landing pads.[38] In summary, this new generation of all silicon oscillators seems to pose greater threat to the quartz crystal and crystal oscillator industry than the MEMS solutions as it is truly integrable. But again its acceptance by customers is too early to tell.

7. Discussions

In Sec. 2 the author reviewed the current status of the quartz crystal and crystal oscillator industry. On one side, the industry is quite at ease with its standing in the high-end market (*high stability* telecom crystal, XO, VCXO/VCSO, TCXO, OCXO, etc.) as the non-quartz solutions (MEMS oscillator, all silicon oscillator, etc.) don't seem to pose any threat in the foreseeable future. The industry is looking forward to the full recovery of the telecom market. On the other side, the industry is continuing its successful efforts in the last decade which include

i*nnovation,*
miniaturization,
cost reduction,
performance improvement,
ease of use improvement,
reliability improvement, and
development of new applications

of low- and mid-end crystal, XO, PCXO, VCXO, and TCXO to maintain its position as "the clock solution" for the electronics industry. The thrust is to provide the best and cost effective quartz solutions so customers hesitate to consider using anything else. Of course there are lessons to learn for all who participate in the frequency control products industry in the last two years since the aggressive launching of the all silicon MEMS oscillators and the recent modest launching of the temperature-compensated all silicon oscillators.

7.1 Quartz crystal and crystal oscillator market

In many applications designers in general prefer to use crystal oscillators in the early stages of product development and product life. When a product enters wide acceptance, designers tend to switch to use quartz crystal as part of the cost down efforts. Suppliers usually can sell crystal oscillators for certain applications for some durations. This is especially true in the low- and mid-end crystal oscillator markets. That's the reason annual quartz crystal shipment (number of devices) is in general 5~6 times more than that of the crystal oscillator. That's also the reason DIP-type AT-cut quartz crystals as discussed in Sec. 2.7 are still selling well as they are the least expensive quartz crystals one can get. The current MEMS oscillator and all silicon oscillator efforts, if proven viable, can only compete in the crystal oscillator market. Quartz crystal and crystal oscillator technology is considered quite mature and it has taken decades to achieve such "perfection". Yet manufacturers still struggle daily with yield issues stemming from drive level dependency (DLD), negative resistance margin, frequency jumping, etc. Participants in the development of non-quartz solutions need to truly understand the quartz crystal and crystal oscillator industry in order to compete with it.

7.2 Customers' perspectives on new technologies

As early as in 2003, Forman commented "the challenge for Discera is in convincing customers to abandon an entrenched, known technology (quartz crystal technology) in favor of something new- convincing them to go with the devil they don't know."[39] Indeed, customers are more familiar with and have confidence on quartz crystals and crystal oscillators. Quartz crystal and crystal oscillator suppliers have been able to satisfy the customers' expectations on price, performance, quality, reliability, and delivery in the past decade. For a new technology to be successful in displacing the quartz crystal and crystal oscillator technology, it must have to do more other than simply offering the perspective of "it would be a cheaper solution". Even if the technology is viable, it may be best being pushed by the crystal oscillator suppliers whom the customers have confidence with. This seems to apply to the timing products suppliers who began to offer crystal oscillators (with quartz crystal inside) in 2004 as discussed in Sec. 2.4. Customers tend to go to crystal oscillator suppliers whom they are familiar with if they need crystal oscillators. That's one reason, except for one or two suppliers mentioned in Sec. 2.4, the timing products suppliers in general find it difficult to sell crystal oscillators directly to customers.

7.3 Customers' perspectives on integrated solutions

Customers prefer integrated solutions. Integration was a key selling point for FBAR in the early days as it could possibly be integrated onto the silicon-based handset transceiver IC platforms.[40] About 20 to 25 years ago, thin film resonators (TFRs) were vigorously discussed and researched. After that it came 5 years or so of a quiet period. In 1994, HP personnel presented the first report on film bulk acoustic resonator (FBAR)[41] and in 2001 Agilent announced the production of FBAR duplexers. FBAR, with its small size, silicon etching process and sacrificial layer removal step, can be considered as a MEMS component. As said in Sec. 4, FBAR filter and duplexer are the only "new" piezoelectric frequency control components which penetrate successfully in the handset applications in the last few years. Interestingly, they are still packaged individually like the RF SAW devices. As said in Sec. 7.1 designers accomplish cost-down through the use of quartz crystals. If a low-cost crystal is not functioning well (in general not likely), a designer can simply replace it with another one. If an on-chip resonant element like a MEMS resonator is not functioning well, the designer will have to discard the entire IC chip. The scenario applies to FBAR also. FBAR integration is not likely to happen in the foreseeable future. Instead, FBAR efforts now are more on the development of high frequency oscillators.[42] Overall, customers prefer proven and least expensive solutions than potentially integrable solutions.

7.4 Lesson to learn from FBAR

Two factors contributed to the successful launching of the first FBAR product (or any products)- right product and specification compliant product. First, Agilent picked a product which SAW technology wasn't able to do then- PCS duplexer with narrow transmitting and receiving separation. Agilent attached a FBAR transmitting filter and a FBAR receiving filter on an unsightly FR-4 board and the assembly became a duplexer. It was much smaller than the dielectric resonator duplexer solution then. Second, Agilent was successful in overcoming the technical difficulties in depositing high quality AlN thinfilms which plagued many researchers earlier. The product, though not grand in appearance, met all specifications. The product was a success. The FBAR technology established the confidence from the customers and respect from the competing SAW product suppliers (small size PCS SAW duplexer is also available now). The recent aggressive launching of all silicon MEMS oscillators succeeded in the aspect of offering the "right" products as they were pin-to-pin compatible to the crystal oscillators. Customers could supposedly drop them into current crystal oscillator sockets. However, data indicated the products exhibited some issues as discussed in Sec. 3. The all silicon MEMS oscillators tested in [29] came from distributors. Customers would expect them to perform 100% to specifications. After all, customers aren't really concerned with what inside an oscillator- may it be quartz crystal, MEMS, or other resonant elements. Customers care more about price, performance, quality, reliability, and delivery (multiple sources) of the final products.

7.5 Continuous improvements

The quartz crystal and crystal oscillator industry needs to continue monitoring the development efforts of the MEMS oscillator and all silicon oscillator. Evidence is clear that oscillator circuitries especially those based on PLLs will get better and better as time progresses. As said in Sec. 2.5., the author believes the future impacts on the quartz crystal and crystal oscillator industry will be coming not only from the variants of the resonant element (MEMS resonator, FBAR, RLC, ceramic resonator, etc.) but also from the oscillator circuitry improvements. In the future circuitry improvements may surprise us by totally compensating the deficiencies of the non-quartz resonant elements. Comfortingly, the quartz crystal and crystal oscillator industry is not done with quartz. The author commented in a 2004 paper[14]- *Quartz continues to be the material of choice for stable temperature SAW applications. From the early investigations of generalized surface acoustic wave, STW, and LSAW to the recent development of HVPSAW, SAW researchers continue to gain new insights in what this material can offer… In the earlier days of SAW filter development, electrode finger reflection was to be supressed to reduce passband ripples. Finger reflection today instead is the corner stone allowing us to realise low-loss SAW filters. As in other sciences, SAW researchers sometimes need to slow down and look back what we missed in the past. What was "bad" in the past may now be important. With persistent study of this material, we shall see more surprises in the future.* More surprises hopefully will also come from the quartz crystal and crystal oscillator industry.

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