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Study of XECO Frequency Measurement Systems

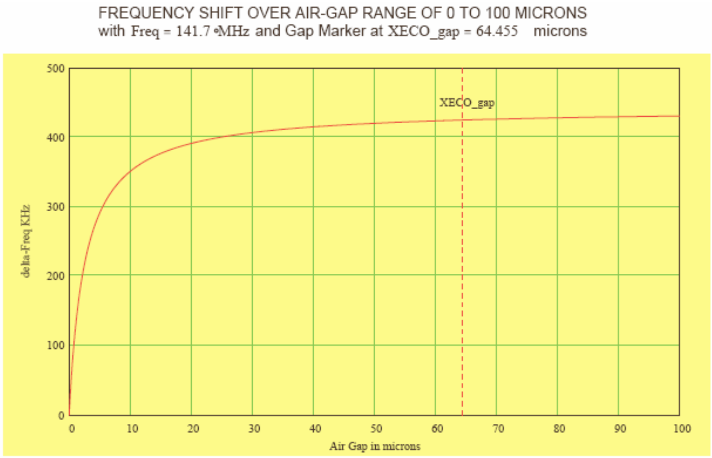
Crystal makers generally agree measuring crystal blanks is not precise; only after crystal blanks are plated can the frequency be accurately measured. Typical measurement systems employ an airgap fixture, which introduces a number of measurement uncertainties that must be accounted for, including; variations in the gap distance, crystal blank placement, and the possible touching of the crystal to an airgap element. Differences between transmission measurements and balanced bridge approaches also exist, and each has merit.

Study Parameters

In this study, three electrode sizes (20, 40 and 80 mils) were inter-compared using a fixed airgap distance and XECO designed balanced-bridge measurement system. A population of 85 blanks of the SM141 style with a nominal frequency of 141.7 MHz was measured 5 times with each element size/system, with a wash and repositioning of the blank between each measurement. The blanks were then base-plated with a Cr/Au electrode having a diameter of 17 mils (0.43 mm) at 0.55 f-squared. The electrode plated blank frequency was then measured using an HP-E5100 Network Analyzer; this data was then used as the reference from which the un-plated measurements could be compared. The findings and analysis of the data collected from this study are summarized and contained in this report.

Airgap and Test setup

Setting an airgap for minimum gap allows measurements to be closer to the absolute crystal frequency; however, these measurements have increased variability compared to setting the airgap wider. Increasing airgap spacing increases the frequency offset from the absolute crystal blank frequency, and therefore imputes the need for a frequency offset adjustment. This can be inferred from the curve on Graph 1 at the right:



Graph 1

XECO selected the balanced bridge approach as it allows for smaller electrode diameters at larger airgap spacing without increasing RF power excessively. Setting the airgap wide improves repeatability for same blank placement and airgap variation. The compromise is that an offset for frequency is required to account for the larger airgap spacing. The best repeatability should result in the tightest plating distributions. From our perspective, the blank measurement approach which yields the narrowest distribution after plating is best.

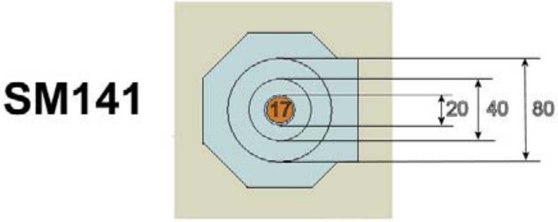
During the past two years we have developed a 20 mil (0.5mm) element with enhanced measuring capability in addition to our older 40 mil (1mm) and 80 mil (2mm) elements.

XECO continues to use the 40-mil element for “Legacy” or existing products and continues to use the original test equipment setups to avoid the need for establishing a new correlation with customers.. We have used the newer smaller element system for newly specified products and for XECO plated blanks. The 80-mil electrode was made obsolete several years ago.

Blank placement accuracy is another significant factor to attain repeatable measurements. XECO has improved the blank placement accuracy (in the airgap) to <0.025mm and airgap variation to <0.0025mm. The importance of this to standard deviations will become apparent later in this report.

Mesa Layout

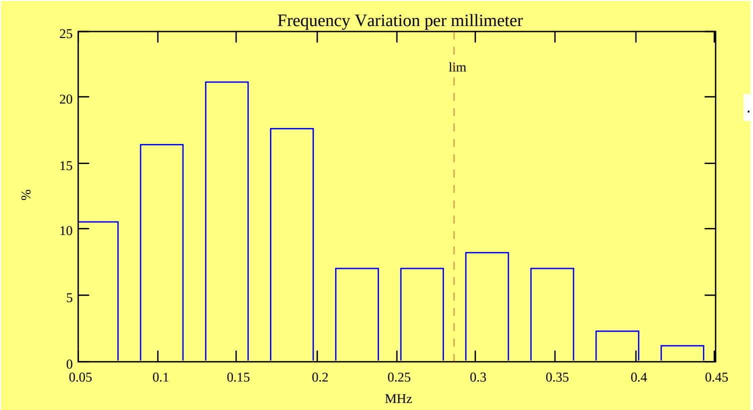
Drawn atop the SM141 is the 80, 40 and 20 mil element size plus the 17 mil electrode used in study



Mesa Characteristics - parallelism

The parallelism of the blanks used in this study is represented in the histogram in Graph 2. The “lim” marker represents the cut-off point at which, XECO would reject blanks during final inspection. This cut-off point represents three light-bands, which, equates to approximately 286 kHz per millimeter of frequency variation, at a nominal frequency of 141.7 MHz. As can be seen, the majority of the blanks used in this study are centered at about 150 kHz/mm. This equates to about one and one-half light bands. This is representative of average material used at XECO to produce inverted-mesa blanks. It is important to understand the frequency variation that can exist across the mesa, and this contributes significantly to the difficulty in making repeatable measurements. This also adds understanding to why differences occur in comparing systems utilizing different electrode diameters.

Graph 2



Measurement Repeatability

Un-Plated Measurement Repeatability (kHz)			
Electrode	**median**	**mean**	**stddev**
20 mil (0.5 mm)	5.6	12.9	54.2
40 mil (1.0 mm)	1.0	40.1	143.7
80 mil (2.0 mm)	1.2	98.2	469.8

Measurement repeatability was determined by calculating the standard deviation of the 5 measurements made for each blank. The median, mean and standard deviation of the population of data was then calculated and is reported below. From the values represented in the table, it is evident that the use of a smaller electrode will yield significantly more repeatable frequency measurements. The fact that the 20 mil system has a greater median value than the other two systems is attributed to its sensitivity to blank positioning repeatability of this particular setup, although the overall standard deviation of the 20 mil electrode is nearly an order of magnitude smaller than the 80 mil electrode standard deviation!

Frequency Distribution

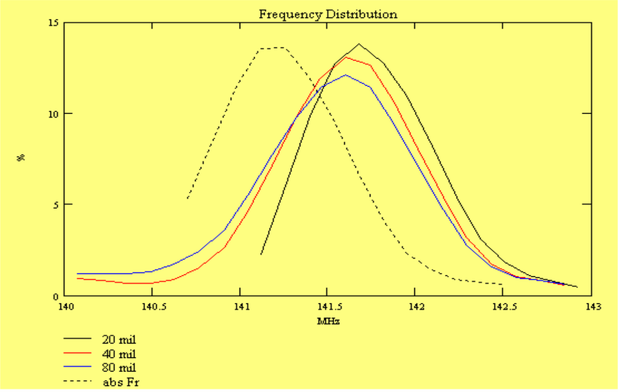
Frequency distributions of the summary table at right and Graph 3 were determined by the median value of the five frequency measurements made on each blank. The bandwidth of the histogram represented in the graph is 69.5 kHz. The actual or absolute blank frequency (abs Fr) was calculated from the 20-mil electrode data and is shown for reference.

Frequency Distribution (MHz)			
Electrode	**median**	**mean**	**stddev**
plated 17 mil (0.43 mm)	131.473	131.412	0.364
20 mil (0.5 mm)	141.618	141.716	0.347
40 mil (1.0 mm)	141.577	141.569	0.378
80 mil (2.0 mm)	141.510	141.444	0.514

From this Frequency Distribution table, three observations are made:

Frequency increases as the electrode diameter is reduced. This can be attributed to the fact that much less of the quartz is being excited.

Graph 3



The frequency distribution between compared with base plated blanks and the 20-mil measurement relationship is as expected; one would expect a slightly larger distribution after plating compared to the distribution prior to plating.

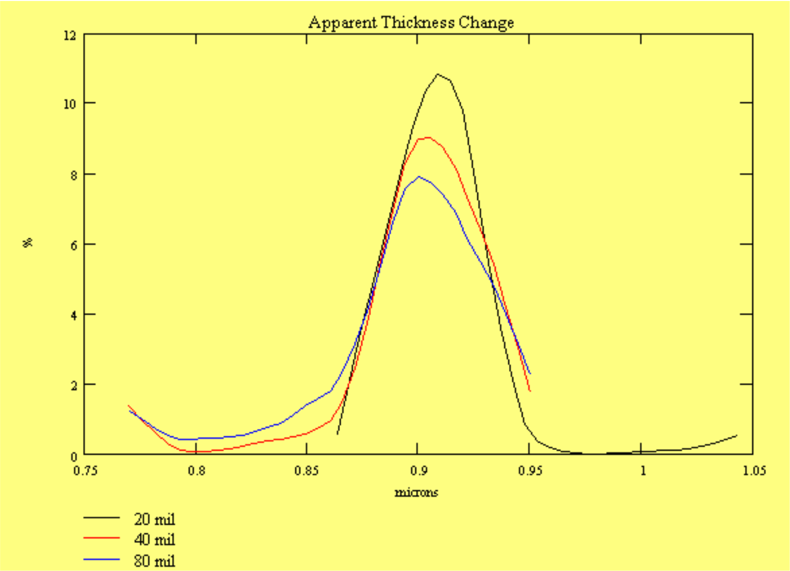
40 and 80 mil distributions shown are actually greater than the plated blank distributions. This supports our observation that smaller electrode diameters approximating the electrode matches well to the final plated frequency. Moreover, the normal case is that plated distributions will be somewhat larger than the blank distribution. A raw population of blanks tested with 40 mil or 80 mil elements will yield a distribution somewhat higher than each elements respective standard deviation.

Calculated Apparent Thickness Change, Un-Plated vs. Plated

The values represented in the table at right were calculated using the median value of the un-plated blank measurements for each of the respective electrode sizes using the following equation: KK *(Un-plated Freq – Plated Freq / Un-plated Freq * Plated Freq). Whereas K is, equal to the quartz frequency constant in MHz-microns. The histogram represented in the Graph 4 has a bandwidth of 5.6 nanometers. As predicted from the frequency distribution data, the standard deviation of the 20 mil electrode is much smaller than that of the 40 and 80 mil electrodes. This is also seen in Graph

Apparent Thickness Change (un-plated vs. plated)				
Electrode	**median**		**stddev**	
20 mil (0.5 mm)	0.917	um	26.89	nm
40 mil (1.0 mm)	0.903	um	32.70	nm
80 mil (2.0 mm)	0.897	um	44.89	nm

4, that the peak of the population of the 20 mil electrodes is greater than that of the 40 and 80 mil electrodes. This would support the idea that the 20-mil electrode un-plated blank measurements could be used to make a more accurate prediction of the final plated blank frequency.



Summary points and recommendations

1. Increasing element size increases standard deviation of measurement
2. The specification for frequency tolerance for a 141.7MHz crystal is nominally 400kHz. The 80 MHz element is incapable of providing the accuracy needed, the 40 mil element is poor or marginal at best. The 20 mil electrode provides acceptable repeatability and accuracy
3. Comparing the three blank groups, the larger the element, the lower the frequency and higher the standard deviation.
4. The 20mil (0.5mm) element measurements exhibit the best correlation to plated blanks.

Some other factors which may need to be considered include:

1. Close airgap spacing may allow crystals to touch causing lower frequency readings
2. Effective element size may be larger than physical
3. Potential for Rim / Mesa structure effects to occur increase for larger elements

XECO sets frequency range tolerance and tested to these values without guardbands or consideration that customers may choose to perform incoming inspection on an absolute frequency measurement basis. This has generally not been performed due to the combined cost and potential unnecessary yield losses incurred from the inherent inaccuracies and differences in testing crystals and mechanical yield losses incurred by re-testing. The objective has always been to supply the tightest distribution possible so that the plated electrode distributions would be as best as possible. We believe XECO methodology maximizes that objective.

Specific recommendations

Sizing element to more closely match working electrode sizes is best as:

A. Known variations in mesa frequency from center to edge are significantly reduced and improve the standard deviation of tests
B. Testing the mesa with an element size more consistent to the final electrode size will simply result in the best correlation between blank and final electrical plated frequency.
C. For best repeatability, reduce variation of cyrstal position in airgap to as small as possible and increase airgap to 40 microns minimum, or to limit of what electronics allow.
D. Characterizing the tester standard deviation for mesas, including variation for airgap and blank placement accuracy is helpful in determining a good understanding of test results.

Tester Correlation: Additional discussion regarding test and re-testing, and plating

Correlating blank crystal frequency testers is difficult due to the inherent inaccuracies of the testing methods used, and most of the time, the additional mechanical and electrical losses through re-test have are proven to be uneconomical. Plating operations have their own inaccuracies as well. So the normal manufacturing approach is to have a crystal lot with a frequency range and make a small test run with a few crystals to determine the plateback amount needed to bring the entire lot into final frequency range. The resulting frequency distribution will be a function of the frequency tolerance of the blank plus whatever additional plating distribution adds to it. This approach has been consistently used by nearly all crystal manufacturers. So if a crystal lot with a known distribution is used, then a prediction of the lot distribution after placing can be made once the normal plating distribution has been determined, but the exact frequencies have typically been undetermined or not extremely important to as the tuning process automatically adjusts for small frequency differences.

Some difficulties with this approach occur when the anticipated frequency distribution is not achieved, for it is not known whether this is the result of a plating uniformity problem or blank frequency distribution. Re-testing mesa blanks with a larger or significantly different element may be misleading, as the higher frequency distributions which result are caused by the higher standard deviations, and testing the mesa in unused areas increases the correlation error to the plated crystal. Hence, this testing will either be confusing or misleading. It is confusing if the distribution and variances are greater than the plated crystals. It is misleading if the distributions and variances are less than the plated crystals, as the calculated contribution of distributions and variances attributed to the crystal and plating will be incorrect.

When blanks are retested with different setups and methodology which result in different frequency offset and larger standard deviations, re-test failures can be expected unless adequate guardbands which account for the standard deviations and offsets are built into the specifications. For hard absolute frequency values and the goal for <1% failures, this would be typically be established as +/- (Frequency range +1.5*($\text{stddev}_{\text{tester}}$), which equates to a 3 sigma or CPK=1.33.

In the case of a 141.7MHz blank with a nominal 400 kHz tolerance range, the “datasheet” test limits would need to be increased as follows:

Element	Stddev kHz	Production frequency tolerance range, kHz	Guardband limits: freq tolerance + 3 * $\text{stddev}_{\text{tester,}}$ kHz
20 mil (0.5 mm)	54	400	562
40 mil (1.0 mm)	143	400	829
80 mil (2.0 mm)	514	400	1942

Making these changes is appropriate for a scenario for test and re-test at customer sites, however, this may have no real benefit considering the normal electrode plating scenario. Additionally, if the customer test set up has a larger standard deviation than the XECO tester used, the guardband limits can still be exceeded and result in apparent failures. All these issues and tradeoffs must be made when considering re-test of blanks.