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Parasitic analysis and π -type Butterworth-Van Dyke model for complementary-metal-oxide-semiconductor Lamb wave resonator with accurate two-port Y-parameter characterizations

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The parasitic effects from electromechanical resonance, coupling, and substrate losses were collected to derive a new two-port equivalent-circuit model for Lamb wave resonators, especially for those fabricated on silicon technology. The proposed model is a hybrid π -type Butterworth-Van Dyke (PiBVD) model that accounts for the above mentioned parasitic effects which are commonly observed in Lamb-wave resonators. It is a combination of interdigital capacitor of both plate capacitance and fringe capacitance, interdigital resistance, Ohmic losses in substrate, and the acoustic motional behavior of typical Modified Butterworth-Van Dyke (MBVD) model. In the case studies presented in this paper using two-port Y-parameters, the PiBVD model fitted significantly better than the typical MBVD model, strengthening the capability on characterizing both magnitude and phase of either Y11 or Y21. The accurate modelling on two-port Y-parameters makes the PiBVD model beneficial in the characterization of Lamb-wave resonators, providing accurate simulation to Lamb-wave resonators and oscillators. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4945801>]

I. INTRODUCTION

Lamb wave resonators have many applications in sensor systems, clock generations, etc. Recent literatures suggest that Lamb wave resonators have comparative advantages on size reduction, cost savings, and higher resonant frequencies¹⁻³ over competing alternatives. Lamb wave resonators can be made on CMOS compatible technology, making them attractive System-on-Chip (SoC) applications. Thus, there is a critical need for an accurate equivalent circuit model to describe such resonators for better resonator and oscillator designs.

Recently, modified Butterworth-Van Dyke (MBVD) model,^{7,8} which is an improvement on Butterworth-Van Dyke (BVD) model,^{8,9} is a typical equivalent model in the characterization of one-port (i.e., one interdigital transducer (IDT) which consists of two interlocking comb-shaped arrays of metallic electrodes) Lamb-wave resonators,³⁻⁶ as shown in Fig. 1. Recent designs of Lamb-wave resonators have higher resonant frequencies, up to GHz, and smaller sizes.^{1-6,12} To seek better modelling accuracy, many extensions have been proposed to amend the parallel capacitor of the MBVD model,³⁻⁶ which proves accurate for one-port S/Y-parameter (i.e., S11/Y11) characterization, where one of the terminals

of the Lamb resonator is grounded. At hundreds of MHz or GHz, the parasitic reactance becomes manifest because it is proportional to frequency. As a result, electromagnetic coupling among the IDTs and ground increases significantly, the effects of which will be clearly observed using two-port S/Y-parameters (i.e., S11/Y11, S21/Y21).

On the other hand, an accurate two-port S/Y-parameter model for one-port Lamb-wave resonators is more desirable as most of the oscillator designs,¹⁰ and RF applications⁵ use both terminals of a resonator. Hence, accurate modelling on both phases and amplitudes of the two-port Y-parameters is crucial to avoid failed oscillator designs. Several two-port S/Y-parameter models were reported for surface acoustic wave (SAW) transformers/filters,^{11,12} but differences in the architectures limit their application for modelling of Lamb-wave resonators. Another model¹³ can characterize the magnitude of S21, but obvious errors would exist in phase of S21 as well as magnitude and phase of S11.

In this paper, we propose hybrid π -type Butterworth-Van Dyke (PiBVD) model for the two-port characterizations of Lamb-wave resonators. Our proposed model achieves higher precision through the introduction of several effective new features such as the following: Ohmic losses for accurate expressions of substrate or device-layer effects; the concept of interdigital capacitance (IDC) which accounts for the effects from both plate and fringe coupling capacitances; and a new expression for the resistance of the IDT. Proven with

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FIG. 1. Illustrations of (a) BVD model and (b) MBVD model.

experiments, the PiBVD arrives at superb agreements on both the measured phases and amplitudes of the two-port Y-parameters of a Lamb-wave resonator.

II. PIBVD MODEL AND PHYSICAL ANALYSIS

The PiBVD model is illustrated in Fig. 2(b). The substrate losses and interdigital coupling occur between the IDTs and the top three dielectric layers, as shown in Fig. 2(a). The topmost layer can be an oxide passivation or exposed air surrounding the IDTs. The middle layer is made up of piezoelectric dielectric and other insulation dielectrics. The bottom layer can be metal, silicon device layer, silicon substrate, etc. The motional behavior of the resonator is modeled by a series R_m - L_m - C_m . Each element is the parallel combination of all sub-motional elements that appear between the top metal fingers and the bottom electrode. The derivations of R_m - L_m - C_m values have been reported in the previous literature.^{3-8,15}

A. Interdigital transducer and capacitance

The coupling capacitance between the fingers of IDTs is inadequately described using the parallel-plate capacitance in the MBVD model. Due to the small metal thickness, T , the electromagnetic (EM) fields between two fingers of the IDT are not uniformly distributed like plate capacitance illustrated in Refs. 1-8. To obtain an accurate deduction of the coupling capacitance, the IDTs can be regarded as an IDC, C_{IDC} , by considering the piezoelectric film as a dielectric. The electro-mechanical behavior is ignored in this study as C_{IDC} is mainly

FIG. 3. Illustrations, micrographs, and dimensions of the fabricated Lamb wave resonator.

instigated by EM waves. Following the study in Ref. 14, the approximated coupling capacitance of the resonator can be derived as (assuming that the width and space of metal strips are equal, $W = S$)

$$C_{IDC} = (\epsilon_f + 1) L [(n - 3) c_1 + c_2], \quad (1)$$

where ϵ_f is the dielectric constant of the piezoelectric film. c_1 represents coupling capacitance per unit length at each spacing among the $n - 2$ inner fingers, where n is the total number of the IDT fingers; c_2 represents fringe coupling capacitance per unit length that is induced by the two exterior fingers. Values of c_1 and c_2 can be accurately predicted by simulating two patterns with different number of fingers in *Ansys HFSS*. Next, the series resistances of the IDT are

$$R_{IDT1} = \frac{4}{3} \cdot \frac{L}{n_1 W} \cdot \frac{\rho}{T} \text{ and } R_{IDT2} = \frac{4}{3} \cdot \frac{L}{n_2 W} \cdot \frac{\rho}{T}, \quad (2)$$

where W , L , and T refer to the width, length, and thickness of a single metal strip, respectively (Fig. 3). ρ is the resistivity of finger material. $R_{IDT1} = R_{IDT2}$ when $n_1 = n_2 = n/2$. The R_{ESR} is an equivalent series resistor to model the dielectric loss of

FIG. 2. (a) Distributed circuit components of Lamb wave resonator, (b) schematic of the extracted PiBVD model, and (c) dimensions of Lamb wave resonator.

the capacitor, C_{IDC} ,

$$R_{ESR} = \sigma_{IDC} / (\epsilon_{IDC}' \omega^2 C_{IDC}), \quad (3)$$

where σ_{IDC} and ϵ_{IDC}' are the equivalent conductivity and the real part of the equivalent permittivity of the IDC dielectric, and ω the angular frequency. Defining the pad resistances as R_{PAD1} and R_{PAD2} , the resistances, R_{S1} and R_{S2} , are

$$R_{S1} = R_{PAD1} + R_{IDT1} \text{ and } R_{S2} = R_{PAD2} + R_{IDT2}, \quad (4)$$

$R_{S1} = R_{S2}$ when the IDTs are symmetrical.

B. Piezoelectric film and bottom substrate

The high resonant frequencies of Lamb-wave resonators are meant that they suffer from EM transmission losses through the piezoelectric film and the substrate. The coupling parasitic between the IDTs and bottom layer can be represented by the piezoelectric film capacitance, C_f . Ohmic loss (I^2R) in the conductive substrate due to displacement current conducted through C_f is modeled by the RC network comprising of R_b and C_b . R_b and C_b are functions of the IDT area as well as the type of substrate materials. Based on the study on microstrip line,¹⁶ C_{f1} can be expressed as

$$C_{f1} = \epsilon_0 \epsilon_{me} \cdot \frac{A_{e1}}{t_m} \text{ and } \epsilon_{me} = (t_{film} \epsilon_{film} + \sum t_i \epsilon_i) / t_m, \quad (5)$$

where ϵ_{me} and t_m are the equivalent permittivity and the thickness of middle layer, respectively. ϵ_i and t_i are permittivity and thickness of the i th insulator. A_{e1} and A_{e2} are the total bottom surface areas of the two electrodes. ϵ_0 , ϵ_{film} , and t_{film} are vacuum permittivity, permittivity constant, and thickness of piezoelectric film, respectively. Similarly, C_{f2} can be derived in the same way. Equation (5) applies to a single piezoelectric layer as well as a combination of piezoelectric dielectric and

other mounted isolators. The area of electrode is calculated as

$$A_e = n_e (L + G) W + l_e d_e + A_{PAD}, \quad (6)$$

where n_e (i.e., n_1 and n_2 for electrode-P1 and electrode-P2) and A_{PAD} are the number of fingers and pad-connection area. Dimensions of l_e and d_e are plotted in Fig. 3. Lossy resistances R_{b1} , R_{b2} and capacitances C_{b1} , C_{b2} can be defined as

$$R_{b1} = \frac{t_b}{\sigma_b \cdot A_{e1}} \text{ and } R_{b2} = \frac{t_b}{\sigma_b \cdot A_{e2}}, \quad (7)$$

$$C_{b1} = \epsilon_0 \epsilon_b \cdot \frac{A_{e1}}{t_b} \text{ and } C_{b2} = \epsilon_0 \epsilon_b \cdot \frac{A_{e2}}{t_b}, \quad (8)$$

where ϵ_b , σ_b , and t_b are permittivity, conductivity, and thickness of the bottom layer, respectively. For a symmetrical IDT design, $C_{f1} = C_{f2}$, $R_{b1} = R_{b2}$, and $C_{b1} = C_{b2}$.

III. VERIFICATION AND DISCUSSION

Conventionally, grounded bottom electrode is used in the Lamb-wave resonator. Most recently, electrically floating bottom electrode has been introduced and employed in the designs of the AlN Lamb wave resonators, which improves effective coupling coefficient and loaded quality factor of the series resonance.⁶ In this section, Lamb-wave resonators with both the floating and grounded bottom electrodes were fabricated to validate the efficiency of the PiBVD model.

A. Lamb-wave resonator with floating bottom electrode

First, a CMOS compatible Lamb-wave resonator with floating bottom electrode was fabricated (as shown in Fig. 4) to validate our PiBVD model. The resonator has a 1.2- μm AlN and 100-nm SiO_2 layers deposited on a (100) SOI wafer with 50- μm Si device layer, 1- μm buried oxide (BOX) layer, and

FIG. 4. Illustrations, micrographs, and dimensions of the fabricated Lamb wave resonator with floating bottom electrode.

FIG. 5. Y-parameter comparisons of PiBVD model, MBVD model, and measurement for the Lamb-wave resonator with floating bottom electrode.

TABLE I. Parameters of PiBVD model for the Lamb-wave resonator with floating bottom electrode.

R_m (Ω)	L_m (μH)	C_m (fF)	R_{ESR} (Ω)	C_{IDC} (pF)	$Rs_1 = Rs_2$ (Ω)	$C_{f1} = C_{f2}$ (pF)	$R_{b1} = R_{b2}$ (Ω)	$C_{b1} = C_{b2}$ (pF)
8.8	7.4	14.72	0.5	9.1	1.2	17.1	2.9	2.5

600- μm substrate Si. The 50- μm thick top Si layer is of P-typed, heavily doped with a resistivity of $\sim 0.06\text{--}0.08\ \Omega\text{m}$. The 1.2- μm AlN film is first deposited and patterned on the top of the device Si layer. Subsequently, a 0.6- μm thick Al IDT was fabricated on the AlN film with 52 IDT fingers in each electrode. After front side process, the silicon substrate layer was thinned down to 400 μm by mechanical grinding. Next a 2- μm SiO₂ hardmask layer was deposited on the backside of the wafer for release process. Finally the silicon membrane structure was released by deep reactive ion etching (DRIE). Front side SiO₂ is removed by vapor hydrogen fluoride (HF) for contact open. All other geometrical parameters of the resonator are listed in the inset of Fig. 4. Note that the reflectors in the devices are used to concurrently excite SAW mode¹ rather than Lamb wave mode resonance. The resonant frequency of the fabricated Lamb-wave resonator is found at 482 MHz, which agrees with the designed value defined by the phase velocity, finger's width, and spacing.^{1,3}

The Y-parameters of this resonator were measured using vector network analyzer and were compared with both the proposed PiBVD model and the classical MBVD model in Fig. 5. Both models precisely represent the electromechanical resonance with same L_m - C_m and similar R_m values. PiBVD

TABLE II. Parameters of MBVD model for the Lamb-wave resonator with floating bottom electrode.

R_m (Ω)	L_m (μH)	C_m (fF)	R_0 (Ω)	C_0 (pF)	Rs (Ω)
9	7.4	14.72	0.1	25	2

model attains equally great agreements on Y11 as MBVD model. However, at such frequency, the parasitic effects of the silicon device layer become significant, which induces considerable signal energy losing through the silicon device layer. A lack of efficient modelling of such signal losses fails the characterizations of two-port Y-parameters. Such parasitic effects are modelled by R_b , C_b , and C_f in the PiBVD model. Compared to MBVD model, the PiBVD model provides accurate modelling of the transfer admittance Y21. The parameters of both models are tabulated in Tables I and II.

B. Lamb-wave resonator with grounded bottom electrode

Next, to further validate our PiBVD model, a CMOS compatible Lamb-wave resonator with grounded bottom elec-

FIG. 6. Illustrations, micrographs, and dimensions of the fabricated Lamb wave resonator with grounded bottom electrode.

trode was fabricated as shown in Fig. 6. An 8 in. SOI (100) wafer with 30- μm device layer and 5- μm BOX layer is used to fabricate the resonator. First, a 20-nm AIN is grown by atomic layer deposition (ALD) as seeding layer. Next, by using the physical vapour deposition (PVD) technique, 0.2- μm bottom-Mo layer is deposited on top of the wafer, followed by a 1- μm AIN layer and a 0.2- μm top-Mo layer. Next, to form the IDTs, the 0.2- μm top-Mo layer is patterned using plasma enhanced chemical vapour deposition (PECVD) SiO_2 as the hard mask. On the top of the IDTs is a 0.4- μm PECVD SiO_2 layer deposited for isolation. This 0.4- μm SiO_2 layer and the 1- μm AIN layer are etched to open the windows where the Bottom-Mo-to-Top-Metal vias can be formed, so that the bottom electrode can be connected to the pads. The windows which are used to form the Top-Mo-to-Top-Metal vias are

opened by etching as well. Subsequently, a 0.7- μm Al layer is deposited and patterned to form the vias and bonding pads. The process is finished by backside cavity release using DRIE. The geometrical parameters of this resonator are listed in the inset of Fig. 6. The designed IDT periodicity is 10.5 μm , which corresponds to a half of the wavelength. A resonance is found at 334.1 MHz. Therefore, the phase velocity of the corresponding acoustic wave is about 7016 m/s. This phase velocity fits well with the simulation,³ and it is the lowest symmetric mode, S_0 , of Lamb wave.

Again, the Y-parameters of this resonator were measured and characterized with both the proposed PiBVD model and the classical MBVD model, as shown in Fig. 7 and Tables III and IV. In this experiment, the MBVD model can fit favorable with the Y21, but fails to match Y11. The reason is

FIG. 7. Y-parameter comparisons of PiBVD model, MBVD model, and measurement for the Lamb-wave resonator with grounded bottom electrode.

TABLE III. Parameters of PiBVD model for the Lamb-wave resonator with grounded bottom electrode.

R_m (Ω)	L_m (μH)	C_m (fF)	R_{ESR} (Ω)	C_{IDC} (pF)	$Rs_1 = Rs_2$ (Ω)	$C_{f1} = C_{f2}$ (pF)	$R_{b1} = R_{b2}$ (Ω)	$C_{b1} = C_{b2}$ (pF)
35.5	89.523	2.536	1	1.15	2.6	49	0.09	110

TABLE IV. Parameters of MBVD model for the Lamb-wave resonator with grounded bottom electrode.

R_m (Ω)	L_m (μH)	C_m (fF)	R_0 (Ω)	C_0 (pF)	Rs (Ω)
33.1	89.523	2.536	1	1.25	10

that the MBVD model lacks of correct components to model the signal loss path through the bottom grounded electrode. As expected, the PiBVD model attains great agreements on both the magnitudes and phases of Y11 and Y21 as MBVD model.

Two-port Y-parameters are more useful for evaluating resonator performance and for the design of oscillators. In comparison, our proposed PiBVD model is able to achieve excellent modeling of both the phases and magnitudes of Y11 and Y21.

IV. CONCLUSION

A PiBVD model for Lamb-wave resonator is proposed in this paper. When compared against the conventional models, the PiBVD model caters for the lossy effects from Si substrate, fringe and plate coupling capacitances, and interdigital resistance. From the measurements on Lamb-wave resonators with floating bottom electrode and grounded bottom electrode, our model demonstrates much better accuracy than the conventional MBVD model for two-port Y-parameters characterizations and attains excellent agreements on the measured characteristics. This work can certainly help to provide better foundation for oscillator designs to reduce circuit failures, as well as to better understand the characteristics of Lamb-wave resonator especially those beyond acoustic electromechanical analysis.

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