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EXPERIMENTAL STUDIES ON FLICKER NOISE IN QUARTZ CRYSTAL RESONATORS AS A FUNCTION OF ELECTRODE VOLUME, DRIVE CURRENT, TYPE OF QUARTZ, AND FABRICATION PROCESS

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Abstract - We investigated the effect of electrode size, drive current, sweeping, type of polishing, and ultra-thin electrodes on the 1/f or flicker frequency and phase modulation (PM) noise of quartz crystal resonators. The 1/f noise of resonators with three different electrode diameters was measured and compared. The PM noise performances of all three resonator types, measured in a test oscillator, were similar with an average of -100 dBc/Hz, a variation of approximately ±10 dB, and a minimum value of $\mathcal{L}$(10 Hz) = -110 dBc/Hz. (dBc/Hz refers to dB below the carrier in a 1 Hz bandwidth.) We also found that the 1/f noise in many of these resonators varied significantly (up to 10 dB) with drive current. We also had other groups of resonators made out of swept quartz bars, with a special polishing process and/or ultra-thin electrode edges. These groups yielded similar results: an average PM noise of -98 dBc/Hz, and a variation of ±10 dB. The amplitude-frequency effect of the resonators was also investigated. The frequency versus amplitude curve, measured using a network analyzer, showed discontinuities in some of the resonators with poor noise. There is some indication that these discontinuities or "jumps" may be due to stress relief in the crystal or noisy contacts.

Introduction

The purpose of this study was to investigate possible causes of 1/f frequency and phase modulation (PM) noise in crystal resonators and the reasons for the large (unexplained) variation observed in the 1/f frequency and PM noise in crystal resonators of the same design. Studies of flicker frequency noise in crystal resonators by J.J. Gagnepain, et al. [1], indicated that the 1/f noise depends on the unloaded Q-factor of the resonator ($S_y(f) \propto 1/Q^4$). Nevertheless, as the spread of 1/f noise for resonators of the same Q is large (about a factor of 100), other factors must also contribute to the 1/f noise [2].

Another model of 1/f noise in crystal resonators, proposed by F.L. Walls, et al. [3], predicts that the 1/f noise is also dependent on the electrode volume, i.e. $S_y(f) = \beta V/fQ^4$. This model predicts that small electrodes yield lower 1/f noise assuming all other parameters are constant. It has also been speculated that flicker frequency noise in resonators is related to energy coupling between the main mode and unwanted modes. Since the number and coupling to unwanted modes in a resonator is a function of the electrode size (the number and coupling increases with electrode size), varying the electrode size could affect the 1/f noise of crystal resonators.

Other factors that have been speculated to contribute to 1/f noise in resonators are the presence of impurities and dislocations in the crystal, as well as surface particles, and defects which are residuals from the mechanical polishing process. For these reasons we study the effect of sweeping and the effect of removing surface particles by etching before and after the mechanical polishing process on the 1/f noise of crystal resonators. We also investigate the effect of ultra-thin electrode edges. Ultra-thin gold films (10-40 nm) have been found to strongly adhere to the crystal surface when compared to the adhesion of 100 nm gold films [4]. When electrodes are deposited through a shadow mask, a very thin edge or "rim" which strongly adheres to the crystal is observed at the periphery of the electrode [4]. At the electrode edges, the film thickness does not drop abruptly to zero but decreases gradually, eventually breaking into discontinuous islands. This edge region was suspected of being a possible noise source.

Description of the Experiment

The general characteristics of the resonators used in this study are shown in Table 1. 100 MHz quartz crystal resonators were used because they are less expensive and smaller than 5 and 10 MHz resonators, which allowed more resonators to be obtained from a single crystal bar. Furthermore, their 1/f noise is less affected by temperature fluctuations than lower frequency resonators since the 1/f noise in 100 MHz resonators is approximately 20 dB higher than the noise in similar 10 MHz resonators. Figure 1 shows an overview of the resonator groups used in this study. To investigate the effect of electrode size we had three groups of (12) resonators made from the same crystal bar. The three groups had three different electrode diameters: 2.16 mm (small electrode), 3.05 mm (medium electrode), and 4.32 mm (large electrode). If $S_y(f)$ is proportional to the electrode volume and all other effects on 1/f noise are constant among the resonators, then the 1/f noise of the small electrode group would be 6 dB lower than the 1/f noise in the large electrode group.

Table 1. General characteristics of resonators used in this study. Q refers to the unloaded quality factor of the resonators. Electrode diameter and typical resistance values are given for small, medium and large electrode resonators.

Quartz Crystal Resonators Used:	
Frequency	100 MHz
Overtone	5th
Cut	SC
Q	$\sim 10^5$
Resistance	60, 75, 110
Blank Diameter	6.3 mm
Electrode Diameter	2.16, 3.05, 4.32 mm
Electrode Material	Aluminum
Mounting Points	3
Bonding Agent	silver filled epoxy
Geometry	plano-plano
Turnover Temperature	60 - 80 °C

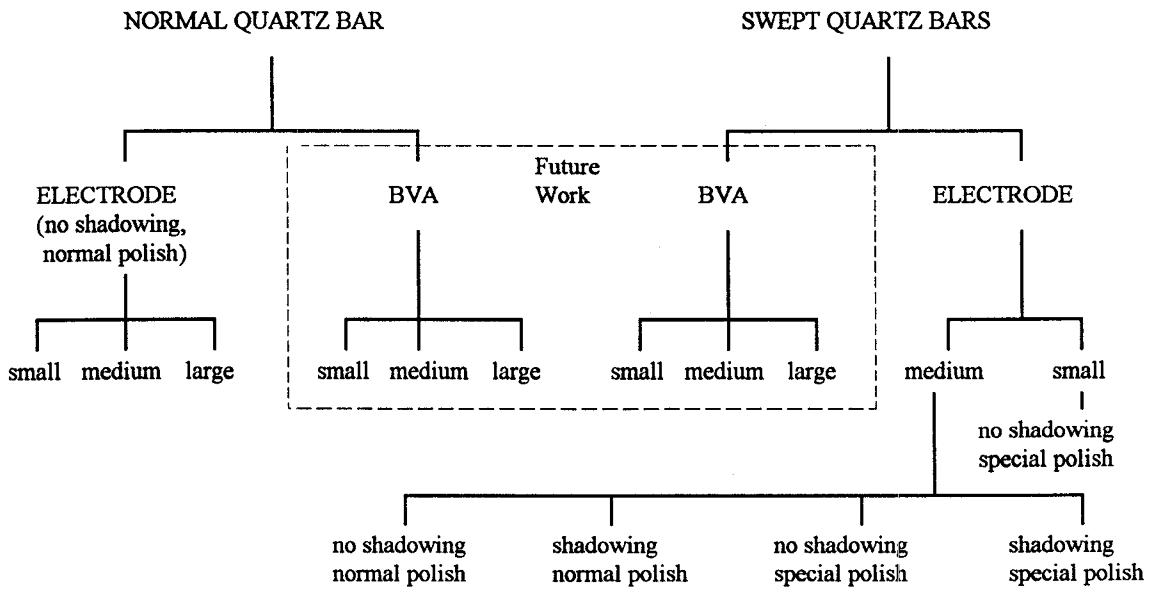

Figure 1. Resonator groups used in this study. Each group included 10-14 resonators.

The rest of the resonators in this study (five groups of 10-14 resonators) were made out of swept crystal bars obtained from a different vendor. Of these five groups, four had the medium electrode diameter, while one had the small diameter. A special polishing technique consisting of chemical etching before and after polishing (to minimize surface defects) was used in some of the groups, and compared with groups that were not etched after the mechanical polishing (with cerium oxide). Other groups had two-layer electrodes deposited through a shadow mask, one an ultrathin (5 nm) film of larger diameter than the thicker electrode, as shown in Fig. 2. This was done to accentuate any effects due to the thin electrode edges, although it was recognized that a 5 nm aluminum film is a poor approximation of the gold rim [4] (especially in view of the fact that a 5 nm "aluminum" film on a quartz surface consists mostly aluminum oxide).

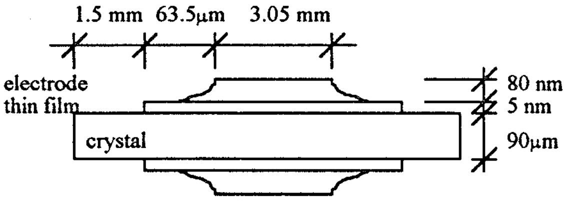

Figure 2. Crystal resonators with ultra-thin film between electrode and crystal.

The BVA resonators of Fig. 1 are in the process of fabrication. 1/f noise results and how they compare to those of electroded resonators will be published in the future.

Mode Structure for Different Electrode Diameters

The transmission function of the resonators was measured using the system shown in Fig. 3. In this system a network analyzer is used to sweep the frequency about resonance and to obtain the transfer function of the resonator. A variable capacitor is used to cancel the holder capacitance, thus obtaining the characteristics of the resonator at series resonance.

The transfer function for small electrode, medium electrode and large electrode resonators is shown in Fig. 4. There are large differences in the transmission of the three resonator types. As expected, the spurious modes of the small electrode resonators are fewer, their magnitude is smaller, and their frequency separation from the main mode is larger than resonators with larger electrodes.

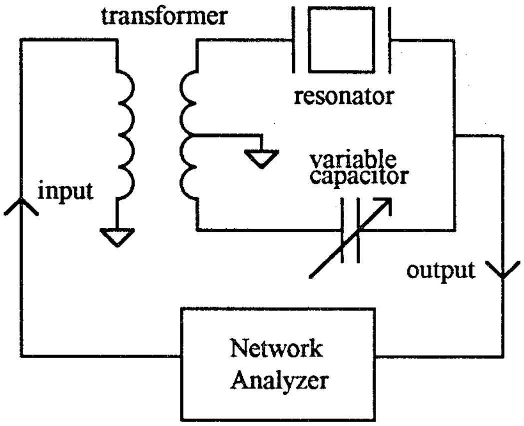

Figure 3. System used to measure the transfer function of the crystal resonators.

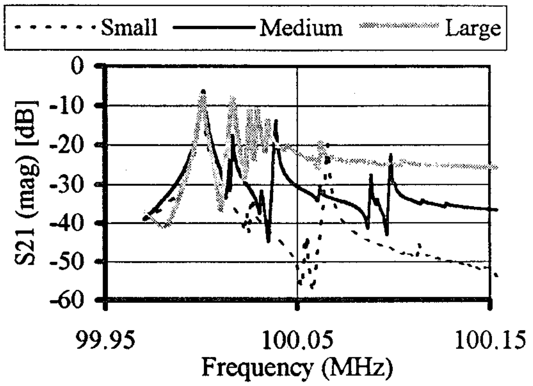

Figure 4. Magnitude of the transfer function (S21) of crystal resonators with small, medium, and large electrodes.

1/f Noise Measurements

In order to measure the 1/f noise in the crystal resonators, the resonators were placed in a test oscillator and the PM noise of the oscillator measured. At Fourier frequencies of 5 to 100 Hz, the PM noise of a 100 MHz crystal oscillator is dominated by the flicker frequency noise of the crystal resonator. In this paper we use $\mathcal{L}$(10 Hz) of the test oscillator to characterize the 1/f noise in the crystal resonators. The measurement system used for measuring PM noise in the test oscillator is shown in Fig. 5. This system uses cross-correlation to eliminate the noise of the reference oscillators and phase detectors [5,6]. The PM noise floor of the measurement system is at least -118 dBc/Hz (dB below the carrier in a 1 Hz bandwidth) at 10 Hz from the carrier, limited by the PM noise of the reference oscillators.

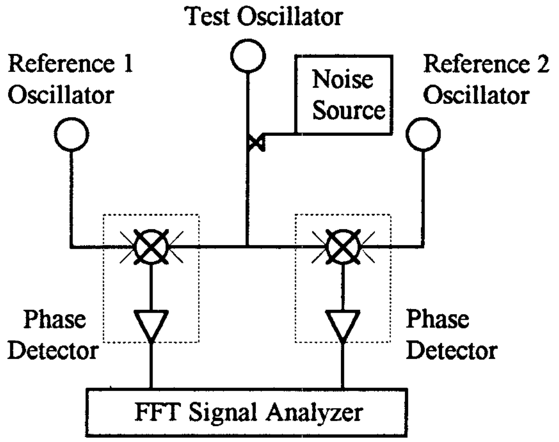

Figure 5. Cross-correlation system for measuring PM noise in an oscillator.

In Fig. 6 we show $\mathcal{L}$(10 Hz) versus drive current for several small electrode resonators. The noise was measured at 2 mA, 2.8 mA, and 4.5 mA. The spread of the 1/f noise is approximately 20 dB, the minimum being -107 dBc/Hz and the maximum approximately -90 dBc/Hz. Some resonators show a variation of up to 10 dB with drive current; in others, the noise is constant with drive current. Curves in Fig. 6 show that the optimum current varies with resonator.

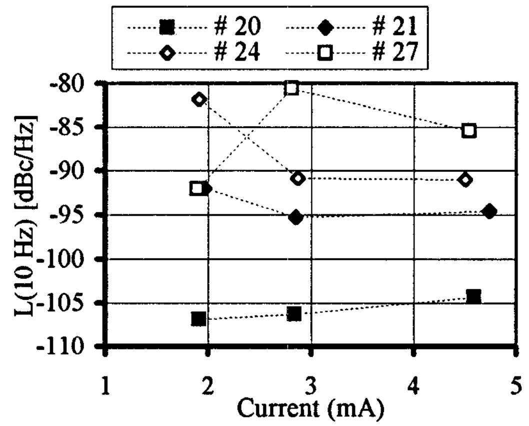

Figure 6. $\mathcal{L}$(10 Hz) versus drive current for small electrode resonators.

Values of $\mathcal{L}$(10 Hz) for all the resonators tested are given in Table 2, columns B and B'. The maximum and minimum values for each group are indicated in italics. In general, all groups showed a large spread of 1/f noise, with the average of the best group being -100.5 dBc/Hz (normal quartz, small electrode) and the average of the worst group being -96.7 dBc/Hz (swept quartz, medium electrode, special polish). Surprisingly, the best noise performance [$\mathcal{L}$(10 Hz) ≈ -110 dBc/Hz] was measured in resonators of all three electrode sizes. It is possible that in these cases the noise was limited by the noise in the electronics of the test oscillator. Columns C and C' show the variation in $\mathcal{L}$(10 Hz) and $\mathcal{L}$(50 Hz) with current; large electrode resonators showed less variation than small and medium electrode resonators, and resonators made of swept quartz had less variations than resonators made of unswept quartz. However, the results may not be statistically significant due to the small number of samples and the large variation of 1/f noise.

Frequency Jumps and Instabilities in the Amplitude-Frequency Curve

Several studies indicate that the frequency dependence on drive current (amplitude-frequency effect) is usually quadratic [7-9]. The amplitude-frequency effect in the resonators used in this study and its effect on flicker frequency noise of oscillators were reported in [10]. As indicated in [10], amplitude noise to PM noise conversion does not limit the flicker frequency noise of 100 MHz (SC-cut, 5th overtone) crystal oscillators. Nevertheless, in some cases the amplitude-frequency curve shows discontinuities or characteristics that cannot be modeled by a quadratic function. We investigated the correlation of these characteristics to the 1/f noise in resonators.

The amplitude-frequency effect of the crystal resonators was measured using the system shown in Fig. 3. In this system a network analyzer was used to sweep the power (current) at the resonant frequency of the resonator.

Table 2. ℓ(10 Hz), variation in ℓ(10 Hz) and ℓ(50 Hz) with drive current and occurrence of jumps on the transfer function for all resonators tested. (RT refers to measurements at room temperature, TO refers to measurements at the turnover temperature.)

Small Electrode				
A	B	C		D
Resonator	ℓ(10Hz) [dBc/Hz]	Change with I in ℓ(10Hz) [dB]	L(50Hz) [dB]	Jump
17	-103.5	3.3	3.6	no
18	-95	4.3	2.4	no
19	*-109.9*	2.4	4.1	no
20	-106.9	2.5	2.4	no
21	-95.3	3.3	3.3	yes
22	-102.7	9.4	3.5	no
23	-104.7	2.7	3	no
24	*-91*	9.2	7.5	yes
25	-105.6	2.6	2.1	no
26	-94.6	3.5	3.9	yes
27	-92.1	11.5	13	yes
28	-104.3	6.4	2.6	no
Average	-100.5	5.1	4.3	4
Median	-103.1	Dev.	6.4 dB	
Large Electrode				
31	-94.9	5	4.2	yes
32	-107.6	2.1	1.9	no
33	-102.6	3.2	4.2	yes-RT
34	-96.2	0.6	0.6	no
35	-88	0.4	1.8	yes-RT
36	-97	2.9	2.1	no
37	*-109.5*	2.9	2.8	no
38	-97.6	0.1	1	yes-TO
39	-104.9	4.4	3.2	no
40	*-83.6*	3.9	3	yes-RT
41	-97.7	10.3	6.3	no
42	-98.5	0.2	1	no
Average	-98.2	3	2.7	5
Median	-97.7	Dev.	7.5 dB	
Medium Electrode, swept, special polish				
C1	-96.1	3.7	2.5	no
C2	-95.5	1.4	0.6	no
C3	-95.4	2.5	2.5	no
C4	-92.2	9	8.2	yes-TO
C5	-103.4	3.5	4.1	no
C6	-99.3	3.2	2.6	yes-RT
C7	*-83*	6.1	6.5	no
C8	-92.3	5.8	1.3	yes
C9	-98.5	2.1	2.2	yes-RT
C10	*-108.8*	4.6	3.9	no
C11	-93.3	12.8	11.8	no
C12	-102.3	4.4	4.6	no
Average	-96.7	4.9	4.2	4
Median	-95.8	Dev.	6.6 dB	

Medium Electrode				
A’	B’	C’		D’
Resonator	ℓ(10Hz) [dBc/Hz]	Change with I in ℓ(10Hz) [dB]	ℓ(50Hz) [dB]	Jump
1	-101.7	2.4	1.5	yes-TO
2	-99.7	6.5	4.4	yes
3	-91.2	6.5	4.9	no
4	-96.5	6.2	7.1	yes
5	-101.6	7.9	5.4	no
6	-107	4	3	no
11	*-89.3*	3.2	3.8	no
12	-102.6	6.5	6.3	yes-RT
13	-98.9	4.4	4.5	no
14	*-110.1*	2.7	2.4	no
15	-102.2	1.4	0.5	yes-RT
16	-102.7	10.2	10.8	no
Average	-100.3	5.2	4.6	5
Median	-101.6	Dev.	5.9 dB	
Small electrode, swept, special polish				
E1	-93.1	4.4	4.1	no
E2	*-107.5*	1.5	1.2	no
E3	-93.5	9.3	6.8	yes-RT
E4	-104.8	5.6	2	no
E5	-105.4	3.8	4.1	yes-RT
E6	-106.6	1.2	1.4	no
E7	-104.6	3.5	3.5	no
E8	-97.3	5.7	5.9	yes-RT
E9	-96.4	6.7	6.4	no
E10	-99.4	2.4	3.3	yes-TO
E11	*-89.3*	1.8	0.9	yes-TO
E12	-103.7	0.6	2.9	no
E13	-102.5	4.3	5.4	no
E14	-98.3	3.61	4	no
Average	-100.2	3.9	3.7	5
Median	-101	Dev.	5.7 dB	
Medium Electrode, swept, special polish, shadow				
D1	*-88.3*	1	1.2	yes
D2	-103.7	3.6	3.7	no
D3	-102.1	2	2.5	yes-RT
D4	-95.4	1.4	1.6	no
D5	-91.6	3.8	4.4	yes-RT
D6	-98.4	1.3	1.6	no
D7	*-105.1*	1.4	1.4	no
D8	-97.9	2.1	3.3	no
D9	-94.7	2.3	2.4	yes-TO
D10	-99.3	0.7	0.5	no
Average	-97.7	2	2.3	4
Median	-98.2	Dev.	5.3 dB	

Table 2. (cont.) ℒ(10 Hz), variation in ℒ(10 Hz) and ℒ(50 Hz) with drive current, and occurrence of jumps on the transmission function for all resonators tested. (RT refers to measurements at room temperature, TO refers to measurements at the turnover temperature.)

Medium electrode, swept				
A	B	C		D
Resonator	ℒ(10Hz) [dBc/Hz]	Change with I in ℒ(10Hz) [dB]	ℒ(50Hz) [dB]	Jump
A1	-101.5	0.7	1.3	no
A2	-95	0.3	0.7	no
A3	*-88*	0.7	2.5	no
A4	-95	0.6	2.8	no
A5	-96.1	0.9	1.3	yes-RT
A6	-97.5	1.1	2.4	no
A7	-104.6	2.5	2.5	no
A8	-100.3	3.1	2.6	no
A9	-103	1.3	1.8	yes-RT
A10	*-104.8*	2	3.2	no
A11	-103.2	3.3	3.2	no
A12	-100.8	0.7	0.6	no
Average Median	-99.2 -100.6	1.4 Dev.	2.1 5 dB	2

Medium electrode, swept, shadowing				
A’	B’	C’		D’
Resonator	ℒ(10Hz) [dBc/Hz]	Change with I in ℒ(10Hz) [dB]	ℒ(50Hz) [dB]	Jump
B1	-97.3	0.9	2.5	no
B2	-97.7	5.1	4	no
B3	-102.5	3.4	2	no
B4	*-106.5*	13.9	13.9	no
B5	-94.1	7.8	8.7	yes-RT
B6	-105	0.6	1	no
B7	-97.2	2.3	2.2	yes
B8	*-91*	5.1	3.9	yes-RT
B9	-102.2	2.7	2.4	yes-RT
B10	-94.8	2	1.9	yes-TO
B11	-99.7	1.8	0.7	no
B12	-93.8	0.7	0.9	no
Average Median	-98.4 -97.5	3.9 Dev.	3.7 4.8 dB	5

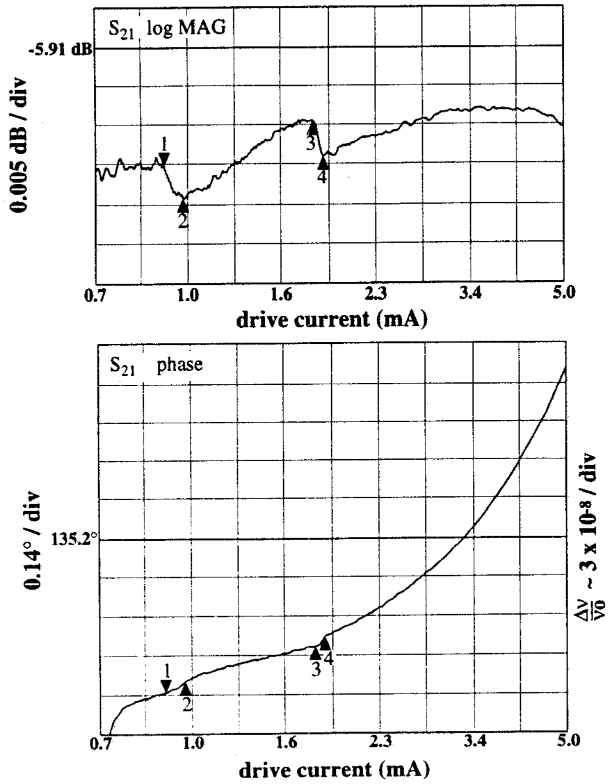

Figure 7. Magnitude and phase of the transmission across resonator 2.

Figure 7 shows the magnitude and phase of the transmission (S21) versus drive current for resonator 2 at the turnover temperature. The fractional frequency axis in the phase plot was obtained using the relation $\Delta\phi = 2Q_L\Delta\nu/\nu_o$, and assuming a loaded Q (Q_L) of 0.4 x 10^5. In this case, the drive current was swept from 0.7 mA to 5 mA. Two discontinuities or jumps (at approximately 1 mA and 2 mA) in the magnitude and phase of the transmission were observed. In an oscillator, phase changes in the loop components translate to changes in the oscillation frequency [11]; therefore these jumps will affect the frequency of oscillation at the currents in which they occur. Discontinuities in the transmission (magnitude and/or phase) were observed in resonators from all 8 groups in Fig. 1. See Table 2 (columns D and D’) for occurrences.

Jumps in the amplitude-frequency curve can affect the 1/f noise of the resonator. In Fig. 8 we show ℒ(10 Hz) for resonator 2 as a function of current. The arrows indicate the direction in which the current was changed. A peak in ℒ(10 Hz) was found at currents close to the current at which the upper frequency jump in the transmission occurred (see Fig. 7).

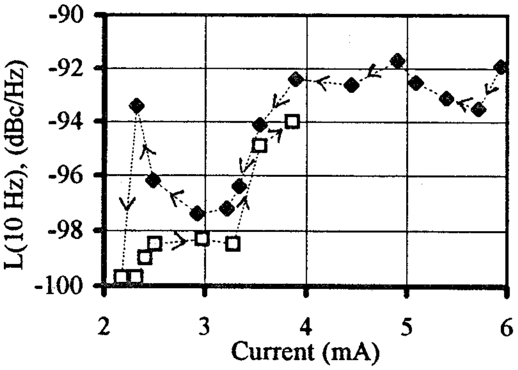

Figure 8. $\mathcal{L}$(10 Hz) as a function of drive current in resonator 2.

A possible explanation for the observed frequency jumps is that they are a result of coupling between the main and unwanted modes. (Coupling to unwanted modes causes the activity dips observed in the frequency versus temperature curve of some resonators [12].) To test this theory, a variable capacitor was added in series with the crystal in Fig. 3 [13]. When the added capacitance is varied, the resonant frequency of the main and unwanted modes changes by different amounts (the motional capacitance varies with mode, and thus the resonant frequency) [13]. If the jumps are due to coupling to unwanted modes, we would expect to see changes in the position of the jumps (current at which they occur) [13]. The load capacitor was changed from 2 pF to 20 pF and no changes in the position of the jumps were observed.

The variation of the jump position with temperature was also investigated. Figure 9 shows the dependence of the jumps observed in resonator 2 with temperature. Trace 1 refers to the lower jump and trace 2 refers to the upper jump. The data indicates that the dependence of the jump position with temperature is roughly linear, and the slope varies for different jumps. Jump position and characteristics in some resonators were also affected when resonators were baked at 100 °C for several days. A possible explanation for the temperature dependence are stresses due to a thermal expansion coefficient mismatch, e.g. between the mounting and the quartz plate. If this is the proper explanation then BVA resonators might not show these discontinuities.

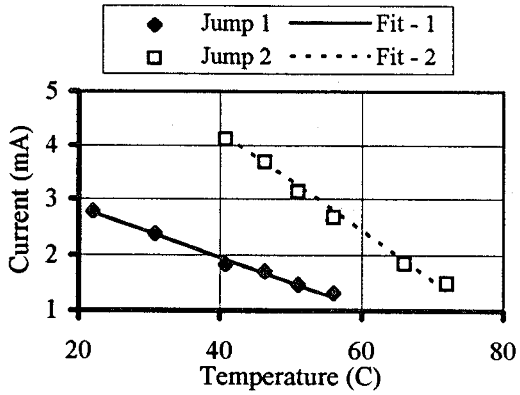

Figure 9. Jump position (mA) as a function of temperature in resonator 2.

The position of the jumps was also affected when the resonator was driven at high currents. In Fig. 10, trace "Initial" shows the initial transmission (magnitude) across resonator 4. A current of approximately 10 mA at resonance was applied across the resonator for about 10 minutes. The magnitude of the transmission was then remeasured ("High" trace, Fig. 10). The position of the jumps changed: jump 1 went from 1.5 mA to 1.35 mA, jump 2 went from 2.5 mA to 1.8 mA.

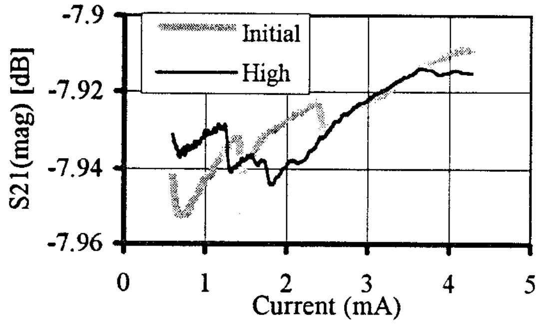

Figure 10. Effect of high drive on the position of the jumps on resonator 4.

The results discussed above indicate that the jumps observed are not due to coupling to unwanted modes, but are probably due to stresses or noisy contacts in the crystal resonator [14,15].

Discussion and Conclusion

1/f noise in all the resonator groups we tested showed a large spread (about 20 dB). The best value measured was $\mathcal{L}$(10 Hz) = -110 dBc/Hz and was obtained for resonators of all three electrode sizes. It is possible that this value is limited by the noise in the electronics of the test oscillator. The possible dependence of PM noise on the electrode volume was difficult to analyze due to the large variation in 1/f noise and the limited number of samples. The median value of the 1/f noise for the 12 unswept large electrode resonators was -97.7 dBc/Hz. For the 12 unswept medium electrode resonators it was -101.6 dBc/Hz, and for the 12 small electrode resonators it was -103.1 dBc/Hz. These results are suggestive but certainly not definitive due to the small number of samples.

The frequency versus amplitude curve of some resonators showed discontinuities or jumps at certain currents. Our results show that the 1/f noise of resonators that had discontinuities in the transmitted signal at the turnover temperature was higher than the 1/f noise of resonators without discontinuities. The average value of $\mathcal{L}$(10 Hz) for resonators showing jumps was -94.8 dBc/Hz, compared to average value of -99.8 dBc/Hz for resonators without jumps. This seems to indicate that jumps observed in the transmission curve are an indication of internal problems in the crystal which lead to poor 1/f noise. Some of the resonators showed a large variation in 1/f noise with current. The reason for this behavior is not clear, although it could be related to the jumps observed in the transmission of some resonators or to self heating of the resonators at high currents. In addition, we observed that in some resonators the frequency versus amplitude curve did not follow the general quadratic dependence. These resonators also show poor 1/f noise: the average $\mathcal{L}$(10 Hz) for resonators with smooth quadratic curves was -100.1 dBc/Hz compared to an average of -94 dBc/Hz for resonators showing jumps and/or non-quadratic dependence on frequency with drive current. This indicates that characteristics of the amplitude-frequency curve of crystal resonators might help identify resonators with internal problems and high 1/f noise.

Acknowledgments

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