Modified Butterworth-Van Dyke Circuit for FBAR Resonators and Automated Measurement System

John D. Larson III*, SM, Paul D. Bradley+,SM, Scott Wartenberg+, Richard C. Ruby+
*Electronic Research Laboratories
Agilent Laboratories, 3500 Deer Creek Road, Palo Alto, CA, 94304
+Wireless Semiconductor Division, Agilent Corp.[1]

Abstract – Microwave Film Bulk Acoustic Resonators (FBARs) may be characterized by means of the Mason transmission line model, but for parameter extraction and design studies, the lumped Butterworth-Van Dyke (BVD) model is more useful.

We propose a modification to the standard five element BVD model, in which a second resistor is added in series with the plate capacitance C_0. This improves the model predictions as compared to the data obtained from a network analyzer (NWA). Here, the modified model will be developed in terms of the resonant frequencies, effective coupling constant k_t^2, and the quality factor Q, as determined from the S parameters of an FBAR measured by the NWA.

To evaluate the FBAR resonators on a routine basis, an automated data acquisition & parameter extraction method based on the Modified Butterworth-Van Dyke model (MBVD) is described. An Agilent Technologies 8753ES NWA operating under Personal Computer control is used to acquire and process FBAR data by means of a custom HPVEE ™ program, which transfers data from the NWA, and extracts the six MBVD circuit parameters. Excellent agreement is obtained between the measured data for a typical FBAR resonator and calculated "postdictions" obtained from the MBVD circuit.

Coupled with the automated method, which takes about 10 seconds per resonator to perform a complete extraction cycle, a computer controlled probing station is used to acquire data from several hundred resonators on the wafer upon which the FBARS were fabricated. With this speed and probing capability, it is feasible to wafer map the FBARs for uniformity. Contour plots of the measured resonant frequency and coupling constant k_t^2 will be presented to illustrate the capability.

INTRODUCTION

Thin Film Bulk Acoustic Resonators (FBARS) are conveniently fabricated by micromachining techniques [1] from Aluminum Nitride (AlN) piezoelectric films with refractory metal electrodes. Such resonators may be characterized by means of the one dimensional, 3-port Mason model [2], expressed in a transmission line format [3, 4] for convenient calculation.

For one-port resonators with negligibly thin electrodes, this model may be simplified further to the four element circuit consisting of a plate capacitance C_0 in parallel with a series R_1-L_1-C_1 circuit [5], shown in Figure 1(A). (Note: R_0=0 at this point). There is a series resonant frequency, ω_s, set by L_1, C_1; and a parallel resonant frequency, ω_p, set by C_0 in series with C_1 and L_1. The capacitance ratio r is defined as $r = C_0/C_1$. By adding a series resistor R_s at the input, the electrode electrical losses are included. This equivalent circuit for a piezoelectric resonator is called the Butterworth-Van Dyke (BVD) model [6].

For FBAR piezoelectric plates, vibrating in the thickness mode, and exhibiting weak coupling, the effective electro-acoustic coupling constant k_t^2 may be defined [7] as:

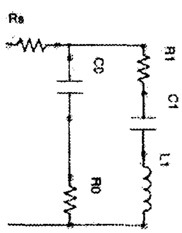
$$(k_t)^2 = \left(\frac{\pi^2}{4}\right)\cdot\left(\frac{\omega_s}{\omega_p}\right)\cdot\left(\frac{\omega_p - \omega_s}{\omega_p}\right) \qquad (1)$$

which is related to the capacitance ratio by:

$$(k_t)^2 = \left(\frac{\pi^2}{8}\right)\cdot\left(\frac{1}{r}\right)\cdot\left(1 - \frac{1}{r}\right) \qquad (2)$$

The BVD model yields a circular impedance locus on a Smith Chart. Experimentally, we find that our FBARS, operating in the 1900 MHz frequency range, exhibit an impedance locus with departures from a circular locus. This effect was analyzed many years ago [8], and described as due to material losses. The results can be summarized by adding a resistor of value R_0 in series with the plate capacitance C_0. This sixth component produces substantial agreement of the circuit model predictions to the measured data for FBAR resonators.

Figure 1(A) illustrates the modified Butterworth-Van Dyke circuit (MBVD), Figure 1(B) illustrates an impedance locus 1) as measured, and 2) as fitted by a circuit simulator [9] implementation, which optimizes all six MBVD circuit component values in a least mean squares sense, to best fit the measured data. Shown in Figure 1(B) is the fit with a five component BVD model (R_0=0Ω) and the improvement with the MBVD six component model (R_0= 0.85 Ω).



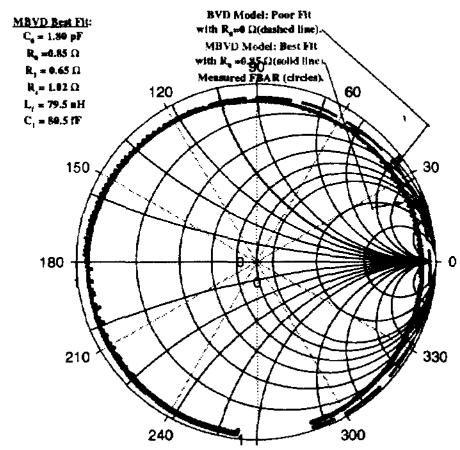


Figure 1(A) – Modified BVD Model (R_0 > 0 Ω).

Figure 1(B) – Measured & Fitted FBAR Response for BVD Model (R_0 = 0) & MBVD (R_0 = 0.85 Ω).

Thus, a model with good agreement to the measured data has been demonstrated.

ANALYSIS

Mapping out the variations in frequency and coupling across a wafer, is very useful to the fabrication facility for diagnostic purposes, so a rapid procedure is desired.

Although the above procedure produces a very accurate equivalent circuit, in practice it is a slow and cumbersome method because 1) the data acquisition is done on an NWA, 2) the data must be transferred to a host computer elsewhere in the laboratory, and 3) the ADS software runs for up to several minutes to produce the exquisite fit seen in Figure 1(A). For routine laboratory use, a method is needed that extracts the circuit parameters accurately, but without the long data processing chain and attendant delay.

It is in the context of several thousand dice per wafer that extracting information rapidly becomes an issue. Measurement and parameter extraction of an individual FBAR must be done quickly enough to allow a significant number (>100) to be measured in under an hour (rate>1 per minute). To this end, an analytical form of the modified BVD model will be derived that conveniently relates the measurable quantities of frequency, Q-factor, and capacitance to the circuit parameters, and can be fully integrated into a data acquisition system where the data reduction can be done with a personal computer.

The starting point for this system is to derive a convenient form of the complex input impedance $Z(\omega)$ = $R(\omega)+jX(\omega)$ for an FBAR resonator for the equivalent circuit of Figure 1(A). With a few minor approximations, the impedance $Z(\omega)$ takes the following form:

$$Z(\omega) = \frac{X_p}{j\cdot\left(\frac{\omega}{\omega_p}\right)} \cdot \frac{\left[1-\left(\frac{\omega}{\omega_s}\right)^2 + j\cdot\left(\frac{\omega}{\omega_s}\right)\cdot\frac{1}{Q_{so}}\right]}{\left[1-\left(\frac{\omega}{\omega_p}\right)^2 + j\cdot\left(\frac{\omega}{\omega_p}\right)\cdot\frac{1}{Q_{po}}\right]} \qquad (3)$$

where:

$$r = \frac{C_0}{C_1} \qquad \omega_s = \frac{1}{\sqrt{L_1 \cdot C_1}} \qquad \left(\frac{\omega_p}{\omega_s}\right)^2 = 1 + \frac{1}{r}$$

$$X_p = \frac{1}{\omega_p \cdot C_0} \qquad \frac{1}{Q_s} = \omega_s \cdot R_1 \cdot C_1 \qquad \frac{1}{Q_e} = \frac{\omega_s \cdot R_0 \cdot C_0}{r}$$

$$\frac{1}{Q_{s0}} = \frac{1}{Q_s}\cdot\left(1 + \frac{R_s}{R_1}\right) \qquad \frac{1}{Q_{po}} = \left(\frac{\omega_p}{\omega_s}\right)\cdot\left(\frac{1}{Q_s} + \frac{1}{Q_e}\right)$$

It is apparent that all six modified BVD circuit parameters are contained in these expressions, and that they are related easily to frequencies or to Q factors, both of which can be very accurately measured.

DATA ACQUISITION SYSTEM

To acquire experimental data, two miniaturized Cascade RF probes as illustrated in Figure 2, contact the two FBAR resonators at a given die location. The probes are connected respectively to port 1 or port 2 of an Agilent Technologies model 8753ES [10] vector microwave network analyzer (NWA), as shown in Figure 3. The NWA measures the S_{11} or S_{22} parameter of the respective resonator vs. frequency, and converts it to a complex impedance or admittance, in this case for S_{22}.

The probe/NWA combination was calibrated previously by means of a short/open/load calibration procedure, which establishes a reference plane at the FBAR terminals and removes the imperfections of the intervening coaxial lines as well as the residual errors of the NWA. For accurate measurements, it is necessary to establish the reference planes to within an accuracy of +/- 1 degree in phase, i.e. to be sure that respectively the open and short circuit calibration standards produce reflection coefficient outputs at: 1@ 0 degrees and 1@ 180 degrees.

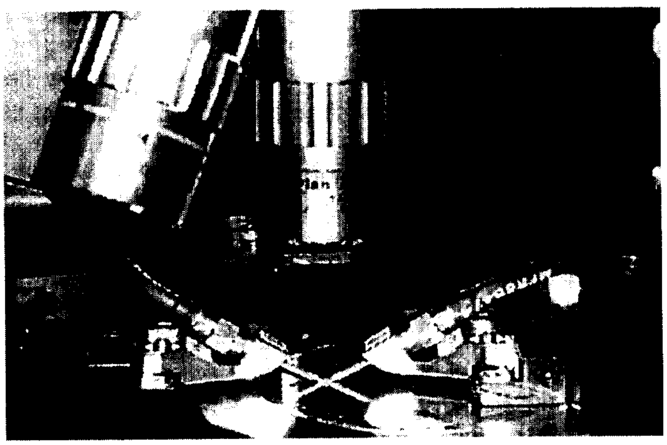


Figure 2 – FBAR Resonators on a Silicon Wafer, & Two RF Probes Contacting Adjacent FBARS on a Die.

PARAMETER EXTRACTION

To extract the six parameters of the modified BVD circuit at a given frequency ω, six measurements are needed. These are conveniently: the series and shunt resonant frequencies; the effective quality factors Q_{s0} and Q_{p0}; and the capacitance and resistance at frequencies far away from the series or shunt resonance. In this work, the expected resonant frequencies are around 1.90 GHz, so 1, 1.2, 3, 3.2, 3.4, and 4 GHz are chosen for the "off resonance" frequencies, see Figure 4, for a "wideband sweep" of the real part R. The real and imaginary parts of the input impedance are measured at these frequencies. The resistance R (real part) at the six "off resonance frequencies" is averaged, and the result is used in the

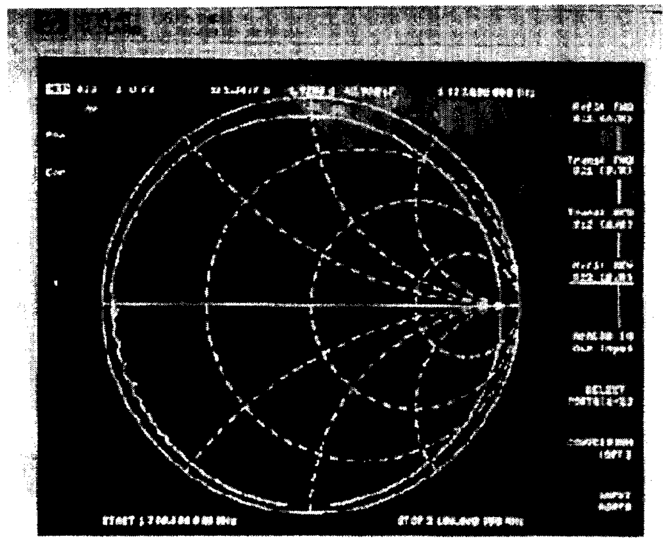


Figure 3 – Network Analyzer with a Smith Chart Display of the FBAR S_{22} Reflection Coefficient.

calculation of R_s and R_0. The reactance $X(\omega)$ (imaginary part) at each frequency is multiplied by the corresponding radian frequency ω, the result inverted and averaged, to obtain the capacitance C_0.

The resistive terms R_s, R_0, and R_l are determined by solving the expressions for Q_{s0} and Q_{p0} in equation (3), and combining the result with the resistance value obtained above.

Figure 5 illustrates the result of converting the measured input S-parameter to magnitude of admittance $|Y(\omega)| = |1/Z(\omega)|$ vs. frequency. The series resonance corresponds to a maximum in admittance (minimum in impedance) and can be found automatically by the NWA. Likewise, the NWA can measure the –3 dB bandwidth of the resonance and report the quality factor, Q_{s0}. To obtain the shunt resonance f_p and the quality factor Q_{p0}, the procedure is repeated for the magnitude of impedance $|Z(\omega)|$ vs. frequency.

The capacitance ratio r is determined by measuring the resonant frequencies ω_p, ω_s at which the impedance or admittance is pure real, and by means of the relationship $r=[(\omega_p/\omega_s)^2-1]^{-1}$.

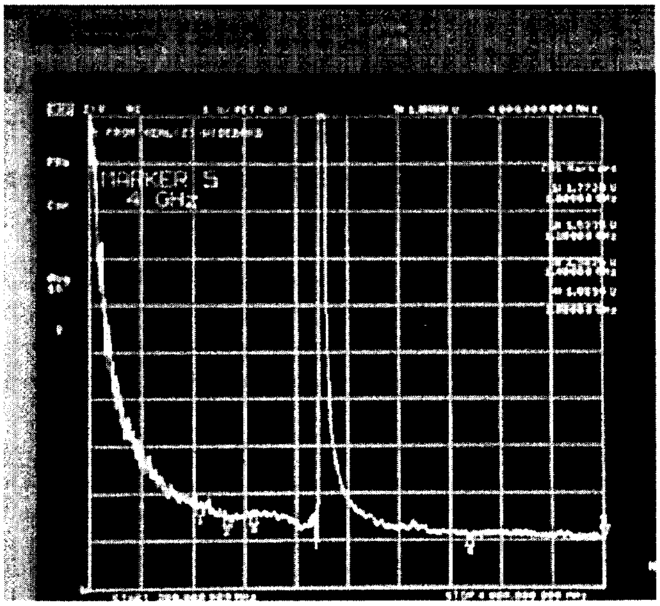


Figure 4 – Real Part of Impedance vs. Frequency for a Wide Frequency Sweep (0.5 to 4 GHz). Used to Obtain Model Resistors R_0, R_1.

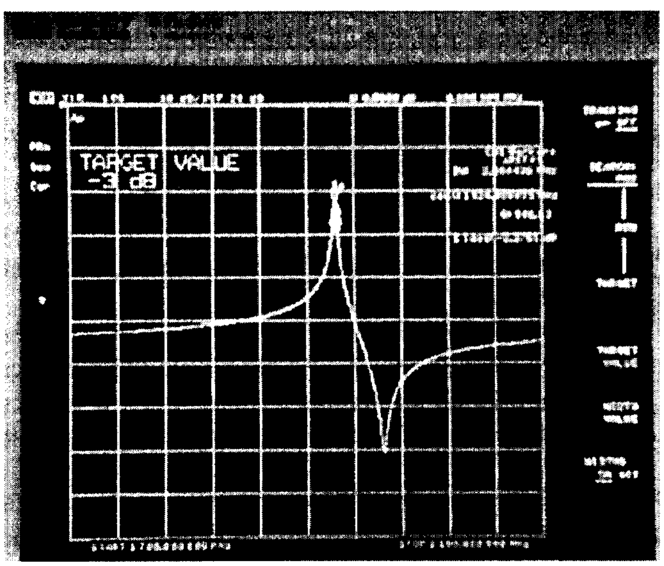


Figure 5 – FBAR Input Admittance |Y| vs. Frequency. Illustrates Series Resonance f_s & Measured Q_{s0}.

The effective electro-acoustical coupling constant k_t^2 is determined from equation (1). The capacitance C_1 is determined from r and C_0. The inductance L_1 is determined from ω_s and C_1. These relations are captured in the data reduction program, to be described next.

Computerized Data Reduction

A personal computer (PC) controls the data acquisition, and provides a convenient means to reduce the measured data to the six BVD circuit parameters. The computer communicates with the NWA by means of a General Purpose Instrument Bus (HPIB). The data collection is accomplished by means of a resident control program, written in the HP VEE (TM) Visual Programming Language [11]. This allows the computer to use the internal frequency and Q determining routines in the 8753ES NWA, for high precision measurements of the FBAR resonant frequencies, f_s, f_p, and the quality factors Q_{s0}, Q_{p0}. The six BVD circuit parameters are calculated as per the previous section.

A routine then takes the derived parameters and calculates a Smith Chart plot of the complex reflection coefficient S_{11} or S_{22}, and plots it along with the measured data to check for gross errors. No attempt is made to improve the fit.

When a personal computer with ~ 100 MHz clock rate is used, the program acquires data from two FBAR resonators, reduces it to the MBVD parameters, calculates the "postdiction", and plots the results in ~ 10 seconds per resonator.

Figure 6 illustrates the Output Panel as seen on the computer monitor, with the six MBVD parameters displayed for each of two FBAR resonators, whose frequencies are typically ~ 3% apart. These are the prototypical units used to build a ladder filter. The equivalent circuit usually produces a very good fit to the measured FBAR resonator data. On occasion, the fit deviates due to ripples at the cardinal frequency points, or at the off-resonance frequencies where the plate capacitance C_0 may deviate.

Wafer Mapping

A major goal of this work is to produce 3" diameter silicon wafers with several thousand or more identical ladder filters, composed of multiple

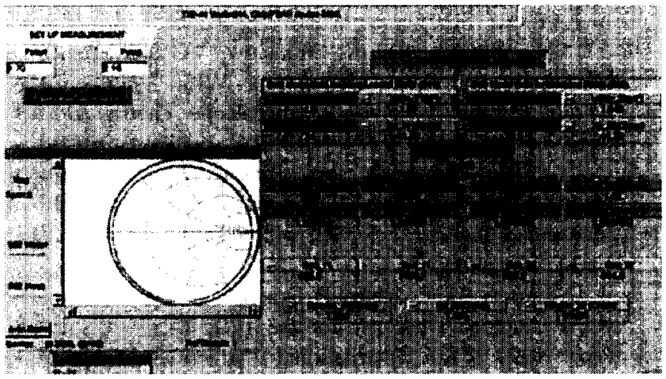


Figure 6 – Front Panel Display of Measured BVD Circuit Parameters for Two FBARS (Numerical Entries), & Computed Reflection Coefficient S_{22} as Overlaid on the Measured Data (Smith Chart).

FBAR resonators set to precise frequencies [6,12]. A technique to map important parameters, such as parallel frequency f_p and the effective coupling constant k_t^2, is needed. An Electroglas 2001 computer controlled probing table was added to move the wafer under the Cascade miniature RF probes, and raise it into electrical contact, when the proper die location is reached. The automated data acquisition part of the above system then measures the current FBAR, and stores the data in a file for eventual plotting.

The Electroglas probe table can move & index in less than a second, so it is not the major limiting factor in acquiring the wafer map data. By selecting the diagnostic FBAR resonator dice on the wafer (~300 units), it was possible to map a wafer completely in somewhat more than one hour.

Figure 7(A) illustrates a contour map of the effective k_t^2 with contour intervals every 1% from $k_t^2 = 0$ to $k_t^2 = 7\%$ in 0.5% intervals. Approximately 300 die were measured to obtain this map. The particular wafer shows FBAR resonators with very good uniformity over the central 2" of the 3" wafer diameter, with greater variations occurring further out.

Figure 7(B) is the map of the parallel resonant frequency $f_p(x,y)$ across the wafer, expressed as deviation from the average value $< f_p >$, in [%] of f_p. Here the contour intervals are 0.5%, the average is 1923.3 MHz, with a standard deviation of 35 MHz or 1.8% of $< f_p >$. Over the central 2" diameter of the wafer, the uniformity does not degrade more than +/- 0.5% from the mean.

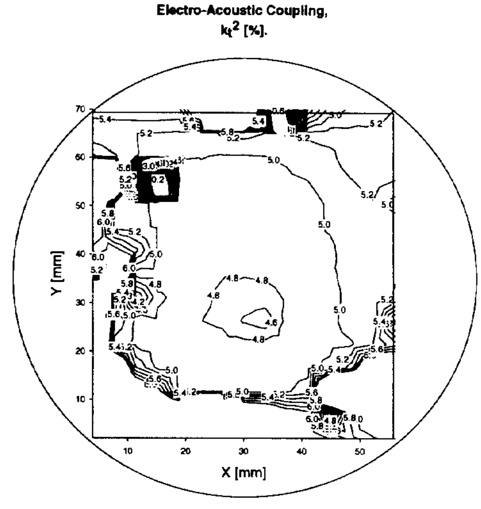


Figure 7(A) – Contour Map of effective k_t^2 for AlN Thin Film FBAR Resonators.

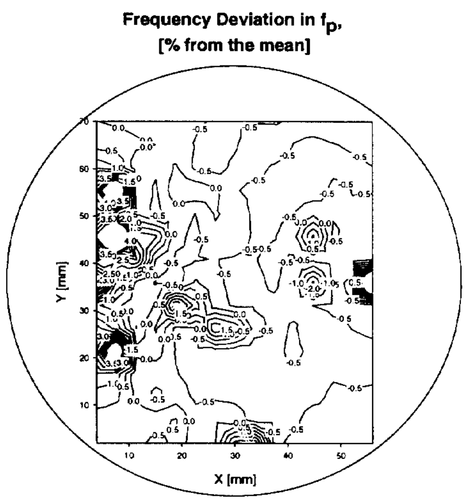


Figure 7(B) – Contour Map of Frequency Deviation for f_p from the Mean $<f_p>$, [%].

Conclusions

An additional circuit element in the standard BVD model is required to obtain good agreement between the measured data of an AlN FBAR resonator and the theoretical "postdictions" of the BVD circuit.

A new model, the Modified Butterworth-Van Dyke circuit, is introduced and characterized in terms of the measurable quantities – resonant frequencies, Q factors, "off resonance resistance", and capacitance. This six element equivalent circuit is found to produce "postdictions" which agree with the measured data, usually within 5% for the reflection coefficient magnitude.

A microwave network analyzer based measurement system, controlled by an HP VEE Visual Program on a PC - and utilizing the measured series & parallel resonant frequencies along with the measured Q's and capacitance - extracts the parameters for the modified BVD model. An individual resonator may be characterized in as little as 10 seconds.

Wafer mapping has been demonstrated. An automated probe station moves the wafer under a pair of miniature probes and lifts the wafer into contact with the appropriate die probe. The PC commands a data dump from the NWA into the PC, which reduces the data, plots it, and stores it to a file. Over a 3" diameter wafer, frequency uniformity is found to be less than 0.5% over 2/3 of the wafer.

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