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Piezoelectric Aluminum Nitride Micro Electromechanical System Resonator for RF Application

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Abstract

This paper presents the design and the finite element analysis of one port piezoelectrically transduced micro electromechanical system resonator based on the contour mode vibrations (CMV) on lateral field excitation (LFE) suitable for high frequency (~2.28GHz) application with high quality factor 1600. The piezoelectric material, aluminum nitride (AlN) has been used to achieve high frequency-quality factor (f.Q) product for radio frequency (RF) applications as an oscillator and/or filter part of RF transceiver. Furthermore, this piezoelectric material accounts for high acoustic velocity and low dielectric loss. Along with material solution, the device dimensions have been scaled both in lateral and vertical directions in order to increase the frequency of operation with a relatively small value of motional resistance. Mode shape and frequency of the device has been confirmed by the analytical method and the statistical data evaluated is used to simulate the design. Fabrication procedure of the statistically optimized & simulated structure with only two level electron beam lithography is also proposed.

Keywords: MEMS, CMV, LFE, Quality factor, RF

INTRODUCTION

Frequency selective devices have become an important part of RF transceivers. Demand for high quality factor (Q) in resonators and filters have initiated. Need of various researchers to find solutions to these demands in the radio frequency micro electromechanical system (RF MEMS). Electrostatically or piezoelectrically transduced RF MEMS resonators are CMOS compatible and have shown the ability to provide multiple frequencies on a single substrate. It also has the potential to realize a channel select RF front-end [5], however, utilizing a narrowband filter bank in such devices is a major challenge. Electrostatically actuated devices are very promising as they have Q greater than 10,000 still they suffer from large motional resistance. This makes their interface with standard 50Ω systems very difficult [1]. In MEMS devices contour mode operates in the transverse direction, in which frequency is defined by in-plane dimensions but is independent of the piezoelectric layer thickness, so such devices provide for different frequencies. In spite of the frequency variations, these devices can be fabricated and integrated on the same chip [4].

In this paper, focus is on the design of one port contour-mode AlN resonator and its finite element analysis. In this work use of bottom electrode is eliminated that will reduce a fabrication step. Literatures on one port structure having different design aspects provide different value of Q and resonant frequency. Our paper presents one port structure with aluminum electrode and piezoelectric film of AlN. Most importantly, the shape of the design considered by us will lead to change in design aspects.

High resonance frequency 2.28 GHz is attained by scaling dimensions both in lateral and vertical directions. However, change in dimensions to a certain minuscule extent gives a key increase in motional impedance. Furthermore, the scale down contributes to an increase of the power handling capacity of the designed resonating device. This increased hurdle is overcome by coupling a large number of these devices mechanically in the form of micro-strips.

These micro-strips are developed easily by patterning the top electrode in inter digited form on AlN layer. On top of the A1N layer, the aluminum (Al) electrodes are patterned into 21 IDT (Inter digited) fingers an important design constraint. This large number of micro-strips IDT fingers further reduce motional resistance, Rm of resonator and increase its electrical capacitance, which are both essential conditions to enable the device on chip actuation and sensing.

ALUMINUM NITRIDE RESONATOR DESIGN AND WORKING

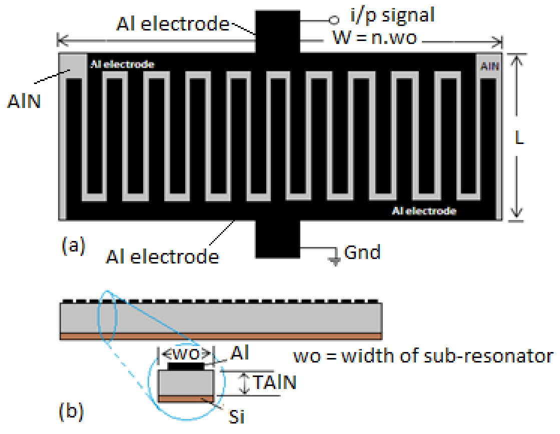

Figure 1: One port 21 IDT fingers AlN contour mode resonator (a) top view (b) elevation

Figure 1 shows the schematics of one port AlN contour mode resonator. In our design, the AlN layer (slab) is on the top of Si and no bottom electrode is employed. Al layer is arranged in the form of 21parallel IDT electrodes on the top of AlN. The placements of these Al electrodes are kept in such a way that, the input actuation is applied to one end whereas the ground reference is applied to other end. The device starts vibrating in contour-extensional mode through the equivalent d_{31} piezoelectric coefficient of AlN, where this vibration is the source of the resonance frequency. The fine frequency selection in this mechanical resonator can be tuned by adjusting the total width of resonator i.e. W= n.wo. Equation (1) helps us analytically evaluate the resonance frequency of the mechanical device [1].

fr = ***Error! Objects cannot be created from editing field codes.*** ………..(1)

Where *Eeq* and *ρeq* are Young's modulus and density respectively. In this way, one device dimension (wo) sets resonance frequency, whereas the other two (length, L, and thickness of the AlN slab, T) can be used to define the equivalent motional resistance of the resonator i.e.

$Rm \; \alpha \; (T / L)$ ………… (2)

From scaling point of view, this is an important advantage of the AlN contour-mode over electrostatically transduced resonators for which frequency scaling is generally associated with an increase in device resistance. As AlN thickness reduces, very less effect is observed in resonant frequency but piezo-activity parameter such as electrical capacitance is increased. In general, decrease in AlN thickness results in reduction of motional resistance and rise in quality factor which is the great requirement in the wireless transceiver communication. But when the device will be fabricated, these performance parameters will get affected due to parasitic losses.

Considering all factors, statistical analysis of various parameters has been carried out. For a broad-line MEMS resonator through statistical analysis, material properties and device dimensions are tabulated in Table 1 and Table 2 respectively.

Table 1. Material Properties.

Parameters	Value
Density of Al	2700 kg/m^3
Al Young’s modulus	71 GPa
Density of AlN	3300 kg/m^3
AlN Young’s modulus	310 GPa
AlN Dielectric constant (ε_{33})	8-9 F/m
Piezoelectric coefficient (d_{31})	2 pC/N

Table 2. Device dimensions.

Parameter	dimensions
Number of IDT’s (n)	21
Total width of resonator (W)	50.4 um
Width of sub-resonator (wo)	2.4 um
Thickness of AlN layer (T)	250 nm
Length of resonator (L)	17 um
Thickness of Al electrode	100 nm

DEVICE SIMULATION

AlN based resonator structure has been simulated to validate analytical calculations and to support functional verification. In general, physical and material properties are chosen to offer best possible performance. The design requires resonance frequency which is obtained by defining in-plane geometry and number of IDT fingers. The designed structure of CMR is shown in Figure 2.

The design dimensions have been chosen to get ease in fabrication. With respect to the chosen dimensions and utilizing these dimensions for a different set of IDT’s one can see that there is a negligible effect on the resonance frequency, but this variation of a number of IDT’s adversely affects the admittance (S).

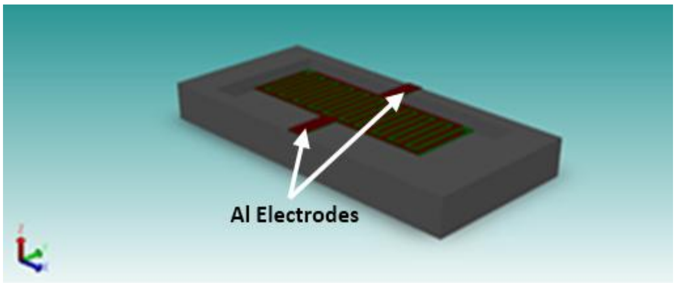

Figure 2: CMR design

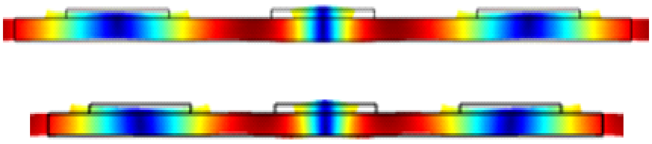

Figure 3: LFE resonator, eigenfrequency analysis of displacement mode shape for wo = 2.4µm, 2.2µm

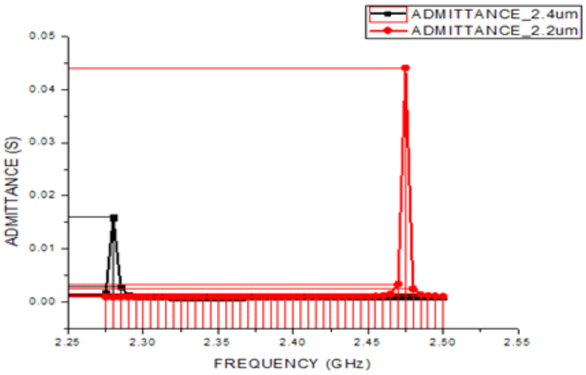

Figure 4: Admittance vs. freq. graph for wo = 2.4µm, 2.2µm simulated in COMSOL^{TM}

The optimized parameters are then simulated for verification using COMSOL^{TM} multiphysics. The simulated modal response is shown in Figure 2. and eigenfrequency analysis of displacement mode shape for wo = 2.4µm, 2.2µm is shown in Figure 3. It is observed from the simulation that by changing the width of sub-resonator wo in the CMR design from 2.4µm to 2.2µm there is about 0.2GHz deviation in resonant frequency (fr) from the expected analytical value. The increase in admittance was observed as shown in Figure 4. This increase is the motivation to provide less motional resistance. The reduction in width further offers a decrease in the device capacitance $Co\ \alpha\ (WL/T)$ [1], to the point that its value can fall below the parasitic capacitance. This decrease in parasitic capacitance affects the electrical response of the device adversely. Therefore, keeping all the positive as well as negative effects in mind a width of 2.4µm was well thought-out and utilized for development.

A. Mode shapes with different IDTs:

For the chosen width the mode shape for different numbers of IDT's for vibration in the resonator is also estimated as shown in Figure 5. The simulated frequency for chosen different eight structures with varied IDT'S is found approximately equal to 2.28 GHz. From Figure 7. one observes that increase in the value of IDT's will increase in the admittance (S) which reduces the motional impedance further. Furthermore, adjusting the thickness of AlN to a comparable lower optimized value has resulted in an increase of the resonant frequency as in Figure 6.

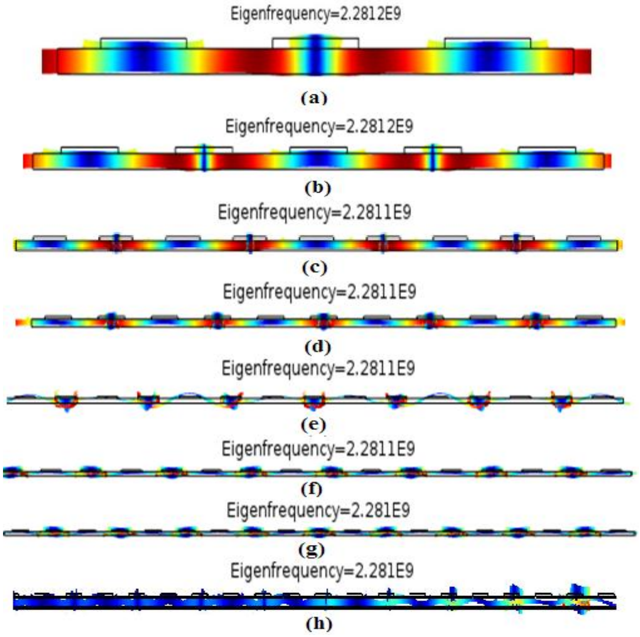

Figure 5: Mode shapes for (a) 3 IDT's (b) 5 IDT's (c) 9 IDT's (d) 11 IDT's (e) 15 IDT's (f) 17 IDT's (g) 19 IDT's (h) 21 IDT's

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Figure 6: Effect of Thickness of AlN on frequency

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Figure 7: Number of IDT's vs Admittance

B. Resonator quality factor:

The mechanical quality factor of a resonator describes the ratio of energy stored (vibration stored in the resonator) to energy dissipated per cycle of vibration a well-known fact [6].

$$Q = 2\pi \frac{\text{peak energy stored}}{\text{energy dissipated per cycle}} \quad \ldots\ldots\ldots. (3)$$

Hence in our design considering wo = 2.4µm, the simulated quality factor Q of the designed structure is approximately 1600 as highlighted in Figure 8. This value of quality factor providing less loss is fighting fit for communication circuitry.

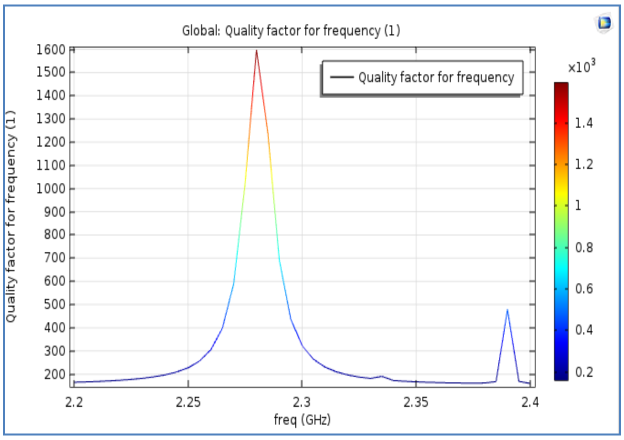

Figure 8: Quality factor vs frequency plot for n = 21(COMSOL^{TM} simulation)

FABRICATION PROCEDURE

Fabrication flow deals with three basic steps - deposition, lithography (mask) and etching (photoresist removal). Fabrication can be done using surface micromachining process [2]. Two level lithography process flow is presented, where AlN film can be deposited on Si substrate but for MEMS applications, it is advantageous to use a 200 nm layer of SiO_2 for cavity formation. Aluminum metal can be deposited on AlN by thermal evaporation for electrodes on top and patterned by electron beam lithography. The wet acidic etchant, Pg remover is to be used to remove residual Al metal. Etching of AlN will be done by reactive ion etching. Finally, isotropic etching of SiO_2 film can be done so that SiO_2 by SF_6 – O_2 plasma. SF_6 and O_2 can be mixed in a ratio of 1:10 to 1:5 for better performance [3]. This fabrication steps to be utilized for the desired device can be better understood via Figure 9. Contact pads for proper electrical probing and testing to validate the simulated design will be developed.

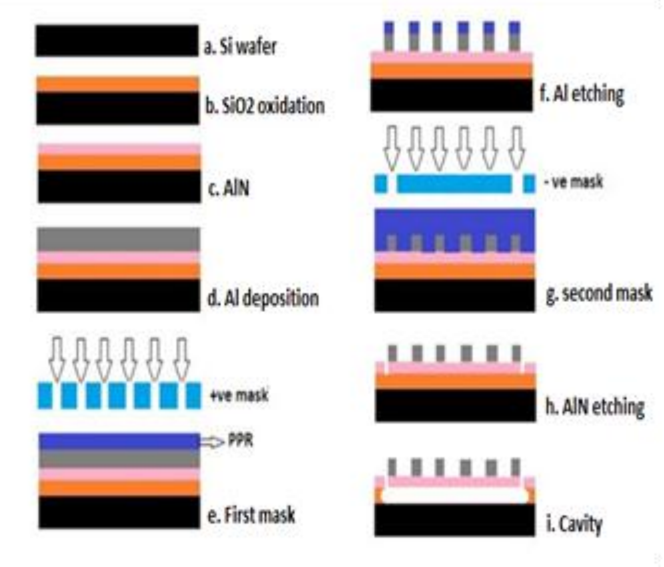

Figure 9: a. Si wafer. b. SiO_2 deposition. c. AlN deposition. d. Al deposition. e. First Mask. f. Al etching. g. Second mask. h. AlN etching. i. Isotropic etching of the cavity.

CONCLUSION

One port piezoelectrically transduced micromechanical resonator is presented in this paper. The device working is based on contour mode vibrations (CMV) through lateral field excitation (LFE). The optimized & simulated performance parameters such as quality factor, 1600 and the resonance frequency, 2.28GHz can be scaled to the higher value by further scaling & optimizing the dimensions for development considerations. AlN as a piezoelectric material is used due to its excellent properties for high-frequency achievement. The small change in resonant frequency by varying thickness of AlN piezoelectric material is found in simulation. The thickness of IDT fingers width is kept small to get the high resonant frequency and the thickness of piezoelectric stack is decided so as to keep the electrical capacitance greater than parasitic capacitance with negligibly small change in the resonant frequency. Further, as IDT fingers go on increasing, the resonant frequency remains same but increase in admittance is calibrated through the simulation. This may yield the improvement in motional resistance of the structure our primary objective. This requires verification through the development of the device and future citation.

ACKNOWLEDGEMENTS

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