AGING PERFORMANCE OF SMALL SIZE MHZ QUARTZ CRYSTAL UNDER HIGH DRIVE

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The recent advancement in fabrication and packaging technology has made small size MHz quartz crystals available down to 1.6mmx1.2mm. Larger size quartz crystals in general can handle drive level easily up to 1 mW. As the quartz crystal size drops, the crystal bulk material can handle less and less power. This paper will review the reasoning behind low drive level specification of nowadays small size quartz crystals and to discuss quantitatively the aging result of a small size quartz crystal driven to close to 1 mW.

Keywords: Quartz Crystal, Drive Level, Aging

1. INTRODUCTION

The recent advancement in fabrication and packaging technology has made small size MHz quartz crystals available down to 1.6mmx1.2mm. This was considered unachievable ten years ago. Portable equipment like smartphone doesn't seem to get smaller due to ergonomic consideration. However, more and more functions are being packed into them. Portable equipment suppliers continue to demand smaller and smaller components. Component suppliers continue to reinvent themselves by meeting the challenge. Larger size quartz crystals in general can handle drive level easily up to 1 mW. As the quartz crystal size drops, the crystal bulk material can handle less and less power. For the smallest size quartz crystals, suppliers routinely specify as low as 100 μW maximum drive level and recommend say 10 μW drive level for normal use. And when inquired what would happen if the operation drive level exceeds the maximum drive level specification, suppliers routinely respond qualitatively- the quartz crystal may see excessive aging, may see frequency perturbation, and may shatter in the most serious situation. This paper will review the reasoning behind low drive level specification of nowadays small size quartz crystals and to discuss quantitatively the aging result of a 2.5mmx2.0mm fundamental 20 MHz quartz crystal driven to close to 1 mW.

2. SMALL SIZE QUARTZ CRYSTALS

As nowadays small size quartz crystals are still being manufactured mostly with the "singulate" method (in contrast to the CSP and WLP methods), the smallest quartz crystals in the market are not necessary of the highest volume and most cost efficient. Small size hermetically sealed quartz crystals are usually comprised of three key components- a high temperature co-fire ceramic (HTCC) base [1], a nickel-plated kovar metal lid, and a quartz crystal. Quartz crystal suppliers receive the ceramic bases usually in the form of sheet arrays. The suppliers break the arrays into individual bases after a cleaning process and then carry the remaining quartz crystal production through with the singulate method. The smallest quartz crystal being shipped in high volume is the 1.6mmx1.2mm (1612) one (Fig. 1). The most capable suppliers are ready to sample the 1.2mmx1.0mm (1210) one. 1.0mmx0.8mm (1008) one is also being planned.

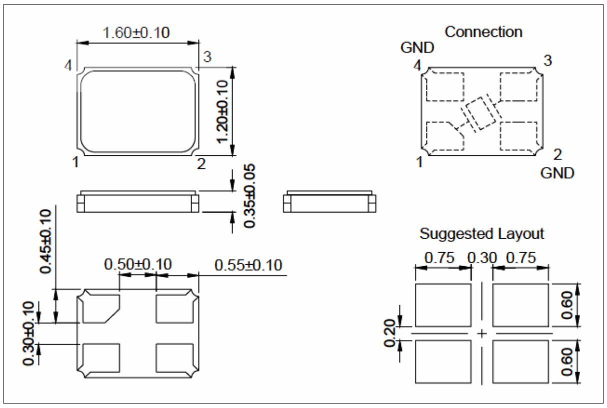

Fig. 1 1.6mmx1.2mm Quartz Crystal from TXC Corporation

Table 1 lists the smallest quartz crystals currently available from six different suppliers. One noticeable rule of thumb is that it gets more difficult to sustain low motional resistance (R_m) at lower frequency as size becomes smaller [2]. That prompted couple of suppliers to use the Lamé mode of a different cut (in contrast to the Thickness-Shear mode of AT-cut) of quartz crystal to achieve 4 MHz in a 3.5mmx2.5mm (3225) package for some special applications [3].

Suppliers	1210	1612	2016	2520	3225
A		30~54 MHz	24~54 MHz	12~48 and 52 MHz	12~60 MHz
		50/100 µW	100 µW	100 µW	10~100 µW
		30~32 MHz 200Ω	24~26 MHz 80Ω	12~16 MHz 150Ω	12~13 MHz 100Ω
		32~36 MHz 100Ω	26~54 MHz 60Ω	16~25 MHz 80Ω	13~20 MHz 80Ω
		36~54 MHz 80Ω		25~30 MHz 60Ω	20~25 MHz 60Ω
				30~35 MHz 50Ω	25~30 MHz 50Ω
				35~48 MHz 40Ω	30~60 MHz 40Ω
B	In Development	26~60 MHz	18~60 MHz	16~60 MHz	10~60 MHz
	30~60 MHz	10,20 µW	30 µW	30 µW	30,50 µW
	100 µW typical	60~200Ω	60~300Ω	60~80Ω	10~13 MHz 30~200Ω
	300Ω				13 to 60 MHz 120Ω
C		26~80 MHz	24~80 MHz	16~80 MHz	12~150 MHz
		200 µW	200 µW	200 µW	200 µW
		26~32 MHz 150Ω	24~26 MHz 80Ω	16~20 MHz 80Ω	12~13 MHz 100Ω
		32~38 MHz 100Ω	26~40 MHz 60Ω	20~30 MHz 60Ω	13~20 MHz 80Ω
		38~80 MHz 80Ω	40~80 MHz 50Ω	30~35 MHz 50Ω	20~54 MHz 50Ω
				35~80 MHz 40Ω	40~100 MHz 140Ω
					100~150 MHz 100Ω
D		30~60 MHz	18~60 MHz	13.56~60 MHz	12~54 MHz
		100 µW	100 µW	100 µW	100 µW
		30~40 MHz 200Ω	18~26 MHz 150Ω	13.56~16 MHz 200Ω	12~13 MHz 200Ω
		40~60 MHz 100Ω	26~36 MHz 80Ω	16~19.2 MHz 100Ω	13~15 MHz 150Ω
			36~40 MHz 60Ω	19.2~26 MHz 80 Ω	15~16 MHz 100Ω
			40~60 MHz 50Ω	26~30 MHz 60Ω	16~20 MHz 80Ω
				30~60 MHz 50Ω	20~26 MHz 50Ω
					26~54 MHz 40Ω
E	In Development	30~80 MHz	18~80 MHz	13.5~80 MHz	10~60 MHz
	36~80 MHz	100 µW	100 µW	200 µW	200 µW
		100 Ω	18~20 MHz 300Ω	13.5~16 MHz 300Ω	10~16 MHz 200Ω
			20~25 MHz 200Ω	16~20 MHz 150Ω	16~30 MHz 100Ω
			25~40 MHz 100Ω	20~30 MHz 100Ω	30~60 MHz 50Ω
			40~80 MHz 60Ω	30~80 MHz 60Ω	
F		24~54 MHz	20~54 MHz	12~54 MHz	10~54 MHz
		200 µW	200 µW	100 µW	100 µW
		24~30 MHz 100Ω	20~30 MHz 100Ω	12~13 MHz 150Ω	10~16 MHz 100Ω
		30~54 MHz 80Ω	30~54 MHz 80Ω	14~30 MHz 100Ω	16~20 MHz 80Ω
DL is Max.				30~54 MHz 60Ω	20~54 MHz 60Ω

Table 1 Small Size Quartz Crystals from Six Different Suppliers (Public Domain Information)

The other rule of thumb is that suppliers specify lower maximum drive levels as the quartz crystals get smaller. One of the authors of commented earlier [4], "…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…" The cost saving is attractive to designers. However, designers then have to struggle with specifying the quartz crystals with the right load capacitance, maximum R_m, correct frequency set tolerance in ppm, etc. so to guarantee normal oscillation in their own circuits. Maintaining large enough negative resistance to R_m ratio (usually >5) and driving the crystal within the specified maximum drive level are important factors for normal oscillation.

3. DRIVE LEVEL

Figure 2 depicts a typical Pierce oscillation circuit with the crystal being driven in its parallel resonance (f_p). Rf is the feedback resistance which is in general imbedded inside the oscillator circuit (on-chip) so to provide DC bias to the inverting amplifier. R_f is about 1 MΩ for oscillating with fundamental MHz quartz crystal. R_d is the control resistance which can be implemented off-chip to limit the current going into the quartz crystal and to adjust the available negative resistance of the oscillation circuit. Its value can be anywhere from several Ω to kΩ.

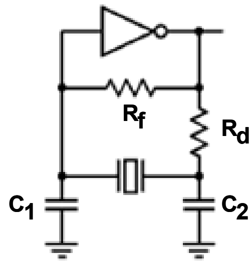

Fig. 2 Typical Pierce Oscillation Circuit

C_1 and C_2 are the load capacitances to ground which present a combined load capacitance (C_L) of $C_1 \cdot C_2/(C_1+C_2)$ to the quartz crystal. The power P_c dissipated by the quartz crystal can be approximated by [5]-

$$P_c \approx \tfrac{1}{2} (2\pi \cdot f_p \cdot C_e \cdot V)^2 \cdot R_m \qquad (1)$$

V is the oscillator driving voltage. C_e is equal to C_o+ C_L where C_o is the static capacitance of the quartz crystal. Take the example of a 2.5mmx2.0mm 12 MHz quartz crystal with C_o of 0.6 pF, C_L of 12 pF, and R_m of 90Ω driven in 1.8V, the dissipated power is about 120 µW. Note that the actual voltage across the quartz crystal no longer equals to the oscillator driving voltage with the presence of R_d. As said in the previous section, suppliers specify lower maximum drive levels as the quartz crystals get smaller. The physical reasoning is clear as there is less available material to dissipate the energy for smaller size quartz crystals. It can also be seen from Eq. 1 that more power is dissipated for higher R_m which is typical of smaller quartz crystals. Designers are familiar with the general trend of frequency shift versus C_L (pullability) as shown in Figure 3. We include the effect of varying the value of the control resistance R_d in the figure. Changing the C_L is known to change the drive level (as shown in Eq. 1). It of course also changes the negative resistance available from the oscillation circuit. Figures 4 and 5 combine the changes with varying the R_d value. Nowadays many quartz crystal suppliers provide complimentary circuit analysis service to customers on oscillation circuit and quartz crystal matching so to limit the power driven into the ever size decreasing quartz crystals and to maintain large enough negative resistance to R_m ratio.

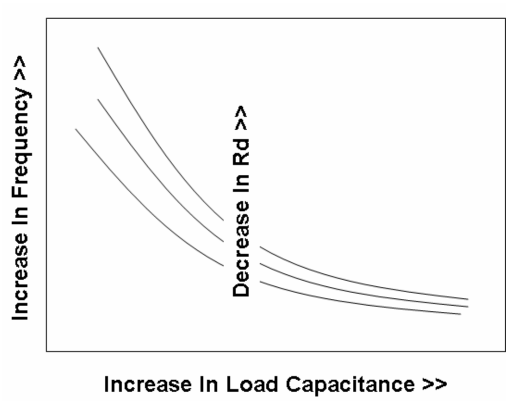

Fig. 3 Frequency vs Load Cap with Varying Rd

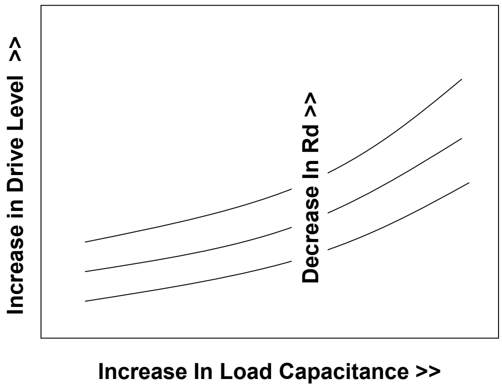

Fig. 4 Drive Level vs Load Cap with Varying Rd

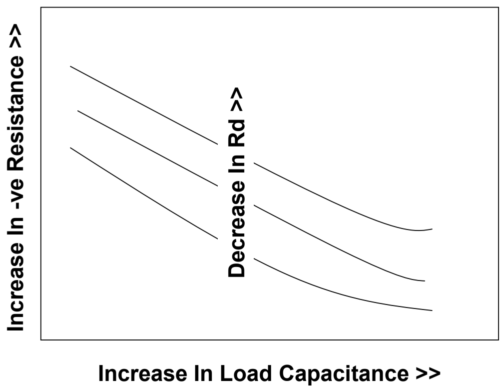

Fig. 5 Negative Resistance vs Load Cap with Varying Rd

4. AGING OF OVER-DRIVEN QUARTZ CRYSTAL

Even with early planning, some customers occasionally find that they over drive the quartz crystals near the end of their product development. By then, the board designs are fixed and customers are no longer able to adjust the C_L, to adjust the (or to add) R_d, or to change to larger size quartz crystals. As said in the Introduction section, quartz crystal is known to age faster under high drive. However, the authors are not aware of any published aging data of small size quartz crystal under high drive. Our study here is on a 2.5mmx2.0mm 20 MHz quartz crystal of silver electrodes with typical C_o of 0.64 pF, C_L of 16 pF, C_l (motional capacitance) of 1.95 fF, and R_m of ~25Ω. The maximum drive level specification is 100 μW. The frequency specifications are <±7 ppm at 25±3ºC, <±10 ppm over -20 to 70ºC, and <±3 ppm first year aging. The quartz crystal went through the regular reliability qualification including an accelerated aging test (at 100 μW dissipation) at 85ºC for 1,000 hours. [6] The quartz crystal drifted down less than 1 ppm at the end of the test. Two sets (six devices each) of the same quartz crystal went through the same accelerated aging test at 650 μW and 950 μW dissipation respectively using a 7400 IC with C_1=C_2=15 pF. The first set was aged till 1,000 hours at 85ºC (Figure 6). The second set was aged to 1,500 hours at 85ºC (Figure 7).

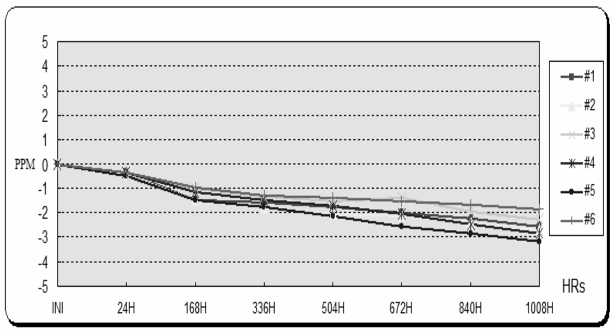

Fig. 6 Accelerated Aging Test at 650 μW Dissipation

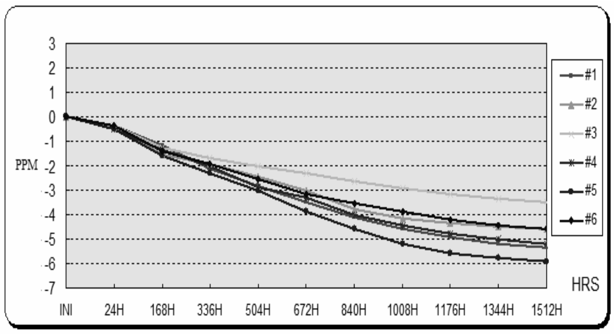

Fig. 7 Accelerated Aging Test at 950 μW Dissipation

The first set of quartz crystals aged down 2 to 3 ppm after 1,000 hours. The second set aged down 3 to 5 ppm after 1,000 hours and reached 3.5 to 6 ppm at 1,500 hours. The second set also began to show sign of stabilization at ~1,100 hours. No significant increase in R_m was observed for all twelve quartz crystals. As the quartz crystal has a total of ±17 ppm frequency allowance at 25ºC plus over the temperature range of operation and the oscillator is not expected to run continuously at 85ºC, it's likely the customer should have no problem with their oscillator from the frequency drift and negative resistance to R_m ratio point of view even though they drive this specific quartz crystal way over the spec.

5. CONCLUSION

A small size (2.5mmx2.0mm) 20 MHz quartz crystal, specified at a 100 μW maximum drive level, went through accelerated aging at 85ºC to 1,000 hours at 650 μW dissipation and to 1,500 hours at 950 μW dissipation respectively. As expected, higher than normal drift (down in this case) in frequency was observed under high drive. The quartz crystal though experienced no significant increase in motional resistance and no catastrophic failure (crystal cracking or shattering) was observed. The result for this specific quartz crystal is encouraging. However, the authors intend to present observed high drive aging results only and they do not endorse driving quartz crystals beyond the maximum drive level specified by suppliers as there are other issues like possible activity dip appearing at high drive, increasing in noise, etc. were not investigated. A more systematic and encompassing study for the smallest quartz crystals is being planned.

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