Piezoelectrically Actuated Reconfigurable Multi-Frequency AlN Resonators

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***Abstract*— The need for reconfigurable and miniaturized radio frequency (RF) resonators that can operate in the high traffic commercial and military communication spectrum is growing. Tunable resonators have been demonstrated [1-3] but face frequency range limitations due to material and geometric deformation limits. Switchable banks of resonators allow multi-band radios with broad spectrum coverage. The development of piezoelectric transduction by Aluminum Nitride (AlN) with contour-mode resonator (CMR) technology has become a promising option as it achieves high quality factor, precise wide frequency control [4-5] and CMOS compatible manufacturing process. Moreover, the phase change switch can be introduced [6] to realize the dynamic configurability within a single resonator with the lower insertion loss of phase change vias due to the monolithic integration in the AlN fabrication flow. The methods explored here merge the phase change via multi-mode reconfiguration [6] and multi-frequency tuning [7] methods for AlN resonators. Theoretical analysis, COMSOL and Cadence simulations are conducted to present two reconfigurable switching topologies for AlN resonators.**

I. Introduction

The need for reconfigurable and miniaturized radio frequency (RF) resonators is growing. Reconfigurable devices can lessen the pressure on the high traffic commercial and military communication frequency spectrum. Tunable single resonators have been demonstrated [1-3] but face frequency range limitations due to material and geometric deformation limits. Switchable banks of resonators allow multi-band radios with broad spectrum coverage but require multiple resonators that may be underutilized. Considering both reconfiguration mechanisms are viable, the material platforms of these microstructures determine the reconfiguration potential of reconfigurable resonators.

The development of piezoelectric transduction by Aluminum Nitride (AlN) with contour-mode resonator (CMR) technology has become a promising option as it is a CMOS compatible process. This enables micro-scale AlN resonators to be included in wafer-level fabrication [4-5]. Miniaturizing enables large scale production, but also reduces power handling and less overall volume to displace. The piezoelectric effect of AlN is well defined by the resonator geometry, limiting the ability to excite multiple frequencies through tuning once a geometry is fixed. AlN microstructures motivates the development of RF switching banks to select a single geometry from a broad frequency range. The large network of RF switches and resonators introduces many parasitic resistances and interconnect capacitances, which degrades the quality of the additional RF switches. Because of the losses of merging a RF switch network with AlN resonators, a switching mechanism that may be integrated into the AlN fabrication process is of great interest.

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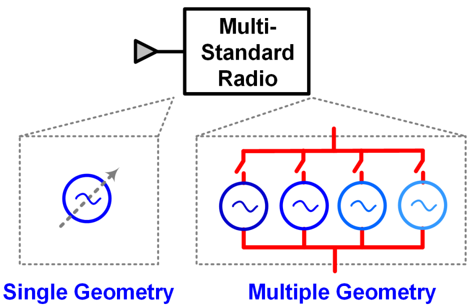

Fig.1: Multi-standard radio using reconfigurable resonators

One option is using a phase change material (PCM) which takes on a low resistance ON state and a high resistance OFF state. Here, Germanium Telluride, $Ge_{50}Te_{50}$, is utilized. The integration of $Ge_{50}Te_{50}$ allows vias formed by the PCM which create uniquely addressable resonators thereby selecting a particular frequency. PCM switches introduce dynamic ON/OFF behavior without degrading the electromechanical quality of the resonator. With up to 10,000 ON/OFF cycle transitions and ON resistances of as low as 1Ω, PCM vias show a promising option for switchable networks of resonators.

Single-geometry multi-mode resonator reconfiguration (Fig. 1) using PCM switch [6] is described in Section II. Fabrication procedure for monolithic integration of PCM switch in AlN resonator fabrication flow is described in Section III. Section IV describes multi-geometry reconfiguration for wide frequency tuning, and proposes PCM based reconfiguration solution to merge these methods for reconfiguring AlN resonators. Section V presents calculated and simulated (using COMSOL and CADENCE) results of reconfiguration, and section VI concludes the report.

II. Single-Geometry Multi-Mode Reconfiguration

A. *Multi-Mode Reconfiguration*

The PCM vias allow each resonator to have four different excitation modes. The different modes change the electric field strength by acting as ON/OFF RF switches that connect the top and bottom metal electrodes through the vias of the AlN resonator. PCM vias have a significant change in resistance (~10^6) between the on (crystalline) and off (amorphous) state. The via can switch between these two states through Joule heating, applied by electric pulses. The

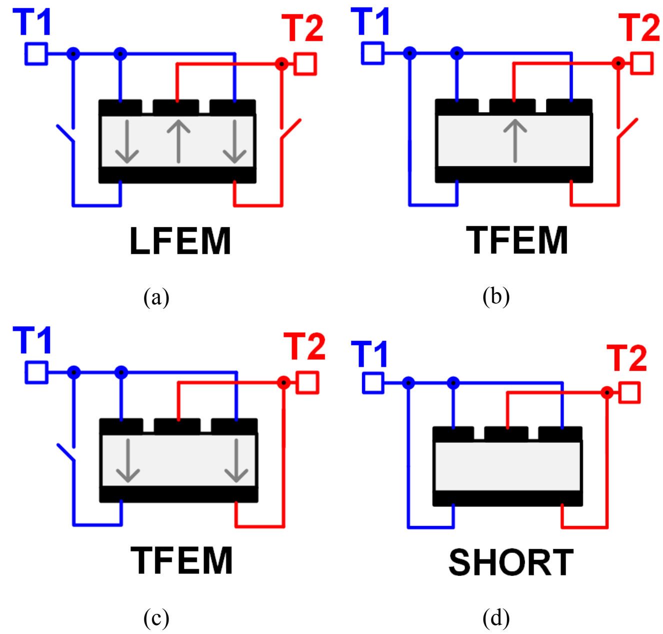

Fig. 2: (a) LFEM, (b) TFEM-HI, (c) TFEM-LO, and (d) SHORT mode reconfiguration. [6]

reversible switching chemistry of PCM vias, as well as the ability to monolithically integrate the vias with established AlN fabrication processes motivates the reconfiguration of resonators through PCM switching. The four excitation modes are enabled through the independent control of the two PCM vias:

- *Lateral Field Excitation Mode (LFEM)* both vias are OFF which leaves the bottom plate as a floating potential. This mode has the lowest C_0 thus highest impedance. (Fig. 2a).
- *Thickness Field Excitation Mode - High Impedance (TFEM-HI)* has only via 1 ON which creates a higher value of C_0. (Fig. 2b).
- *Thickness Field Excitation Mode - Low Impedance (TFEM-LI)* when only via 2 is ON, the highest value of C_0 is obtained. (Fig. 2c).
- *SHORT* mode is when the bottom electrode shorts the two ON vias. (Fig. 2d).

As aforementioned, the static capacitance, C_0, changes in the different modes. The dynamic switching of the vias allows for reconfiguring of the system and the real time changing of lumped motional parameters of Butterworth Van Dyke (BVD) electrical model for the piezoelectric system.

B. The Butterworth Van Dyke Model

The motional components of the BVD circuit model (Fig. 3) take on the following expressions.

$$f_0 = \frac{1}{2W}\sqrt{\frac{E_{eq}}{\rho_{eq}}} \tag{1}$$

Where f_0 is the resonant frequency, W is the finger width, E_{eq} and ρ_{eq} are the equivalent Young's Modulus and material density of the resonator stack. The motional lumped parameters take on the following geometry and material

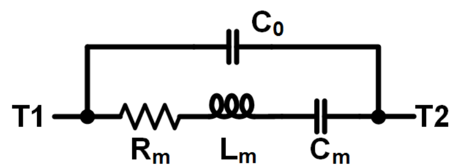

Fig. 3: Butterworth Van Dyke Model of AlN resonator.

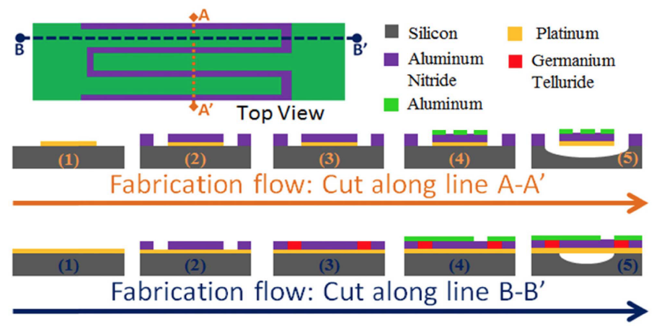

*Fig 3 of [6]

Fig. 4: AlN-PCM monolithic fabrication procedure.

defined expressions:

$$R_m = \frac{\pi}{8}\frac{T}{L}\frac{\rho^{\frac{1}{2}}}{QE_p^{\frac{3}{2}}d_{31}^2},\ L_m = \frac{1}{8}\frac{WT}{L}\frac{\rho}{E_p^2 d_{31}^2},\ C_m = \frac{8}{\pi^2}\frac{WL}{T}E_p d_{31}^2 \tag{2}$$

W, L, and T are the resonator width, length, and thickness, respectively. The AlN Young's Modulus, E_p, piezoelectric strain tensor, d_{31}, and density, ρ describe the complete BVD model. These expressions were used to approximate the motional parameters of the BVD model. The electromechanical coupling coefficient, k_t^2, was determined by the resonance (f_r) and anti-resonance frequencies (f_a) of the COMSOL simulation. It depends on the dimensions of the structure, the piezoelectric material, the electrical and mechanical loading conditions. We can assume that the piezoelectric strain tensor, d_{31}, is difficult to determine accurately outside of simulation data. k_t^2 was derived from COMSOL results by the following expression:

$$k_t^2 = 1 - \left(\frac{f_r}{f_a}\right)^2 \tag{3}$$

The electromechanical coupling of LFEM modes is less than that of TFEM modes, causing a reduced motional resistance of the LFEM mode. The causes the quality factor, Q, of the LFEM mode is less influenced by the electrical loss of the metal electrodes active in TFEM modes [5]. The figure of merit (FOM), defined by the Qk_t^2 product, similarly varies across modes.

We then extracted the same motional components from the simulation results presented in section V. A quality factor, Q, of 2700 was enforced for all calculations and COMSOL simulations.

III. Programmable Resonator Fabrication

The fabrication process for programmable aluminum nitride resonators with phase change vias is well defined [6]. The

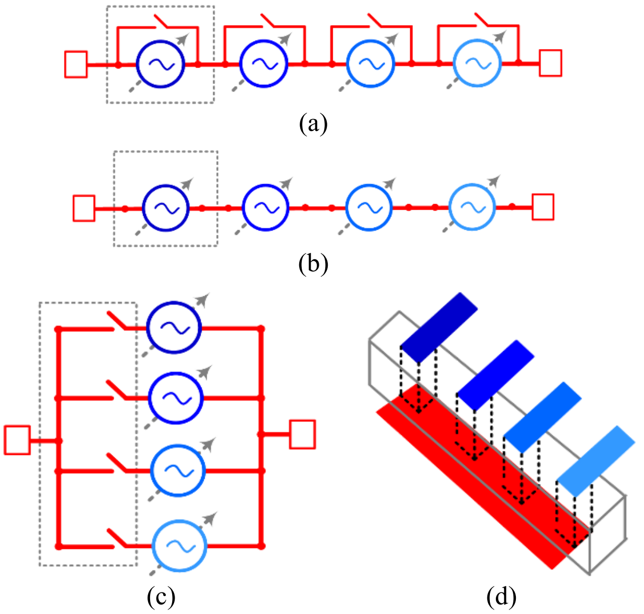

Fig. 5: (a) Series switching multi-geometry multi-mode reconfigurable resonator bank using explicit switch for reconfiguration, (b) Series switching multi-geometry multi-mode reconfiguration using short circuit mode of individual resonator, (c) Parallel switching multi-geometry multi-mode reconfigurable resonator, (d) Phase-change via based switching array structure for parallel switching reconfigurable resonator.

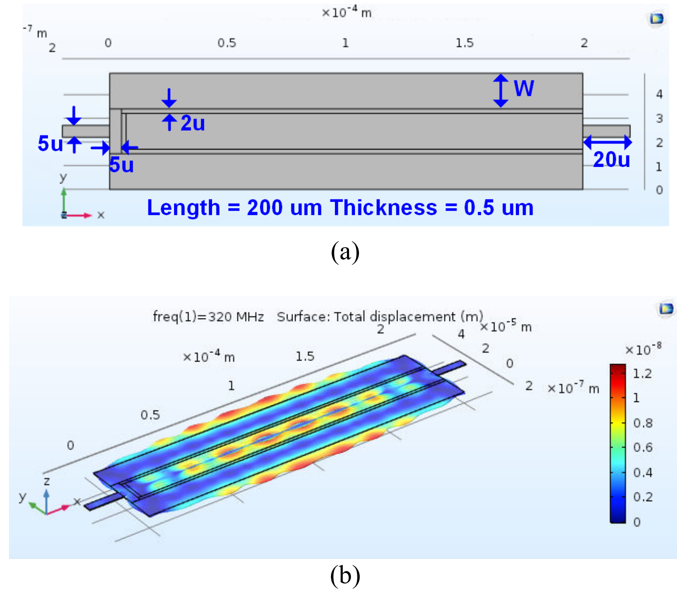

Fig. 6: (a) Resonator geometry (note that W is a variable for different geometries (b) LFEM-LO contour mode resonance mode shape for W=15 μm.

fabrication process presented below uses a post-CMOS compatible 4-mask flow borrowed [6] (Fig. 4). The only difference we expect is the PC via mask which enables the parallel or series phase change topology discussed in the following section.

To monolithically integrate phase change vias the fabrication process started with a high resistivity Silicon (Si) substrate, patterned with a Titanium/Platinum (Ti/Pt) layer deposited via RF/DC sputtering. The AlN layer is then deposited on top of the Ti/Pt layer. The AlN is etched to create open vias with Inductively Coupled Plasma (ICP), using Cl2 chemistry. The phase change material, Ge50Te50, is deposited with DC pulse/DC sputtering and patterned using liftoff. After depositing the Al probing pad, the entire structure is released from the Si by isotropic Xenon Diflouride (XeF2) [6].

IV. Multi-Geometry Multi-Mode Reconfiguration

A. Multi-Geometry Series and Parallel Switching Approach

Although single-geometry multi-mode resonators [6] (described in Section II) can realize easily reconfigurable resonator-electrical-impedance, they achieve almost no frequency tuning. As the resonance frequency of the resonator is well defined by the geometry (Equation 1), frequency reconfiguration is only possible by using multiple resonator geometries in a bank of resonators, and select one of them using series/parallel switch. Two such switching architectures are shown in Fig. 5(a) and (c). As shown in Fig. 5(a), in a series switching approach, resonators with different geometries are put in series, and a shunt switch is use around each resonator to bypass all of the resonators except the desirable one. On the other hand, as shown in Fig, 5(c), in a parallel switching approach [7], resonators with different geometries are put in parallel, and a series switch is used with each resonator to select only the desirable one out of all.

B. Proposed Multi-Geometry Multi-Mode Reconfiguration

To get benefit both from multi-mode and multi-geometry reconfiguration here we proposed to use the PCM-reconfigurable multi-mode resonators [6] as the building block for series/parallel switching resonator bank. PCM via based switches are used both for multi-mode and multi-geometry reconfiguration. In the series switching mode, short circuit mode (Fig. 2(d)) of each individual resonator can be exploited for bypassing, thereby eliminating extra parallel switch for each resonator (Fig. 5(b)). However, in a series switching mode, switch non-idealities from two on-state switches in each bypassed resonator can degrade individual resonator quality factor severely. A parallel switching mode with multi-mode resonators (Fig. 5(c)) can overcome this drawback as a single switch is present in each path. The PCM via based implementation of switching array is shown in Fig. 5(d). Four blue terminals in the top surface are connected to four different geometries with a shared bottom surface, and one extra PC-via per geometry is used to connect top terminal to bottom, thereby implementing the switching.

V. Calculated and Simulation Results

3D finite element method (FEM) simulations were conducted in COMSOL to confirm the calculated BVD components of the AlN resonator. The PCM vias were modeled as ideal open and short circuits in the COMSOL simulations. The resonator geometry used in COMSOL simulation is shown in Fig. 6(a) where W is a variable chosen as 9, 11, 13, and 15 μm for four different simulations. All the other dimensions mentioned in Fig. 6(a) are same for all the geometries. LFEM-LO mode resonance mode shape for $W=15$ μm is shown in Fig. 6(b). The theoretical calculation is performed according to the guideline mentioned in Section

TABLE 1: Calculated and Extracted Parameters of Different Resonators

Width (μm)	Mode	f_r (MHz)		k_t^2 (%)	C_0 (fF)		C_m (fF)		L_m (μm)		R_m (Ω)	
		Calculated	Extracted		Calculated	Extracted	Calculated	Extracted	Calculated	Extracted	Calculated	Extracted
9	LFEM	541	525	1.82	220	296	3.6	4.4	28	21	35	27
	TFEM-HI	541	524	0.7	329	407	1.9	2.3	49	40	60	50
	TFEM-LI	541	524	1.47	659	687	7.9	8.2	12	11	24	14
11	LFEM	453	440	1.53	262	400	3.3	5	40	26	41	28
	TFEM-HI	453	439	0.7	393	526	2.2	3	59	44	60	47
	TFEM-LI	453	439	1.24	786	1173	8	11.8	17	11	17	12
13	LFEM	390	378	1.57	305	420	3.9	5.4	46	33	40	31
	TFEM-HI	390	378	0.69	457	538	2.5	3	70	60	62	56
	TFEM-LI	390	378	1.31	914	1188	9.7	12.6	18	14	16	13
15	LFEM	342	332	1.64	347	463	4.6	6.2	50	37	39	31
	TFEM-HI	342	332	0.66	521	693	2.8	3.7	83	62	64	51
	TFEM-LI	342	332	1.2	1041	1524	10	14.8	23	16	18	13

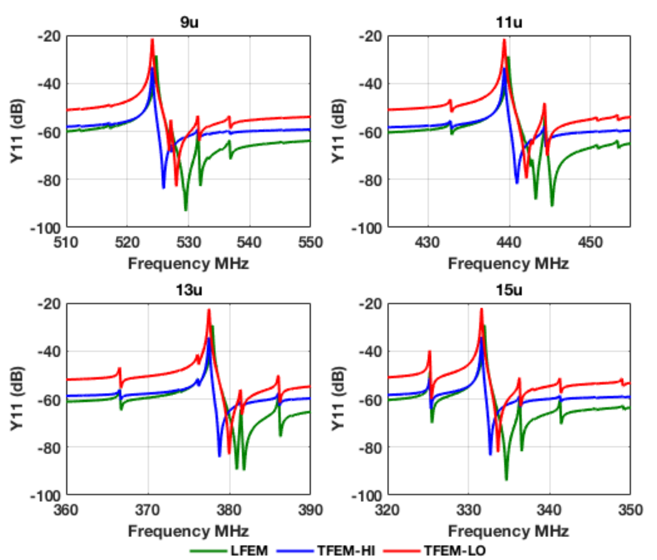

Fig. 7: Simulated (in COMSOL) resonator admittance response for four different geometries (*W=9,11,13,15 um*) and three different (LFEM, TFEM-HI, TFEM-LO) modes for each geometry showing the ability to multi-frequency multi-mode reconfiguration.

II.b. Theoretical calculation parameters and COMSOL simulation extracted parameters are tabulated in Table 1. Admittance plot (Fig. 7) for four different geometries each with three different modes shows frequency and impedance tuning ability. Fig. 5(b) and (c) are then simulated in Cadence using extracted parameters of the resonators, and approximate switch parameters. As it can be seen in Fig. 8, switch non-idealities (i) ON state resistance degrades Q of the series mode more than the parallel, and (ii) OFF state capacitance shifts the anti-resonance frequency more in parallel structure than series. It should also be noted that improving switch parasitic (decrease C_{OFF} from 1 pF for 0.1 pF and R_{ON} from 15Ω to 2Ω) improves the performance of the tank as can be seen in Fig. 8.

VI. Conclusion

Two architectures for multi-mode multi-geometry PCM via based reconfigurable AlN resonators are introduced. Theoretical calculations and simulations are presented to

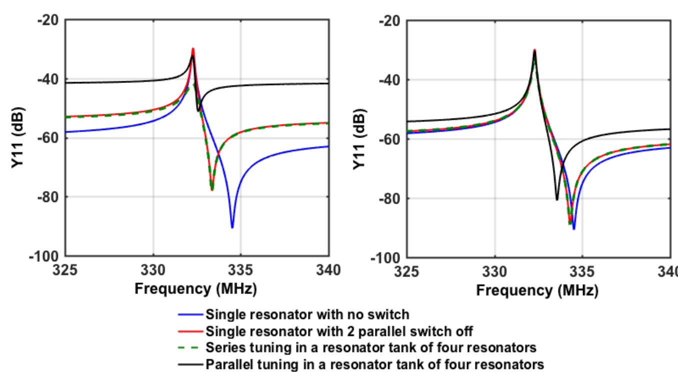

Fig. 8: Admittance plot in Cadence for different switching approaches with PCM via switch (a) C_{OFF}=1pF, R_{ON}=15Ω (b) C_{OFF}=0.1pF, R_{ON}=2Ω.

validate impedance and frequency tuning ability, and to understand the switch non-ideality effects and the trade-offs between different switching approaches.

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