DESIGN AND EVALUATION OF UHF MONOLITHIC FILM RESONATOR - STABILIZED OSCILLATORS AND BANDPASS FILTERS

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M. Driscoll*, R. Moore*, J. Rosenbaum**, S. Krishnaswamy**, J. Szedon**
*Westinghouse Defense and Electronics Center
Baltimore, Maryland 21203

**Westinghouse Research and Development Center
Pittsburgh, PA. 15235

SUMMARY

Monolithic, bulk acoustic wave resonators have been fabricated by sputter-deposition of piezoelectric films into supporting membranes formed in semiconductor substrates.

The resonator equivalent circuit consists of a clamped capacitance in parallel with a series combination of motional inductance, capacitance, and resistance. The ratio of the clamped capacitance impedance to the series resistance constitutes a figure of merit (FOM) that provides a measure of device usefulness in oscillator and bandpass filter circuitry.

One-dimensional acoustic analysis results have sucessfully guided the design and fabrication of UHF resonators operating at the second harmonic vibrational mode and exhibiting exceptionally high FOM values.

Voltage controlled oscillators have been constructed using the prototype resonators as the frequency control element. Tuning sensitivities of 800 KHz per volt with good linearity have been achieved using hyper-abrupt varactor diodes. Measurements of oscillator signal phase noise sideband spectra and resonator self-noise indicates that oscillator flicker-of-frequency noise is due to short-term frequency instability in the resonators themselves. Phototype film resonator self noise levels are substantially higher than those exhibited by UHF, quartz surface acoustic wave (SAW) resonators.

The achievement of high resonator FOM has also allowed fabrication of hybrid, multipole, bandpass ladder filters exhibiting 1% to 4% bandwidth and excellent stopband performance consistent with projected channelized receiver selectivity requirements.

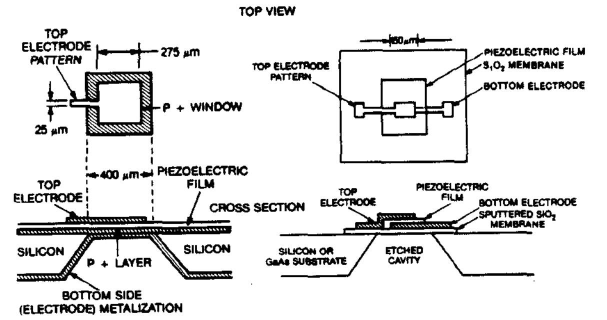
INTRODUCTION

During recent years, work has been progressing toward the development of UHF acoustic resonators that can be fabricated and utilized as stable, high Q, monolithic microwave integrated circuit (MMIC) elements. The aim of these efforts is twofold: (1) circuit simplification and performance improvement associated with stable signal generation and narrowband signal sorting directly at UHF, and (2) resonator volume reduction and fabrication (together with associated active circuitry) in 100% monolithic form.

Monolithic film bulk acoustic resonators are fabricated by sputtering thin films of piezoelectric material such as aluminum nitride or zinc oxide onto supporting membranes formed (by etching) in semiconductor substrates such as silicon or gallium arsenide.[1-4] These resonators are referred to variously as TFRs (thin film resonators), SBARs (semiconductor bulk acoustic resonators), or FBARs (film bulk acoustic resonators). The latter term, of Westinghouse coinage, will be used to refer to these devices.

RESONATOR CONFIGURATIONS

Figure 1 shows two FBAR topologies. The configuration of figure 1(a) is representative of initially utilized prototype devices where the entire (etched) cavity and substrate bottom surface is metallized and constitutes one of the resonator electrodes. In the resonator configuration of figure 1(b), the bottom electrode is sandwiched between the piezoelectric film and the supporting membrane. The latter configuration is preferred since it provides top-side access to both resonator electrodes.



(a) COMPOSITE STRUCTURE WITH BOTTOM SIDE METALIZATION (b) COMPOSITE STRUCTURE WITH BOTTOM ELECTRODE LOCATED BETWEEN PIEZOELECTRIC FILM AND SUPPORTING MEMBRANE

Figure 1 Typical Monolithic Resonator Configurations

RESONATOR FIGURE OF MERIT (FOM)

The FBAR resonant electrical impedance can be represented by the equivalent circuit of figure 2, which is identical to that used for conventional, single crystal (ie, quartz) bulk acoustic resonators.

A resonator figure of merit (FOM) has been defined which provides a measure of resonator usefulness in inductorless oscillator and filter circuitry.[5] Refering to figure 2, the FOM is the ratio, at the device operating frequency, of the impedance of the inter-electrode (or clamped) capacitance to the series resistance. Expressed differently, the FOM is equal to the device unloaded Q divided by the clamped-to-motional capacitance ratio.

$$FOM = \frac{1}{2\pi FoCoRs} = \frac{Qu}{Co/Cm} \qquad [1]$$

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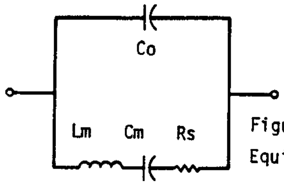

Figure 2 Simplified Resonator Equivalent Electrical Circuit

For the FBAR, achievement of high FOM is dependent on a number of parameters including piezoelectric film acoustic quality (orientation), film/membrane/electrode material selection and thickness, device topology, harmonic mode, and energy-trapping.

<u>FBAR FOM REQUIREMENTS FOR OSCILLATOR STABILIZATION</u>

An important design goal for FBAR oscillator circuitry to be realizable in 100% monolithic form is that the circuit be inductorless. If inductors are required, they should be easily implemented in monolithic form; namely as physically small (low inductance low Q) components.

In the majority of inductorless oscillators using acoustic resonators as the frequency controlling element, the resonator is operated between series and parallel resonance where its impedance provides the required circuit inductive reactance. The resonator FOM describes the degree to which the device can provide inductive reactance before substantial resistance increase and Q degradation occurs. For FOM less than or equal to 2, the resonator will not exhibit inductive reactance at all. In contrast, devices having FOM values greater than or equal to 20 can be operated to provide a reactance-to-resistance ratios of 4:1 with only slight resistance increase and Q degradation.

Figures 3 and 4 show two alternative oscillator design approaches. In the Pierce oscillator of figure 3(a), the sustaining stage portion of the circuit can be considered a negative resistance generator to which the resonator is connected. The steady state requirement for oscillation is that the resonator exhibit an impedance equal to, and opposite in sign, of that of the sustaining stage.

The sustaining stage input impedance contains a negative resistive and capacitive reactive component. For an idealized transistor (transconductance generator, no parasitics.

$$Zin = -j\frac{1}{\omega C1} - j\frac{1}{\omega C2} - \frac{gm}{\omega^2 C1C2} \qquad [2]$$

For actual (non-ideal) devices, the achievable (negative) resistance to (capacitive) reactance ratio decreases and higher corresponding resonator FOM values (inductive reactance to resistance ratio) are required. In addition, if varactor diodes are added in series with the resonator to effect a frequency tuning capability, the resonator must supply additional inductive reactance to "tune out" the diode capacitance.

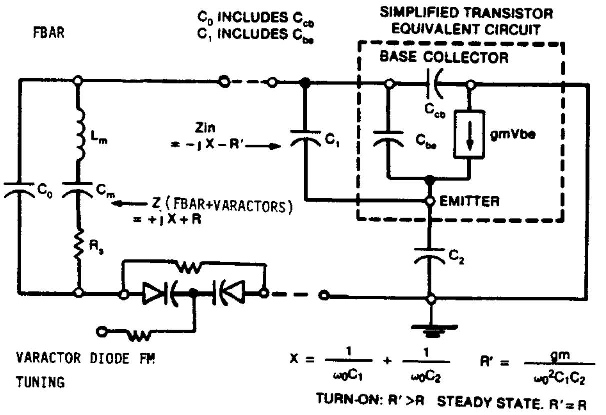

Figure 3 Pierce Oscillator Simplified Block Diag.

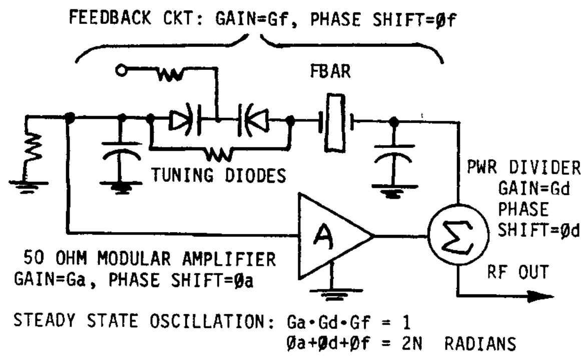

Figure 4 FBAR Oscillator Using Avantek MSA-0370 Monolithic Modular Amplifier

In figure 4, the oscillator is configured as a feedforward (50 ohm) amplifier with the resonator included in the positive feedback path. In order to satisfy the steady state requirement of unity closed loop signal gain and $2N\pi$ closed loop signal phase shift, the resonator included in the feedback circuit must exhibit a high FOM (inductive reactance to resistance ratio) impedance in order to provide adequate feedback circuit selectivity and phase shift. Like the figure 3 circuit, addition of varactor tuning diodes further increases resonator FOM requirements. An advantage of the figure 4 configuration is that independent evaluation of oscillator subcircuits at operating point drive level is easily accomplished using 50 ohm test equipment. In either the discrete transistor or modular amplifier oscillators, auxillary AGC or ALC circuitry is used to reduce the circuit gain to the steady state value or the transistor (amplifer) itself is allowed to current limit at a prescribed quiescent signal level. Voltage limiting (saturation) is not utilized in order to avoid resulting signal phase noise degradation.

<u>ONE-DIMENSIONAL ANALYSIS/MODELING</u>

A one dimensional Mason model was employed to predict resonator electrical impedance as a function of device film, membrane, and metallic (electrode) layers. The model is based on the acoustic/piezoelectric properties of each layer. The device equivalent electrical circuit parameters (motional inductance, capacitance, resistance, and interelectrode capacitance) are derived from the calculated impedance-frequency characteristic.

The data has also been used to predict resonator FOM and the variation in FOM as a function of device topology, including membrane-to-film thickness ratio and harmonic (resonant) mode.

Figure 5 shows a typical one-dimensional analysis result for the figure 1(b) configuration using a ZnO piezoelectric film and a SiO2 membrane. One of the implications of the data of figure 5 is that higher relative FOM over a wider range of membrane-to-film thickness ratios is possible using second harmonic device resonance. In addition, second harmonic FBAR operation implies higher achievable device operating frequency for given film thicknesses. Harmonic operation is an important consideration with regard to extending device operating frequency range.

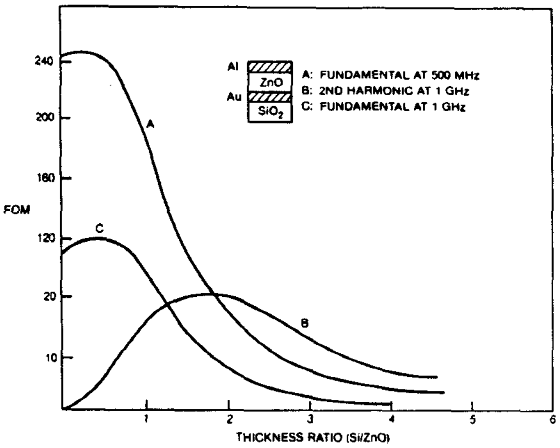

Figure 5 Resonator 1-Dimensional Analysis Results

It should be noted that (figure 5) FOM data scales with the achieved degree of piezoelectric film acoustic quality (acoustic coupling coefficient) and scales inversely with frequency (due to the inverse relationship beween material Q and frequency).

PROTOTYPE RESONATOR CHARACTERISITICS

ZnO-on-SiO2 membrane devices [figure 1(b)] were prepared on silicon substrates at the Westinghouse R&D Center in an attempt to achieve the performance predicted in figure 5. Membrane-to-film thickness ratios of 2:1 (approx. 4 microns : 2 microns) were used to obtain peak FOM values. Several sets of 700 and 900 MHz devices were fabricated. Figure 6 shows device (Smith Chart) resonant impedance characteristics, and typical device equivalent circuit parameters are given in table 1. As shown in figure 6, the device fundamental mode resonant responses are suppressed, eliminating any possibility of unwanted oscillator operation at the fundamental mode.

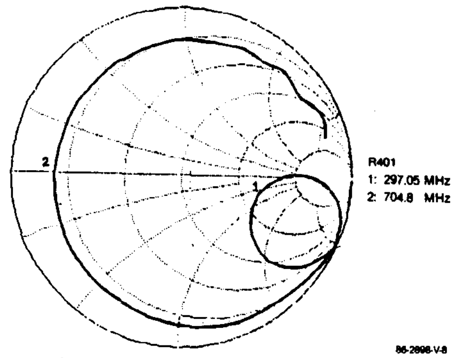

Figure 6 Smith Chart Impedance for Film Resonator 1)Fundamental and 2)2nd Harmonic Resonances

Table 1
Prototype Second Harmonic FBAR Equivalent Circuit Parameters

Resonator Designation	L_M (μH)	C_O (pF)	R_s (ohms)	F_s (MHz)	Q	C_OC_M	FOM
R401	1.5	1.1	5	705.7	1330	32	42
R405	1.6	1.0	7	719.6	1030	33	31
R406	1.8	1.3	11	722.2	740	50	15
R407	1.4	1.2	3	719.5	2100	35	60
R408	1.7	1.4	9	720.2	850	49	17
R470	.49	2.4	5	933.6	575	40	14
R471	.45	2.4	3	942.1	888	37	24
R474	.43	2.4	4	940.9	636	36	18
R476	.33	2.5	4	945.9	490	29	17
R477	.39	2.4	4	936.8	580	33	18

Like other bulk (and surface) acoustic wave resonators, FBARs have been found to exhibit flicker-of-frequency noise. Oscillator signal close-to-carrier phase noise has been found to be normally a result of acoustic resonator self-noise rather than noise sources in the sustaining stage.[6-10]

Measurements of FBAR flicker noise are made by driving the resonator with a stable (synthesized) cw signal and measuring the phase fluctuation spectrum imparted on the carrier signal due to (resonant frequency fluctuation) noise in the resonator.[9,10] The results [in terms of the power spectral density of the fractional frequency fluctuations, Sy (f)[10]] of measurement of FBAR self noise levels are plotted in figure 7. By comparison, similar

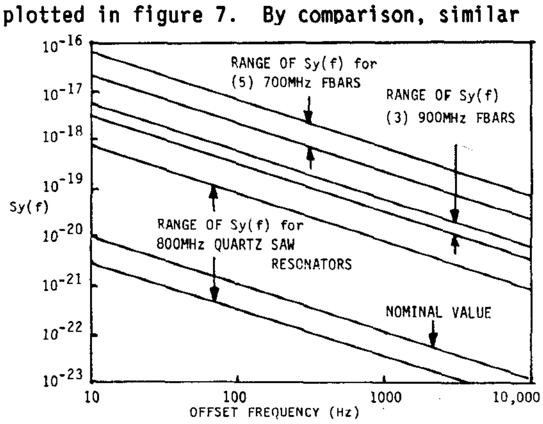

Figure 7 Comparison of Monolithic Film and Quartz SAW Resonator Self-Noise Spectra

data for conventional quartz SAW resonators is also plotted in figure 7. The figure 7 data indicates, as expected, a significantly higher level of short-term frequency instability for the FBAR.

FBAR-STABILIZED OSCILLATOR PERFORMANCE

Prototype voltage controlled, FBAR stabilized oscillators were constructed usng the oscillator configurations of figures 3 and 4 using a 2N4260 transistor and an Avantek MSA-0370 amplifier, respectively. Hyperabrubt varactor diodes were used to provide oscillator voltage-frequency tuning capability.

Figures 8 and 9 show the measured tuning characteristic and phase noise sideband spectra for the prototype oscillators. As shown in figure 9, oscillator near-carrier (flicker of frequency) noise is due to short term frequency instability in the resonator itself. Methods for reducing acoustic resonator self noise levels is currently an area of active investigation in the frequency control community.[6-10] In spite of the currently poorer flicker noise performance, it is anticipated that the advantages of large tuning sensitivity (due to low resonator capacitance ratio), monolithic circuit implemtation, and UHF operating frequency range may make FBAR stabilized oscillator circuitry useful in applications requiring only moderate short-term frequency stability.

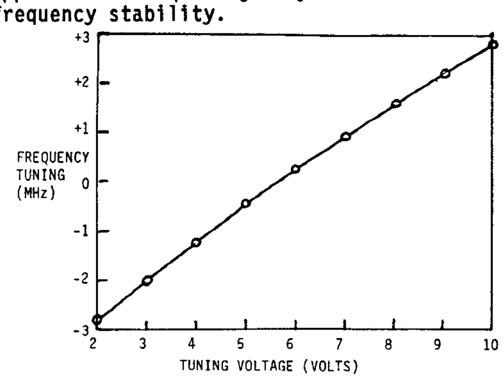

Figure 8 Measured Tuning Characteristic for 700MHz, FBAR-Stabilized VCO

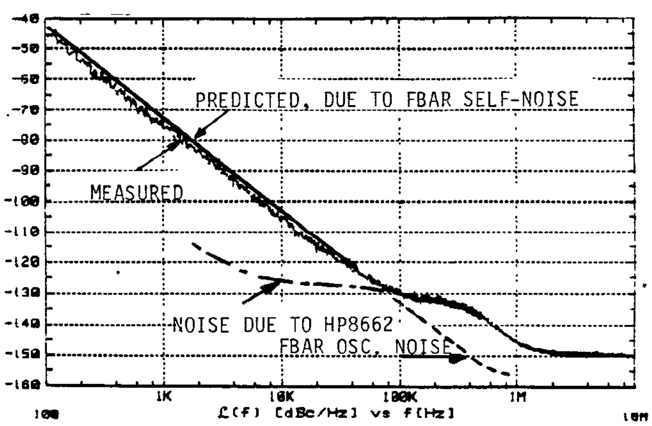

Figure 9 Phase Noise for 700MHz, FBAR-Stabilized VCO

CONCLUSIONS

Monolithic film resonator evaluation, in terms of device figure of merit (FOM) provides a measure of device usefulness in oscillator and filter circuitry.

One dimensional resonator analysis can probide valuable insight eith regard to optimization of device FOM. Three-dimensional analysis is required to adequately predict effects of energy trapping and an harmonic spurious resonances.

In oscillator circuitry, resonator self (flicker of frequency) noise results in signal near-carrier noise levels much higher than that attainable using quartz SAW resonators.

Monolithic processing and high acoustic coupling make the resonator an attractive candidate for UHF monolithic oscillator and multipole filter circuitry.

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