Microchip Oscillators and Clocks Using Microelectromechanical Systems (MEMS) Technology

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OVERVIEW

For decades, oscillators and clocks have relied on quartz crystals for the creation of a stable frequency reference. Crystals perform very well for many applications. However, microelectromechanical systems (MEMS) technology, replacing quartz crystals with MEMS resonators, entered the marketplace ten years ago and is rapidly maturing.

MEMS-based timing devices offer high reliability (including AEC-Q100 certification for automotive use), extended operating temperatures, small size, and low power consumption. Video surveillance, automotive ADAS, general industrial applications, and data transmission to 10 Gbps are prime areas of usage today. The next milestone will be next-generation MEMS resonators that achieve very low phase noise for high-end communication systems.

Microchip acquired MEMS timing technology through the purchases of Discera and Micrel in 2015. Since Discera shipped its first production oscillators in 2008, almost 100 million devices have been manufactured and sold.

This paper describes the benefits of a MEMS-based solution, the resonator technology, and the design of the final product.

KEY FUNCTIONALITY

Microchip's MEMS-based oscillators and clocks offer benefits over traditional quartz solutions (Figure 1). These include stable frequency, small size, high reliability, flexibility, many programmable features, fast guaranteed start-up, and high integration.

	Traditional Crystal Oscillator	Microchip MEMS-Based Oscillator	Features
Frequency Stability Over Temperature	◐	●	■ MEMS offers ±10 ppm over wide temperature range ■ Microchip quartz achieves superior aging
Size	◕	●	■ MEMS offers ultra-small footprints (1.6 × 1.2 mm) ■ Leads industry trend in size reduction
Reliability	◐	●	■ MEMS wafer-stage ultra-clean hermetic seal ■ Microchip quartz separates crystal and ASIC enclosures
Jitter Close-In Phase Noise	◕	◐	■ Microchip quartz is superior with reduced close-in phase noise ■ MEMS and quartz comparable at high-frequency offsets
Features	○	●	■ Selectable frequencies from one output ■ OTP programmable at any frequency, anytime
Start-Up	◐	●	■ MEMS achieves fast start-up time (<2 ms) ■ Eliminate start-up issue of crystal-based designs
Integration	○	●	■ Multiple outputs from a single device ■ Utilizes highly integrated ASIC

● Best ○ Worst

FIGURE 1: *Benefits of Microchip MEMS-Based Oscillators and Clocks.*

MICROCHIP RESONATOR TECHNOLOGY

The FFS Resonator

Microchip's MEMS resonator products evolved out of research at the University of Michigan. That work was some of the earliest to take existing MEMS resonator technology and begin to mold it to fit real wireless and timing applications. The Microchip resonator design is referred to as the FFS resonator, or Free-Free beam Short support resonator, which was an iteration on the Free-Free Beam resonator pioneered at U of M. The FFS design, shown in Figure 2, uses short anchor supports to make the design more rigid, and consists of a wide resonator beam to improve its power handling—a critical feature for oscillator design. The beam contacts the substrate at only the four anchor locations and sits above it, separated by a narrow gap that leaves the resonator free to move. The FFS resonator itself is extremely compact compared to quartz crystals, measuring only 50 µm x 30 µm for an 18 MHz device.

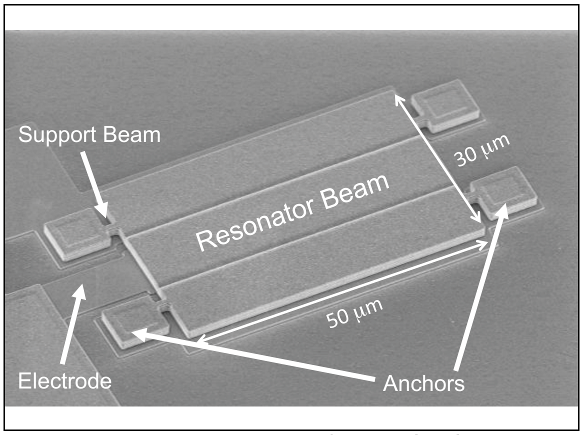

FIGURE 2: SEM of a Production FFS Resonator Beam.

Like quartz crystals, the MEMS resonator relies on a very precise mechanical vibration to provide an accurate frequency output, and the FFS resonator behaves very much like the classical example of a freely-supported, vibrating beam. In fact, it is similar to a xylophone key, which is itself a form of freely-supported beam resonator. And, as with the xylophone, the FFS will only "ring" at a very specific frequency, which can be selected based on material properties along with geometry (length, width, and thickness). Figure 3 is an exaggerated representation of the vibration or "mode shape" during operation, showing how the beam displaces along the short axis, perpendicular to the substrate. The plot of displacement in Figure 4 shows the reason the beam is "freely" supported—there are two locations along the length of the beam that have zero vertical displacement. These make perfect sites for the short support tethers that have little effect on the frequency of the beam and minimize vibrational energy loss to the substrate. This, in turn, maximizes its quality factor and frequency selectivity.

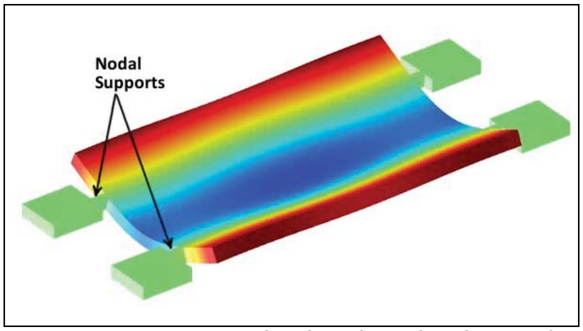

FIGURE 3: Simulated Mode Shape of the FFS Resonator, Showing the Out-of-Plane, Flexural Mode in Which it Operates.

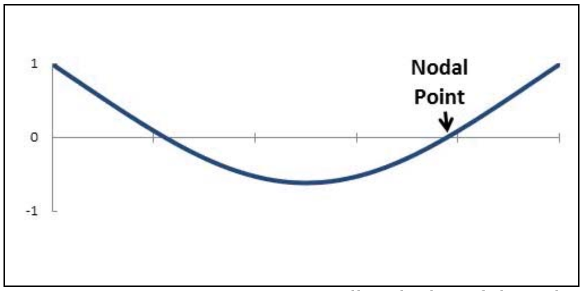

FIGURE 4: A Normalized Plot of the Displacement Along the Beam, Highlighting the Zero Displacement Nodal Points.

Using the mechanical beam in an electrical circuit requires conversion between electrical and mechanical energy. Quartz crystals use piezoelectric transduction to accomplish this task, but integration of piezo materials in a high quality, micro-scale design is challenging. The FFS resonator uses an electrostatic transducer based on the principle that two electrodes held at differing voltages will generate a force between them. So, to this end, a single drive electrode underlies the beam separated by an air gap. Together, the electrode and beam form a parallel plate capacitor, and an input signal in the form of an AC voltage induces a force on the beam, perpendicular to the substrate causing it to move. If the input signal falls at the mechanical frequency of the device, the force is effectively multiplied several thousand times over, resulting in vibration at the resonant frequency. With the vertical motion of the beam relative to the fixed bottom electrode, the transducer gap behaves like a time-varying capacitor, which, when biased, produces an output current at the resonant frequency. As mentioned, the figures show an exaggerated motion; the actual displacement of the beam is only about 1-2% of its thickness.

First Generation Packaging (G1)

Resonator design is important, but packaging of the device is also critical. Crystal resonators have historically relied on hermetically sealed metal and/or ceramic packages in order to isolate and protect them. With MEMS resonators, which require vacuum packaging to achieve high quality factors, the capping and sealing process can be integrated directly into the fabrication process, yielding high-density, wafer-level packaging in a batch process that both reduces cost and improves reliability. The resulting wafer-level package can also be used in a wide array of IC packages from ceramic to the full range of injection molded packages to chip-scale packaging.

The first Microchip legacy product to meet both device and packaging requirements was referred to as G1.0. It consisted of the FFS device design of Figure 2 packaged inside a vacuum cavity created using a silicon cap wafer bonded to the substrate with glass frit. A getter material deposited on the cap ensured that vacuum levels were maintained for long-term reliability. Bond pads were located on a ledge outside the seal area. That package went in to the first commercially available, MEMS resonator-based oscillator, which began shipping in volume in 2008. Despite the somewhat fragile nature of glass frit, the package was also tested in a military-grade ordinance lab and continued operating following high-impact testing in excess of 30,000g.

Second Generation Packaging (G2.x)

While the glass frit package of G1.0 met the operational requirements for MEMS oscillators, the bonding technology placed lower limits on package size and presented a major bottleneck for miniaturization, yield improvement, and cost cutting. The next (and current) generation of resonator packaging, termed G2.x, moved to wafer level silicon fusion bonding. The fusion bonding process demands very clean wafers, which, when combined with the high temperature bond step, eliminates the need for getter material in the vacuum cavity, further improving process efficiency. The silicon bond also requires far less area than glass frit, and interconnects are made by through-silicon vias, allowing the pads to sit entirely within the vacuum cavity footprint. Overall, these technological improvements yield a 10x decrease in die area over G1, dramatically reducing cost per die.

The fusion bonding process is used today in Microchip's MEMS resonator production. As shown in Figure 5, a cap wafer etched with vacuum cavities is placed above the MEMS resonator wafer. The pair of wafers is pumped down to the target vacuum level and then pressed together inside the bond tool causing the silicon layer on the device wafer to bond to the oxide layer on the cap wafer. Once annealed in a high temperature furnace, the resulting bond is extremely strong; in fact, attempts to break open the package by force will eventually result in fractures in the silicon before the bond itself gives way, yielding a vacuum seal that is even stronger than the surrounding material. Figure 6 is an image of a singulated, capped resonator. The entire package is less than 0.5 mm x 0.5 mm. Figure 7 shows a cross section of the package with both the TSVs and cavity clearly visible. Another advantage of the fusion bond is that it can withstand very high temperatures. Operating temperatures of the MEMS die are limited mainly by the metalization on the exterior of the package (AlCu for current production devices) and can be in excess of +200°C.

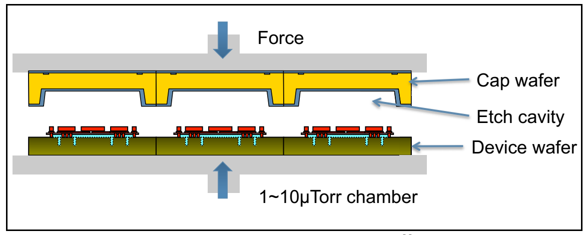

FIGURE 5: Current Bonding Process.

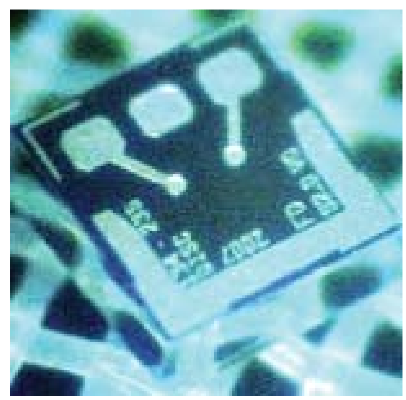

FIGURE 6: Singulated, Fully Packaged MEMS Resonator.

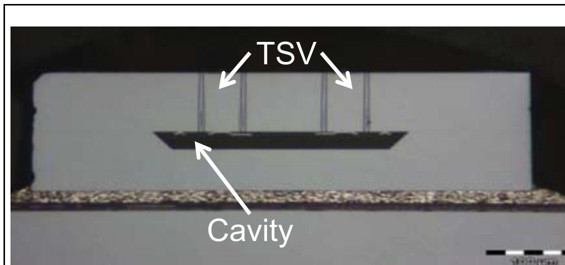

FIGURE 7: Cross-Section of the Packaged Resonator.

The G2 packaging is even more robust than G1. Due to its extremely small mass, the resonator itself can theoretically withstand more than 1,000,000g, though any IC package in which it was contained certainly could not, so a realistic g-limit lies somewhere between the

G1 package at 30,000g and that upper bound, several orders of magnitude beyond what a typical crystal can withstand at around 50g–100g.

Long-term stability, or aging, is also a critical metric for an oscillator. Figure 8 shows a plot of the resonant frequency of eight MEMS devices aged under constant operation at +85°C for 1,000 hours. Average drift is roughly –1.5 ppm over the course of the test (straight line regions in the plot indicate data collection errors; the parts remained powered and at temperature throughout). Figure 9 shows a plot of the calibrated output frequency from 16 different Microchip DSC60xx oscillators under the same conditions. Aging mechanisms in the ASIC cause some spread in the results, but can be limited by careful design. The oscillator shows an average shift of roughly 1 ppm over the course of the aging, closely following the behavior of the MEMS.

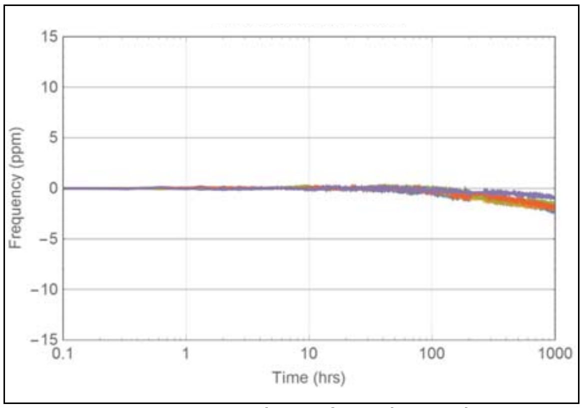

FIGURE 8: *Plots of Device Aging at +85°C for 1,000 hours.*

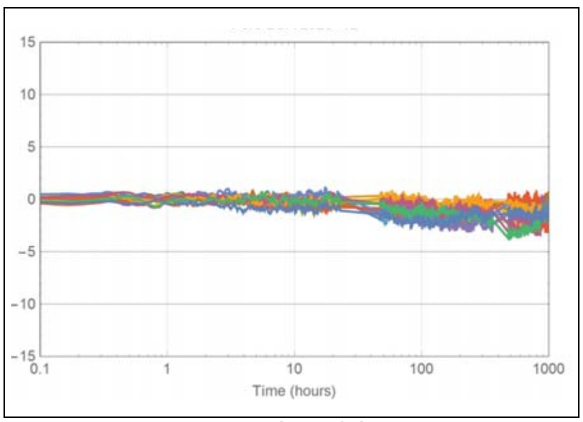

FIGURE 9: *Aging of the DSC60xx.*

Third Generation Resonators (G3 and Beyond)

All products in current production (as of December, 2016) use the G2.x resonators. They provide excellent performance for many XO applications.

A number of design refinements can lead to improved performance for applications that require ultra-low jitter. The G3 resonator, pictured in Figure 10, was designed in order to meet these more demanding applications and to provide reduced jitter and spurs along with the potential for even better temperature stability. The G3 design is a 15th overtone FFS beam resonator operating at approximately 70 MHz. Similar to higher frequency crystals, the resonator utilizes a higher order mode to achieve higher frequency and better performance. In the 15th overtone mode shape, shown in simulation in Figure 11 and simplified form in Figure 12, there are 16 inflection points and 17 nodal points, compared to 1 inflection and 2 nodal points for the G2 fundamental mode design. The result is a much larger resonator with increased transducer area that, when combined with higher stiffness at higher frequency, dramatically increases power handling in-turn improving phase noise and jitter. The higher operating frequency also improves phase noise by reducing the multiplier used in the PLL to up-convert to the VCO frequency.

The G3 resonator was also designed to operate in a differential mode. As shown schematically in Figure 12, electrodes under each inflection point can be grouped together into full, 4-port differential operation. This greatly reduces any common mode noise and interference that could contribute to overall jitter.

While the G3 design offers a path to improved clock purity, other design improvements also lead to improved temperature stability. Overall temperature performance is a complex interaction of factors including temperature sensor accuracy, sensor offsets from actual MEMS temperature, and temperature sensitivity of the MEMS resonator itself. Polysilicon FFS resonators have an inherent temperature coefficient of frequency or *TCf* of about –17 ppm/°C due largely to the decrease in polysilicon stiffness as temperature increases. However, silicon dioxide increases in stiffness with temperature. In a composite resonator structure with alternating layers of polysilicon and oxide, the changes in stiffness can be designed to cancel out, effectively reducing the *TCf* by an order of magnitude or more. This method has been applied to both G2 and G3 designs and has been shown to dramatically improve frequency stability across temperature.

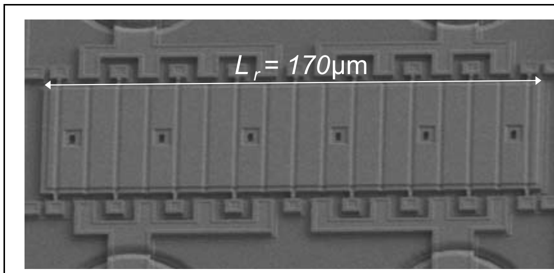

FIGURE 10: *SEM of the G3 Resonator.*

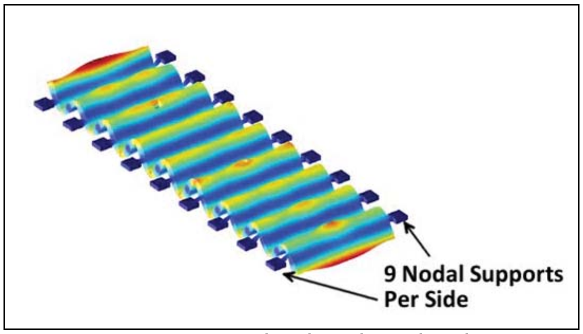

FIGURE 11: Simulated Mode Shape.

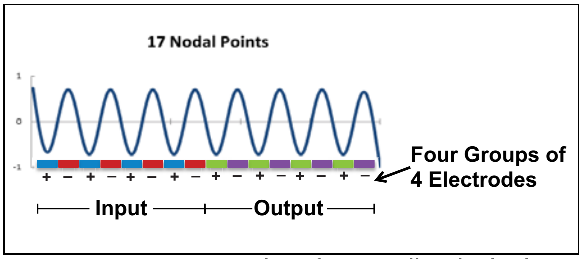

FIGURE 12: Plot of Normalized Displacement Showing the Nodal Points and Electrode Locations for Differential Operation.

SYSTEM DESIGN OF THE OSCILLATOR AND CLOCK PRODUCTS

Packaging and Construction

The MEMS-based oscillator and clock products consist of the tiny MEMS resonator die stacked upon a CMOS ASIC and wire-bonded (see Figure 13 and Figure 14). After plastic injection molding, marking and testing, the final product is created in a plastic VDFN package (see Figure 15).

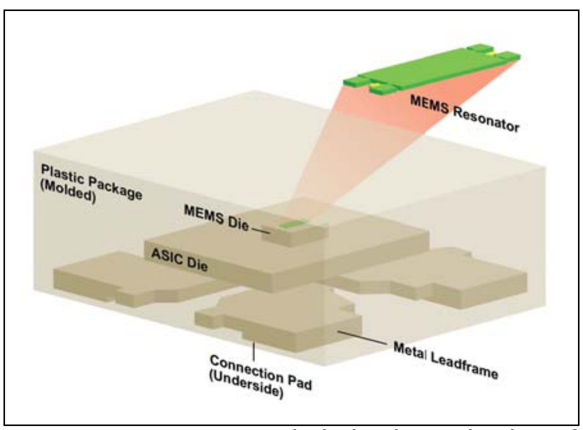

FIGURE 13: Exploded Schematic View of the MEMS Resonator Die Mounted on the CMOS ASIC.

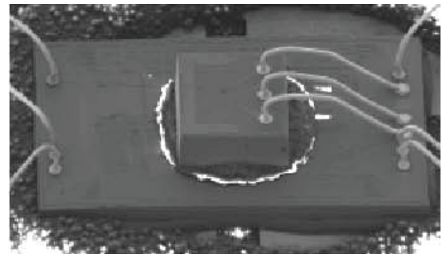

FIGURE 14: Photomicrograph of a Decapsulated MEMS Oscillator.

FIGURE 15: Finished Product in VDFN Package.

System Architecture

As an example of a typical MEMS product architecture, the DSC2xxx is described in Figure 16. This comprises the MEMS resonator on the left, connected to the CMOS ASIC on the right.

The resonator die connects to the three ASIC interfaces: res1, res_agnd and res2. The combination of the resonator and the reference oscillator block (REF OSC) create an oscillator whose frequency is governed by the resonator, similar to a quartz crystal oscillator. The resonant frequency of the G2.x resonator used in this product, and the reference oscillator output, is approximately 18 MHz.

This reference oscillator drives a fractional-N phase lock loop (PLL), which translates the frequency to the desired oscillator or clock output. Output frequency resolution is very fine, generally 100 Hz or less. The PLL drives two programmable divider chains (÷N1, N2) and two protocol-programmable buffers (DRIVERS); CMOS, LVDS, LVPECL and HCSL are all obtainable.

An on-chip programmable non-volatile memory (OTP) and a crossbar switch are key to the flexibility of the product. PLL and divider values (setting the output frequency) are stored here, along with other settings including temperature calibration settings, choice of output protocol, rise/fall time control, enable pin pull-up/down, and many more.

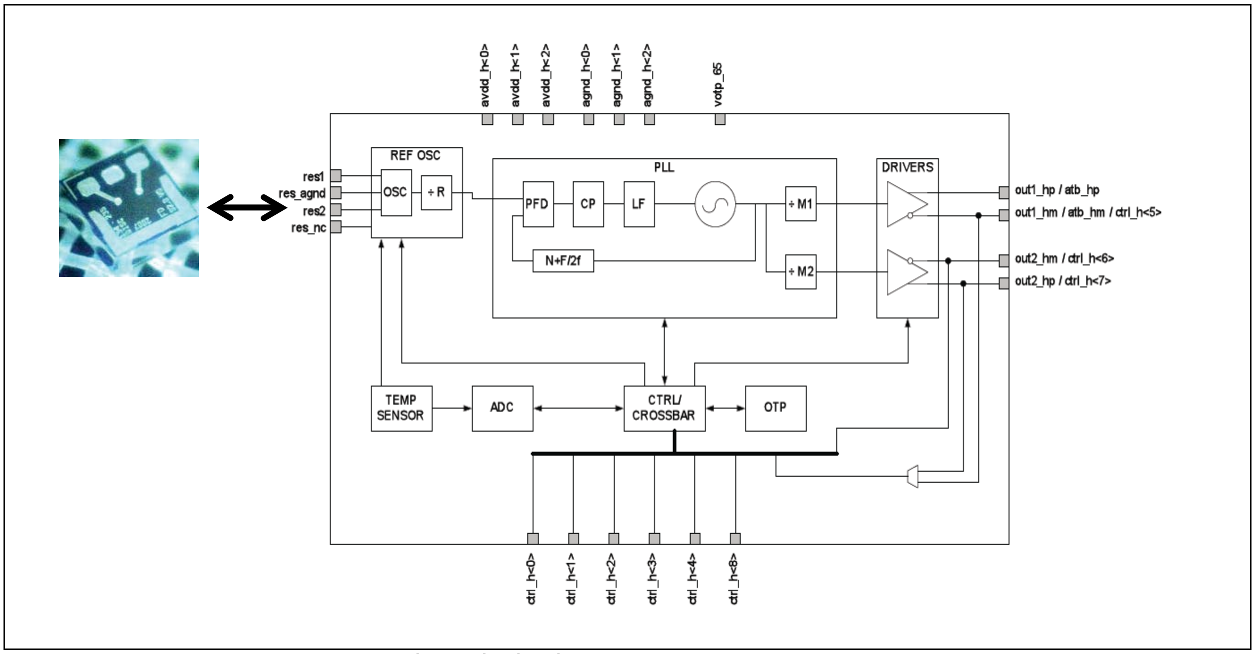

FIGURE 16: *DSC2xxx Product Block Diagram.*

Frequency Stability Over Temperature

The temperature sensor (TEMP SENSOR) produces a digital representation of the die temperature, and this is passed to the fractional-N phase lock loop to correct for natural spreads in the absolute frequency of the resonator, as well as its temperature coefficient. The system is calibrated in manufacturing, with adjustment coefficients programmed into the ROM. The result is an output frequency that is programmable to 100 Hz or so, and extremely stable to ±10 ppm across extended temperature ranges (see Figure 17).

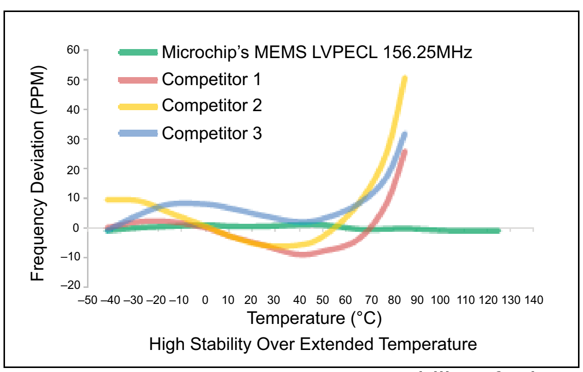

FIGURE 17: *Frequency Stability of Microchip's MEMS Oscillator Compared to Quartz Oscillators.*

Output Clock Jitter

A MEMS resonator produces the lowest jitter if it is driven at a maximum level; however, too high a drive level will produce unwanted frequency shifts. This maximum level varies with die temperature, and the temperature sensor analog output is used to optimize the drive current of the oscillator at all temperatures.

Figure 18 shows the integrated phase jitter of the DSC1xxx and DSC2xxx families, ideal for many networking applications. Different applications are sensitive to phase noise over different frequency ranges; the timing industry generally uses 12 kHz to 20 MHz as a benchmark, dating back to SONET technology. However, today's high speed wired networks, using clock-data recovery locked loops, are tolerant to noise near the carrier (also called "close-in" or "low frequency offset" noise), and are only sensitive to noise in certain bandwidths at higher carrier offset frequencies. The DSC1xxx and DSC2xxx families achieve 450 fs in the 200 kHz to 20 MHz band, suitable for 1 Gigabit Ethernet, and are also qualified for XAUI and PCIe.

MEMS oscillators in production today produce more "close-in" noise (noise at offset frequencies below 5 kHz) than non-PLL fixed-frequency quartz oscillators. This is because the very small resonator produces a low amplitude reference signal closer to the noise floor. At high offset frequencies, this noise is filtered out by the PLL. However at low offset frequencies, it is passed to the output. As explained above, this is a non-issue for most applications, as they are only sensitive to noise above about 100 kHz.

The new G3 generation of MEMS resonators can be driven with more energy and produce even lower phase noise, comparable with fixed-frequency quartz crystal oscillators in the 12 kHz to 20 MHz bandwidth.

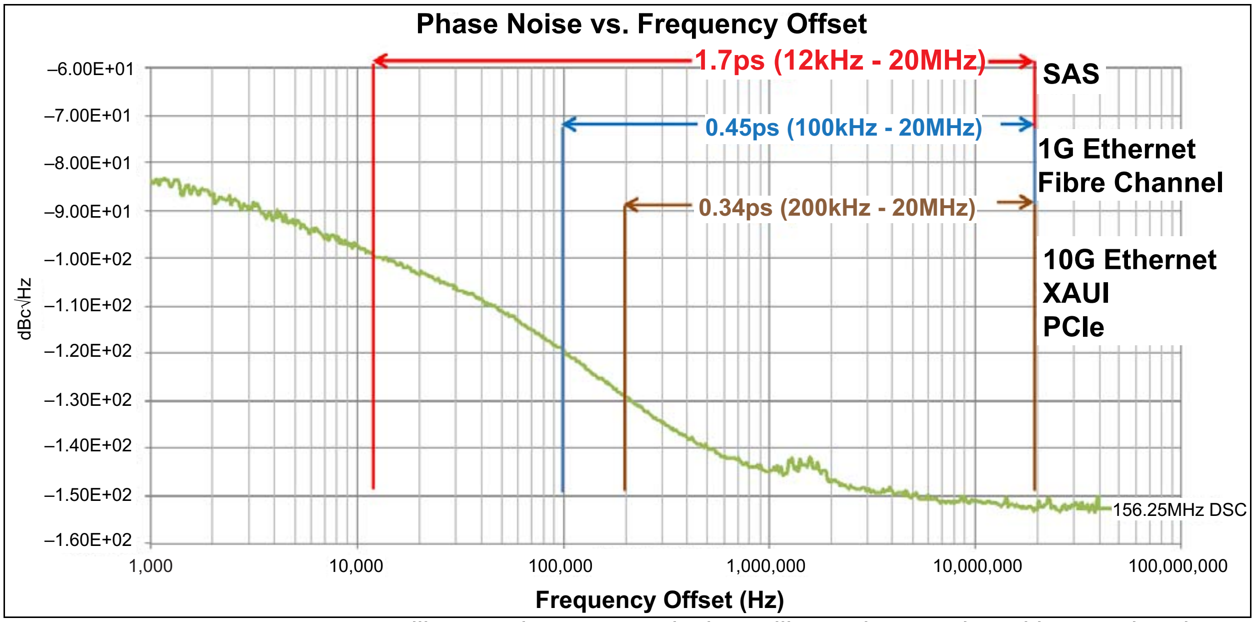

FIGURE 18: *DSC11xx Oscillator and DSC2xxx Clock Oscillator Phase Noise with Associated Networking Applications.*

Features and Integration

Several features have been designed into Microchip's MEMS oscillators and clocks, including:

- Instant selection and programming of output frequency, using the TimeFlash programming tool.
- Fast start-up: from 1 ms to 5 ms.
- Electromagnetic compatibility (avoidance of creating EMI), with programmable rise/fall time and spread spectrum.
- Electromagnetic compatibility (susceptibility to external noise and EM fields): passing the EMC standard EN61000-4-3/4/6.

Size

The newly released DSC6000 product, with a CMOS ASIC not much larger than the resonator die, is available in sizes down to 1.6 mm x 1.2 mm (see Figure 19).

Microchip MEMS Oscillator Reliability

As Table 1 shows, mechanical shock and vibration results from tests complying with MIL-STD-883 show improved performance compared to traditional quartz technology. Reliability data, compiled over several years of production, shows impressive FIT, MTBF reliability, and dppm quality levels.

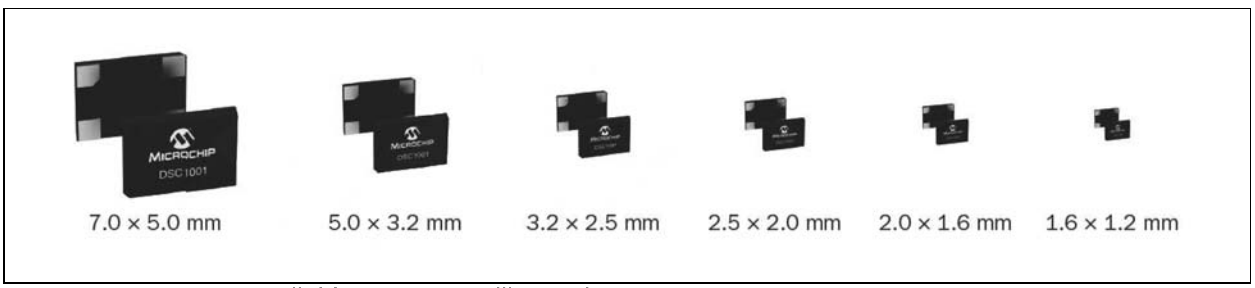

FIGURE 19: *Available MEMS Oscillator Sizes.*

TABLE 1: RELIABILITY DATA

Test	Microchip MEMS Oscillators	Quartz Oscillators	Improvement	Test Condition
Mechanical Shock	50,000g	500g	100x	MIL-STD-883; Method 2002
Vibration	70g	20g	3.5x	MIL-STD-883; Method 2007
Failure in Time (FIT)	1.2	29	24x	Confidence Level = 90%
MTBF	1822 MHr	90 MHr	24x	Confidence Level = 90%
DPPM	<10	100	10x	Over Production Lifetime

MEMS OSCILLATOR AND CLOCK PRODUCT SELECTION GUIDES

Figure 20 and Figure 21 show Microchip's current MEMS products.

Part Number	Output Frequency (MHz)	Output Format	Frequency Stability (ppm)	Jitter (typ) (ps RMS)	Supply current (mA)	Supply voltage (V)	Temp. Range (°C)	Package size (mm x mm)	Custom Configuration
Ultra-Low Power MEMS oscillator*									
DSC60xx	0.002 to 80	LVCMOS	±15/25/50	15	1.3	1.7 to 3.63	-20 to 70 -40 to 85 -40 to 105 -40 to 125	1.6x1.2 4L 2.0x1.6 4L 2.5x2.0 4L 3.2x2.5 4L	
DSC61xx	0.002 to 100			8	2.5				
DSC62xx/63xx	1 to 100 w/ spread Spectrum			10	3				
Low Jitter MEMS oscillator									
DSC1101/ 1121	2.3 to 170	LVCMOS	±10/25/50	1.5	25	2.25 to 3.63	-20 to 70 -40 to 85 -40 to 105 -55 to 125	7.0x5.0 6L 5.0x3.2 6L 3.2x2.5 6L 2.5x2.0 6L	ClockWorks web tool
DSC1102/ 1122	2.3 to 460	LVPECL	±10/25/50	1.5	40	2.25 to 3.63			
DSC1103/ 1123	2.3 to 460	LVDS	±10/25/50	1.5	25	2.25 to 3.63			
DSC1104/ 1124	2.3 to 460	HSCL	±10/25/50	1.5	30	2.25 to 3.63			
Low Power MEMS oscillator									
DSC1001/ 1003/1004	1 to 150	LVCMOS	±10/25/50	10	5	1.62 to 3.63	0 to 70 -20 to 70 -40 to 85 -40 to 105	7.0x5.0 4L 5.0x3.2 4L 3.2x2.5 4L 2.5x2.0 4L	ClockWorks web tool
DSC1033	1 to 150	LVCMOS	±25/50	20	3	3.3			--
DSC1030						3			
DSC1028						2.8			
DSC1025						2.5			
DSC1018						1.8			
Programmable Oscillator									
DSC8101/ 8121	2.3 to 170	LVCMOS	±10/25/50	1.5	25	2.25 to 3.63	-20 to 70 -40 to 85 -40 to 105 -55 to 125	7.0x5.0 6L 5.0x3.2 6L 3.2x2.5 6L 2.5x2.0 6L	TimeFlash Programmer
DSC8102/ 8122	2.3 to 460	LVPECL	±10/25/50	1.5	40	2.25 to 3.63			
DSC8103/ 8123	2.3 to 460	LVDS	±10/25/50	1.5	25	2.25 to 3.63			
DSC8104/ 8124	2.3 to 460	HSCL	±10/25/50	1.5	30	2.25 to 3.63			
DSC8001/ 8003/8004	1 to 150	LVCMOS	±10/25/50	10	5	1.62 to 3.63	0 to 70 -20 to 70 -40 to 85	7.0x5.0 4L 5.0x3.2 4L 3.2x2.5 4L 2.5x2.0 4L	
DSC8002	1 to 150	LVCMOS	±25/50	20	3	1.62 to 3.63			

* New product based on preliminary data, The -40 to 105C and -40 to 125C option will be available in 4Q2016

FIGURE 20: *MEMS Oscillator Selection Guide.*

<table>
<tr><th>Part Number</th><th>Output Frequency (MHz)</th><th>Number of outputs</th><th>Number of PLL</th><th>Output Format</th><th>Frequency Stability (ppm)</th><th>Jitter (typ) (ps RMS)</th><th>Features</th><th>Supply current (mA)</th><th>Supply voltage (V)</th><th>Temp. Range (°C)</th><th>Package size (mmxmm)</th><th>Custom Configuration</th></tr>
<tr><td>DSC2311</td><td>2.3 to 170</td><td>2</td><td>1</td><td>LVCMOS</td><td>±25/50</td><td>1.5</td><td>OE</td><td>25</td><td rowspan="5">2.25 to 3.63</td><td>-20 to 70
-40 to 85
-40 to 105
-55 to 125</td><td>2.5x2.0 6L</td><td rowspan="5">ClockWorks Web tool</td></tr>
<tr><td>DSC20xx</td><td rowspan="3">2.3 to 460</td><td rowspan="3">2</td><td rowspan="3">1</td><td rowspan="4">LVCMOS
LVPECL
LVDS
HSCL</td><td rowspan="4">±25/50</td><td>1.5</td><td>OE/FS
(up to 8 freq per output)</td><td rowspan="3">25 - 76</td><td rowspan="4">-20 to 70
-40 to 85
-40 to 105</td><td rowspan="3">3.2x2.5 14L</td></tr>
<tr><td>DSC21xx</td><td>1.5</td><td>I²C/OE/FS
(up to 2 freq per output</td></tr>
<tr><td>DSC22xx</td><td>1.5</td><td>SPI/OE/FS
(up to 2 freq per output</td></tr>
<tr><td>DSC400</td><td>2.3 to 460</td><td>4</td><td>2</td><td>1.5</td><td>OE/FS
(up to 2 freq per output)</td><td>30-130</td><td>5.0x.3.2 20L</td></tr>
</table>

FIGURE 21: *MEMS Clock Selection Guide.*

CONCLUSION

This paper described the application of MEMS technology to Microchip's clock and timing products. The inherent benefits of this alternative to traditional quartz oscillators are high reliability, small size, frequency stability across extended operating temperatures (automotive Grade 1), and programmability. These are valued across a broad set of applications, including automotive, industrial/medical, digital imaging, and networking.

Three generations of MEMS-based resonators are discussed. Of particular note are the second generation resonators, utilized in all of Microchip's currently produced oscillators and clocks, and the third generation that will soon enable a set of new ultra-low jitter products.

The system design of the oscillator and clock products consists of the MEMS resonator combined with a CMOS die, the last containing an oscillator circuit driving a fractional-N PLL and output buffers. Special aspects include temperature compensation and a high level of programmability. A programming tool called TimeFlash allows special "blank" devices to be instantly programmed to any frequency by the customer.

The paper concludes with an oscillator and clock selection guide. For more information on Microchip's Clock and Timing Solutions, please visit:

http://www.microchip.com/design-centers/clock-and-timing

NOTES:

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
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