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## ZnO Contour-Mode Resonator

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This paper reports on design, fabrication and experimental testing of one port ZnO piezoelectric contour-mode MEMS resonator. This is a rectangular plate formed by ZnO layer between two electrodes platinum and aluminium. A vertical electric field is applied to a layer of ZnO and induces in plane dilation of the plate through the  $d_{31}$  piezoelectric coefficient. In this paper we will look at the rectangular plate vibrating in the length-extensional mode and the width-extensional mode. The frequency equations of the length-extension mode and the width-extensional mode are calculated. The equivalent Butterworth Van-Dyke circuit of resonant microstructure is presented. The equivalent parameters of the resonator for the length-extensional mode are expressed and the  $f_s$  series and  $f_p$  parallel resonant frequencies are calculated. The method of fabrication of the resonator ZnO is presented. The ZnO layer was deposited using radio frequency magnetron sputtering. The SEM of contour-mode ZnO 10x5.6  $\mu\text{m}$  resonator is presented. The electrical characterization of the resonator system was carried out using the  $S_{11}$  scattering parameter measured with a *Suss Microtech* prober coupled with a *Hewlett Packard 8753* Vector Network Analyzer. Key experimentally determined parameters for the contour mode ZnO MEMS resonators are presented. Measured  $S_{11}$  is plotted. Parameters of the ZnO and the AlN contour-mode resonators are compared. The use of contour modes, whose frequencies are set by lithographically defined dimensions, permits the fabrication of multiple filters at arbitrary frequencies on the same chip.

## 1 Introduction

MEMS resonators offer a potential to replace the conventional chip used in communication devices due to their small size, low power consumption and manufacturing cost.

Micromechanical filters have been demonstrated for band-pass filtering in receiver front ends either at RF or IF frequency [1-5], despite their sheer high-Q, they exhibit large values of motional resistance, which complicates the coupling to 50  $\square$  RF systems.

Thin piezoelectric elements have been successfully exploited in Film Bulk Acoustic Resonator (FBAR) [6], achieving GHz frequencies and demonstrating high Q factors. In FBARs resonators, the film thickness sets frequency and do not permit the manufacturing of a single-chip RF module.

Contour-mode Aluminium Nitride MEMS resonators developed by Piazza [7-9], have emerged as a new technology capable of low-loss filtering and frequency synthesis on a single silicon chip in the VHF and UHF bands.

There are many articles published about the film zinc oxide (ZnO) [10-12]. ZnO has good piezoelectric properties and a high electro-

mechanical coupling coefficient. The ZnO is used also because of the maturity of sputtering process [13]. The ZnO film is used too for contour mode MEMS resonators [14,15]. This technology permit the realization of multi-frequency per silicon chip, especially CMOS – compatible. ZnO contour-mode resonators are compared with AlN micromechanical devices.

## 2 ZnO resonator design

This design is composed of a piezoelectric transducer made of a ZnO layer (plate) sandwiched between a bottom platinum electrode and a top aluminium electrode. Figure 1 shows a schematic representation of one port contour-mode ZnO piezoelectric resonator. We assume that the plates made of c-oriented thin ZnO films having a rectangular contour and thickness is small comparably with the acoustic wavelength  $\lambda$ . The only modes observed under these conditions are the lowest-order symmetric  $S_0$  and asymmetric  $A_0$  modes. The dispersion curves for the symmetric  $S_0$  mode is not sensitivity from the piezoelectric thickness of materials contrary to the asymmetric  $A_0$  mode. For this reason we used the symmetric mode for piezoelectric contour-mode resonators.

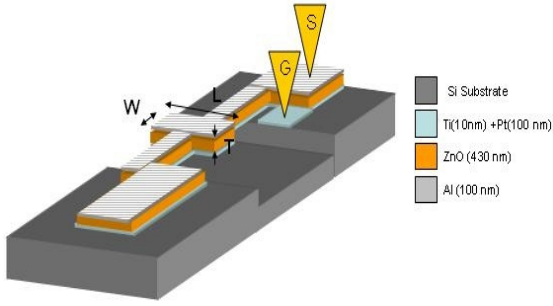


Fig.1. Schematic of one port ZnO piezoelectric contour-mode resonator.

A vertical electric field is applied to a layer of ZnO and induces in plane dilation of the plate through the  $d_{31}$  piezoelectric coefficient [14].

Theoretically, the phase velocity in the  $S_0$  mode of the ZnO is about 5299 m/s. The velocity was obtained by the formula [16]:

$$v_{S_0} = \sqrt{\frac{c_{11} - c_{13}^2}{\rho \cdot c_{33}}} \quad (1)$$

The phase velocity of the thin aluminium nitride (AlN) is 10862 m/s. Parameters of ZnO and AlN were presented by Adachi in [17]. This phase velocity of AlN is about twice higher than for ZnO.

The metal electrodes are found to reduce the equivalent wave speed. We used the Al top electrode and the Pt bottom electrode. The following approximations are used to take the loading effects of the metal electrodes into account

$$v_{eq} = \frac{v_{Al} \cdot T_{Al} + v_{Pt} \cdot T_{Pt} + v_{piezo} \cdot T_{piezo}}{T_{Al} + T_{Pt} + T_{piezo}} \quad (2)$$

where  $v_{eq}$  the equivalent wave speed,  $v_{Al}$ ,  $v_{Pt}$ ,  $v_{piezo}$  are the phase velocities in the Al, Pt, and the piezoelectric material and  $T_{Al}$ ,  $T_{Pt}$ ,  $T_{piezo}$  are thicknesses of the Al, Pt, and the piezoelectric material.

For the metal electrodes of Al and Pt, phase velocities are  $v_{Al} = 6302$  m/s and  $v_{Pt} = 4027$  m/s and are calculated from the formula :

$$v_{Al} = \sqrt{\frac{c_{11}}{\rho_{Al}}}, \quad v_{Pt} = \sqrt{\frac{c_{11}}{\rho_{Pt}}} \quad (3)$$

Parameters values of Al and Pt are given by Royer in [18].

Assume now that thicknesses of Al and Pt are equal 100 nm and the thickness of the piezoelectric material was 430 nm then the phase velocity for ZnO is equal  $v_{ZnOeq} = 5256$  m/s and for AlN is  $v_{AlNeq} = 9053$  m/s.

Similar equations are used for the calculation of  $E_{eq}$  and  $\rho_{eq}$ , where velocities are change with the plane modulus of elasticity  $E$  and the mass density  $\rho$  of the piezoelectric material.

For contour-mode the plate the length  $L$  and the width  $W$  can be calculated from equations:

$$L = \frac{v_{eq}}{2f_1} \quad (4)$$

$$W = \frac{v_{eq}}{2f_2} \quad (5)$$

where  $f_1$  and  $f_2$  are two operation frequencies fundamentals of the symmetrical mode ( $S_0$ ).

We noted that for the equivalent wave speed calculated,  $L$  and  $W$  for AlN are 1.7 higher than for ZnO.

## 2.1 Quality factor

The quality factor of a resonator, defined as the ratio of energy stored to the energy lost per cycle, is limited by various dissipation mechanisms and can be expressed as :

$$Q = \left( \frac{1}{Q_{material}} + \frac{1}{Q_{anchor}} + \frac{1}{Q_{air}} \right)^{-1} \quad (6)$$

damping, anchor loss and air damping respectively.

The loss due to air damping  $Q_{air}$  can be prevented by operating the resonator in vacuum. The piezoelectric resonators are in general less susceptible to air damping.

Anchor loss is attributed to the radiation of acoustic energy from the resonant body through the anchors, which keep the resonator in place. These anchors depending on the design of the resonator can be seen in many different forms but they contribute nevertheless to the final quality factor of the resonator in the same way. The acoustic waves are not completely confined in the resonator and rather radiate through the anchors and leak into the surroundings. To determine the anchor loss we can employ the solution from Hao [19].

Material damping  $Q_{material}$  includes all the energy loss mechanisms that are intrinsic to the resonant structure. Material loss relates to the irreversible transformation of acoustic energy to thermal energy. The contribution of this loss mechanism can be quantified by a coefficient called acoustic attenuation ( $\alpha$ ). The larger this coefficient for a material is the lower the absolute maximum achievable quality factor of the resonator made of that material will be.

We used the quality factor  $Q$  of resonator obtained through measurement.

It can be seen that the quality factor  $Q_{material}$  rises as ZnO thin film thickness increases, and then decreases after a certain point ( $Q \sim 450$ ) [20]. The quality factor  $Q$  for AlN is higher than for ZnO.

## 2.2 Effective Coupling Factor

The effective coupling coefficient  $k_{eff}$  is [16]:

$$k_{eff}^2 = \frac{\bar{\epsilon}_{31}^2}{c_{11} \bar{\epsilon}_{33}} \quad (7)$$

where

$$\bar{\epsilon}_{31} = e_{31} - e_{33} \frac{c_{31}}{c_{33}} \quad (8)$$

$$\bar{\epsilon}_{33} = \epsilon_{33} + \frac{e_{33}^2}{c_{33}} \quad (9)$$

$$\bar{c}_{11} = c_{11} - \frac{c_{13}^2}{c_{33}} \quad (10)$$

We obtain the value of the effective coupling coefficient of ZnO,  $k_{\text{effZnO}}^2 = 8.48 \cdot 10^{-2}$  and of AlN,  $k_{\text{effAlN}}^2 = 3.05 \cdot 10^{-2}$ . The theoretical value of the effective coupling factor of ZnO is more than twice higher than for AlN.

The product of Q and the effective coupling coefficient is a very useful figure of merit (Fig.2):

$$k_{\text{eff}}^2 Q = \frac{1}{\omega_r R_m C_0} \quad (11)$$

We obtain the value of  $k_{\text{eff}}^2 Q$  for ZnO and for AlN:

$$k_{\text{effZnO}}^2 Q_{\text{ZnO}} = 34, \quad k_{\text{effAlN}}^2 Q_{\text{AlN}} = 24$$

where  $Q_{\text{ZnO}} = 400$  and  $Q_{\text{AlN}} = 800$  [21, 22] are measured values.

This product of Q and the theoretical effective coupling coefficient of the ZnO resonator is higher than of the AlN structure.

The contour-mode rectangular plate is the building block for the band pass filters. The basic ladder filter configuration is composed of series and shunt resonators.

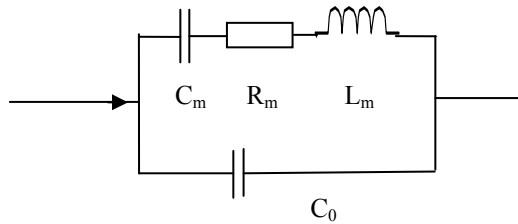


Fig.2. Equivalent Butterworth Van-Dyke circuit representation.

The fractional bandwidth of this filter is set by the distance between the parallel resonance of the series branch  $f_{s2}$ , and the series resonance of the shunt branch  $f_{p1}$ , respectively, and the center frequency  $f_c$

[23 ]:

$$\frac{f_{p1} - f_{s2}}{f_c} = \frac{8}{\pi^2} k_{\text{eff}}^2 \quad (12)$$

Cellular standards such as PCS, GMS, and WCDMA require for RF filters the fractional bandwidths up to 3%. If we compare the theoretical value of the effective coupling factor for ZnO and for AlN than we find that ZnO is the better piezoelectric material with  $k_{\text{ZnO}}^2$  equal 8.48%.

### 2.3 Equivalent parameters for model electric

As derived in [24] the equivalent circuit for the piezoelectric resonator for the length-extensional mode are expressed by the following equations :

$$C_0 = \epsilon_0 \epsilon_{33} \frac{WL}{T}, \quad (13)$$

$$C_m = \frac{8 d_{31}^2 L W E_{\text{eq}}}{\pi^2 T}, \quad (14)$$

$$R_m = \frac{\pi T}{32 d_{31}^2 Q W} \sqrt{\frac{\rho_{\text{eq}}}{E_{\text{eq}}^3}}, \quad (15)$$

$$L_m = \frac{\rho_{\text{eq}} L T}{8 d_{31}^2 E_{\text{eq}}^2 W}, \quad (16)$$

$$\omega_{10} = \frac{\pi}{L} v_{\text{eq}} \quad (17)$$

where T is the thickness of the plate,  $d_{31}$  piezoelectric coefficient of ZnO,  $\epsilon_0$  and  $\epsilon_{33}$  are the dielectric permittivity of air and the relative permittivity of ZnO in the c-axis direction, and  $\omega_{10}$  is the natural frequency of the resonator for the length-extensional mode.

For the width-extensional mode L is substituted by W.

$$R_m = \frac{\pi T}{32 d_{31}^2 Q L} \sqrt{\frac{\rho_{\text{eq}}}{E_{\text{eq}}^3}}, \quad (18)$$

$$L_m = \frac{\rho_{\text{eq}} W T}{8 d_{31}^2 E_{\text{eq}}^2 L}, \quad (19)$$

$$\omega_{w0} = \frac{\pi}{W} v_{\text{eq}} \quad (20)$$

where  $\omega_{w0}$  is the natural frequency for the with-extensional mode and  $C_0$ , and  $C_m$  are similar for the length-extensional mode.

Values  $E_{\text{eq}}$  and  $\rho_{\text{eq}}$  are calculated for Al (100 nm), Pt (100 nm) and ZnO (430 nm) and are equals:

$$E_{\text{eqZnO}} = 115.7 \text{ [GPa]}$$

$$\rho_{\text{eqZnO}} = 7699.8 \text{ [kg/m}^3\text{]}$$

The series  $f_s$  and  $f_p$  parallel resonant frequencies of this resonant microstructure are :

$$f_s = \frac{1}{2\pi \sqrt{L_m C_m}}, \quad (21)$$

$$f_p = \frac{1}{2\pi \sqrt{L_m C_0 C_m}} \quad (22)$$

Theses frequencies of resonator are used during the design of filters.

### 3 Fabrication process

Many resonators were fabricated with different length L, width W and thickness T. For example, the resonator was fabricated thanks to 4 e-beam lithography (*Leica EBPG 5000 plus*) lift off steps. The first one is used to achieve a hard mask of SiO<sub>2</sub> to protect silicon during Xef<sub>2</sub> step (membrane release). The second one is dedicated to the ground electrode made of (Ti : 10 nm / Pt 100 nm) as shown on figure 3-a, the third one to the 430 nm thick ZnO layer as shown on figure 3-b and the forth one to the upper electrode made of 100 nm Al as shown on figure 3-c. Al and Ti/Pt or SiO<sub>2</sub> are used as hard

mask to etch isotropically (100) silicon substrate under the membrane thanks to XeF<sub>2</sub> etching. XeF<sub>2</sub> pressure is 3 Torr and the pumpout pressure is 800 mTorr. The process we use etches around 2 μm/min in every direction. The etch time is 3 mn using 12 x15s cycle etching. The membrane is then released as shown in the figure 3-d.

For each e-beam lithography step ; a bilayer e-beam resist is spin coated (EI 13 % / PMMA 495K 3%). The thickness of the layer is around 600 nm for metal layers lift off and 900 nm for the ZnO layer lift off. For each lift-off step , EBRPG solvent step is used.

ZnO piezoelectric layers were deposited using radio frequency magnetron sputtering techniques (with the following parameters: Power: 120W, Pressure: 15 mT, Ar: 34 sccm, O<sub>2</sub>: 4 sccm. The substrate holder is cooled for ZnO sputtering so that the lift-off step can be possible.

Ti, Pt and Al are evaporated thanks to classical evaporation process (fig.4).

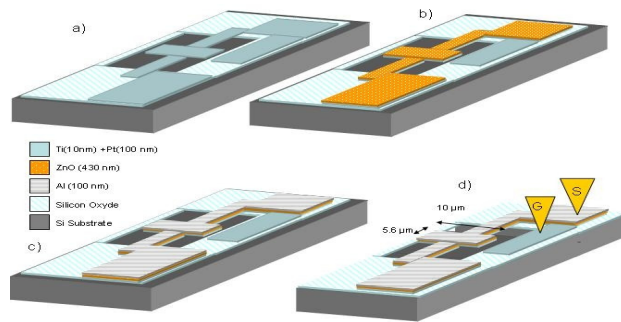


Fig.3. Schematic view of the process used to fabricate ZnO piezoelectric resonator.

a) SiO<sub>2</sub> was deposited by PECVD and etched by RIE technology. Ti and Pt are sputter-deposit on a Si wafer and patterned by lift-off

b) ZnO is sputter-deposit on a Si wafer and patterned by lift-off

c) Al top electrodes are evaporated and patterned by lift-off

d) ZnO rectangular plate with electrodes is released (XeF<sub>2</sub> dry etching).

#### 4 MEMS Characterization

In our experiment, the electrical characterization of the resonator system was carried out using the S11 scattering parameter measured with a Suss Microtech prober coupled with a Hewlett Packard8753 Vector Network Analyzer. All testing is performed in air at atmospheric pressure and ambient temperature.

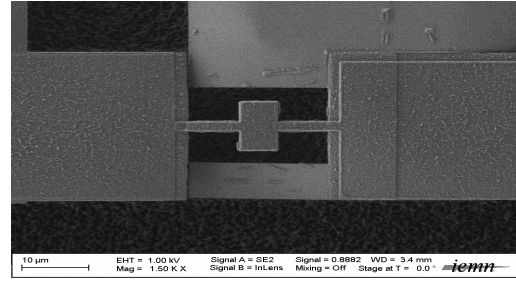


Fig.4. SEM of one – port 10 x 5.6 μm ZnO rectangular plate.

The fabricated resonator can be excited in both length-extensional and width-extensional mode shapes. The measured dimensions of fabricated resonators and experimental results are summarized in Table I and Table II. Electrical parameters of contour – mode ZnO MEMS resonators were calculated with the Matlab program and are given in Table III.

T <sub>Al</sub> (nm)	T <sub>Pt</sub> (nm)	L <sub>ZnO</sub> (μm)	W <sub>ZnO</sub> (μm)	T <sub>ZnO</sub> (nm)
100	100	10	5.6	430
100	100	5	2.8	430

Table I. Geometry parameters values of the fabricated resonators.

L x W [μm x μm]	f <sub>1</sub> [MHz]	Q <sub>1</sub>	f <sub>2</sub> [MHz]	Q <sub>2</sub>
10x5.6	355	400	495	165
5x2.8	722	145	973	112

Table II. Experimental results for plate excited in length-extensional and width-extensional.

L x W [μm x μm]	f <sub>1</sub> MHz	C <sub>0</sub> fF	C <sub>m</sub> fF	L <sub>m</sub> mH	R <sub>m</sub> Ω
10x5.6	355	10.37	0.305	2.2	1681
	495	10.37	0.305	1.2	2282
5x2.8	722	2.59	0.076	2.2	9275

Table III. Calculated electrical parameters values of fabricated ZnO resonators.

The typical electrical response of a ZnO MEMS resonators of 10μm x5.6μm is shown in Figure 5 . This resonator has two frequencies 355 MHz and 495 MHz.

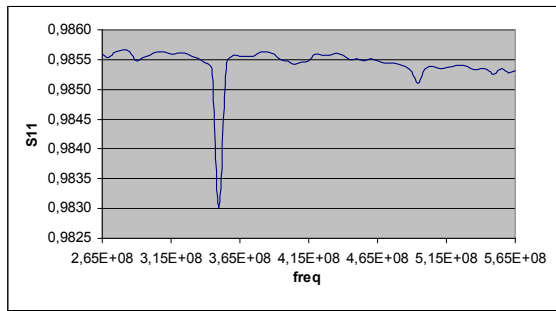


Fig.5.  $S_{11}$  parameter for  $10\mu\text{m} \times 5.6\mu\text{m}$  resonator.

## 5 Conclusions

The design, fabrication and testing of high frequency piezoelectric ZnO on silicon resonators was presented in this paper. We compare the ZnO structure with the AlN resonator. The quality factor Q of the ZnO resonators is smaller than for the AlN structures. The ZnO MEMS has the value of motional resistance higher than AlN.

If we suppose that the Q factor is equal 400 and the length is  $100\mu\text{m}$ , the width is  $56\mu\text{m}$  and the thickness of the plate is  $430\text{nm}$  then we obtain the motion resistance of the ZnO resonator  $R_m$  equal  $168\Omega$ . For AlN with the quality factor Q equal 800 we obtain  $R_m$  equal  $49\Omega$ . The theoretical value of the effective coupling factor for ZnO is equal 8.48%, is higher than for AlN and better adapted for RF filters for cellular standards such as PCS, GMS, and WCDMA.

ZnO and AlN MEMS contour mode resonators have the advantage of combining low motional resistance and high Q with the ability to define multiple frequencies on the same substrate. Although the performance of these resonators are not yet optimized, they promise to open a pathway for single-chip multi-frequency, integrated band pass filter solutions characterized by higher performance and smaller form factors.

Future work includes design optimization and fabrication improvement to enhance the Q performance.

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