Piezoelectric Aluminum Nitride Resonator for Oscillator

O. Mareschal[1, 2, 3], S. Loiseau[1, 4], A. Fougerat[1], L. Valbin[2], G. Lissorgues[2], S. Saez[3], C. Dolabdjian[3], R. Bouregba[4], G. Poullain[4]
[1]NXP Semiconductors, Caen, France
[2]ESIEE-ESYCOM, ESIEE Engineering & Université Paris-Est, Noisy-le-Grand, France
[3]GREYC - CNRS UMR6072, ENSICAEN & Université de Caen Basse-Normandie, Caen, France
[4]CRISMAT - CNRS UMR6508, ENSICAEN & Université de Caen Basse-Normandie, Caen, France

***Abstract*— This work investigates properties of the Thin Film Elongation Acoustic Resonator (TFEAR) [1] operating at MHz frequencies in air. This resonator is composed of a piezoelectric layer of Aluminum Nitride (AlN) sandwiched between two aluminum electrodes (Al). TFEAR works in the extensional mode excited via AlN d_{31} piezoelectric coefficient. A 3D-finite element method analysis (FEM) using ANSYS® software has been performed to model static modal and harmonic behavior of the TFEAR. In order to consider insertion losses into the substrate, equivalent electrical models based on Modified Butterworth-Van Dyke (MBVD) circuit have been improved by adding extra dissipative elements. Thus, a whole model for the on-wafer characterization set-up is given, allowing for automatic de-embedding of the present TFEAR equivalent circuit. Quality factor Q as high as 2500 in air have been recorded with motional resistance lower than 400 Ω. A first oscillator based on a TFEAR resonator was also designed and tested.**

Introduction

In the last few years, Micro-Electro-Mechanical-System (MEMS) technology integration for RF applications has become a new challenge. Several applications like Universal Serial Bus (USB), Radio Frequency Identification (RFID) or Personal Digital Assistant (PDA) use classical quartz oscillators, typically millimeter sized. MEMS resonators are sub-millimeter sized. It's a low consumption component and integrated circuit compatible. The aim of TFEAR is to become a low cost alternative for quartz crystal resonator in the MHz range. Indeed, the manufacturing of TFEAR needs only five masking steps. More, MHz frequencies electrostatic resonators have been presented in earlier papers [2] but most of those solutions operate in vacuum and need high bias resonator voltage (≈ 5 to 100 V). Main advantages of piezoelectric resonators are their low driving voltage (25 mV for the TFEAR) and their good elongation linearity versus applied voltage. In this paper, we report on fabrication process method, modeling and electrical characterization of a piezoelectric AlN resonator. It works in air and is fully adapted for oscillator circuit miniaturization. A first simple oscillator based on TFEAR will also be presented.

Extensional Mode, Modeling and Design

A. *Working principle*

TFEAR is an in-plane extensional mode resonator. It consists of a multilayer beam constituted of insulator, metal, piezoelectric and metal materials. The piezoelectric layer is composed of AlN which is a non-contaminant material and presents high acoustic wave velocity [3]. In opposition to SAW (Surface Acoustic Wave) and BAW (Bulk Acoustic Wave) resonator, which work in longitudinal mode and vertical mode respectively, the TFEAR is directly driven by the piezoelectric coefficient d_{31} of AlN. Therefore, an excitation voltage applied on the piezoelectric thin film allows beam elongation.

B. *Design*

3D-Finite Element Method analysis (3D-FEM), using ANSYS® software, have been performed. It allowed to compare different designs and to predict expected resonance frequencies. The figure 1 shows the result of one modal solution of a FEM calculation for extensional mode along the beam. The simulation takes into account the electrodes and the part of the substrate (Si) where the beam is anchored. The excitation voltage is applied on Al electrode deposited on the whole piezoelectric layer which induced a resonance. The resonance frequency follows the well-known relation

$$f_r = \frac{1}{2L}\sqrt{\frac{\overline{E}}{\overline{\rho}}} \tag{1}$$

where L is the length of the beam, $\overline{E}$ is equivalent Young modulus of the stacked layers, and $\overline{\rho}$ is the beam equivalent density. These two properties are balanced with the thickness of each layer [4].

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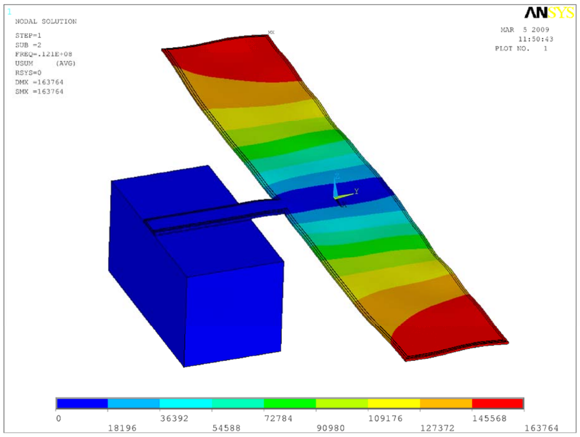

Figure 1. 3D-FEM result for extensional mode in ANSYS® software modal analysis.

MANUFACTURING PROCESS

A. TFEAR Process

TFEAR is realized using conventional integrated circuit manufacturing tools. The resonator is made on silicon wafers covered by oxide silicon (a). Pads and bottom electrode ($AlSi_{1\%}Cu_{0.04\%}$) are deposited by DC-magnetron sputtering tool ((b) and (c)). Thereafter, AlN layer is deposited by an OERLIKON pulsed DC reactive sputtering in nitrogen and argon atmosphere (OERLIKON clusterline 200) (d). Top electrode is deposited like bottom electrode (e). These four layers are patterned by dry etching for the $AlSi_{1\%}Cu_{0.04\%}$ and by wet etching for the AlN layer. Finally, TFEAR is released by designing of the cavity (f) using anisotropic and isotropic dry etching for the silicon oxide layer and the silicon substrate, respectively.

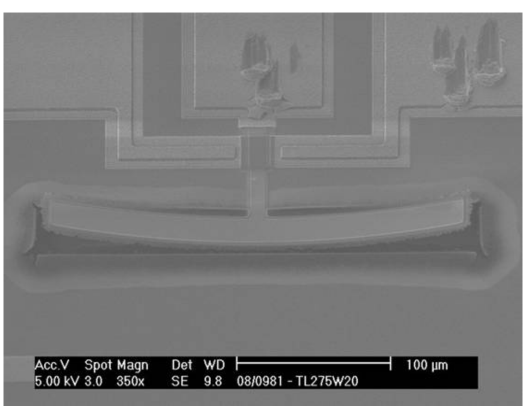

Figure 2. SEM view of a 275 µm length and 20 µm width TFEAR.

The figure 2 shows a Scanning Electron Microscopy (SEM) view of the corresponding investigated resonator design in this paper (T-shaped anchor). A TFEAR manufactured on the above conditions presents a seeming bent beam, which comes from the AlN layer known as a stressing layer. FEM simulations showed that stress in the beam does not changed resonance frequency.

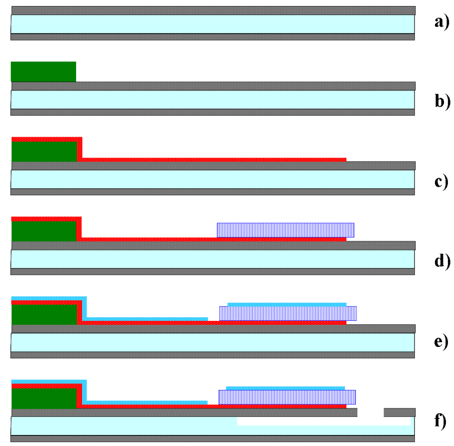

Figure 3. TFEAR cross section process flow views.

B. AlN deposition

Regarding the piezoelectric AlN layer, under-layers had to be optimized in order to have best crystallized material. Then, experimental designs were used to optimize $AlSi_{1\%}Cu_{0.04\%}$ deposition parameters in order to get highest crystallinity of AlN. Layers were characterized by X-Ray Diffraction (XRD). Well result obtained for the bottom electrode is shown on the figure 4. A full width at half maximum (FWHM) of the rocking-curve equal to 4.78° was measured. The FWHM of the AlN film, prepared on this metal electrode and achieved by OERLIKON sputtering tool, is presented in the figure 5 (FWHM = 2.18°). We notice that $AlSi_{1\%}Cu_{0.04\%}$ bottom electrode allows obtaining well crystalline quality of AlN, compared to previous studies [5]. The improvement of AlN layer deposition enable to obtain high piezoelectric coefficient and thus, to maximize the quality factor Q of the resonator.

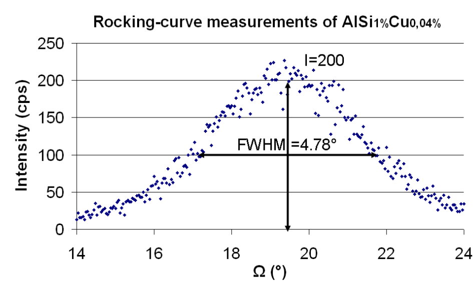

Figure 4. X-ray of the rocking-curve for the bottom electrode.

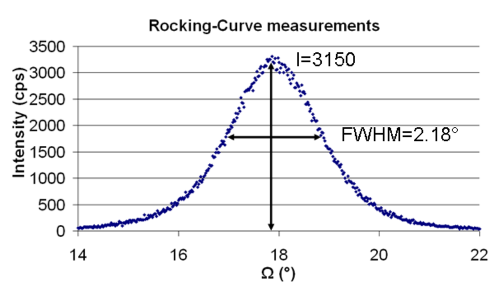

Figure 5. X-Ray of the rocking-curve for the AlN layer.

EXPERIMENTAL RESULTS

A. MBDV equivalent circuit

Equivalent electrical model, based on Van-Dyke Butterworth circuit was previously presented in earlier paper [4]. The model used takes into account resistive and capacitive losses in the Si substrate, as summarized in figure 6.

During measurement, the wafer is connected to the ground. So, intrinsic resonator is in parallel with substrate parasitic equivalent elements. C'_0 corresponds to the capacitance of the resonator induced by the both electrodes of the TFEAR (C_0), in parallel with the capacitance of the substrate. R'_p is the resistance of the AlN layer (≈ GΩ) in parallel with the resistance of the substrate. R_m, C_m and L_m represent the motional arm of the Van-Dyke Butterworth model. The access line resistance and inductance are considered negligible in MHz range TFEAR resonance frequency.

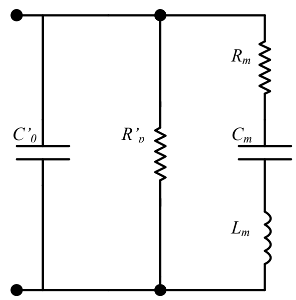

Figure 6. MBVD equivalent circuit of an effective 350 µm length and 50 µm width TFEAR. (f_r = 14.35 MHz, C'_0 = 1.88 pF, R'_p = 9 kΩ, R_m = 375 Ω, C_m = 12.8 fF and L_m = 9.6 mH)

B. Electrical properties and physical relationship

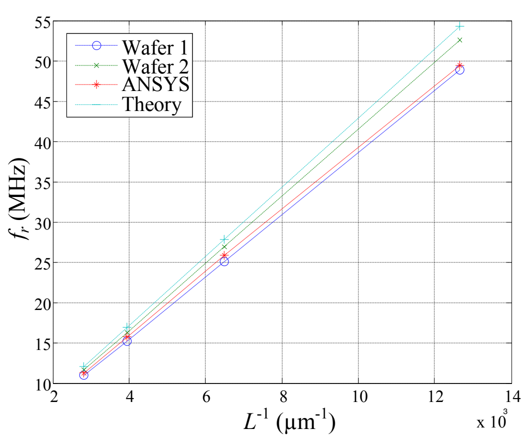

Figure 7. Resonance frequency as a function of resonator beam.

The figure 7 gives the resonance frequency as a function of the inverse length of the TFEAR. We can observe the well matching between measurements made on two wafers, FEM simulation and theory (Cf. Equ. 1). Discrepancies can be easily explained by fluctuations on the layers thickness which can occur during the process. Moreover, for high frequency or low beam length, other resonances modes (e.g. contour mode) can be measured as the width become not negligible compared to the length of the beam. Presently, FEM simulation does not take into account on the access line and substrate losses.

A basic relation gives the geometrical properties of the resonator versus the electrical parameters. Indeed, theory shows that variations of motional capacitance and inductance are proportional to the length of the resonator beam according to the relations

$$C_m = \left[\left(\frac{f_a}{f_r}\right)^2 - 1\right] C_0 = \alpha L W \qquad (2)$$

and

$$L_m = \frac{1}{4\pi^2\left(f_a^2 - f_r^2\right)C_0} = \beta\frac{L}{W} \qquad (3)$$

where f_r and f_a are the resonant and antiresonant frequencies, respectively, α and β are two constants associated to materials (SiO_2, AlSiCu and AlN) and layer thickness. C_0 is the capacitance of the resonator, fixed by the length, L, width, W and thickness, t, of the TFEAR.

The figures 8 and 9 show motional capacitance and motional inductance variations of the resonator versus the length of the TFEAR beam. Theoretical model is deduced from differential equation governing the resonator without considering substrate losses. The cells correspond to measurement series for different devices made on the same wafer. Both figures show that, there is no discrepancy for close resonators on the same wafer. Moreover, the electrical parameter behavior is in good agreement with the theory and is being quite linear with similar slope. Measurements are normalized by C'_0 capacitance (and not by C_0) and the theoretical model does not take into account the SiO2 layer and misalignment appearing during the process. This does not modify the linear behavior of the electrical parameters. However, they justify the shift between theoretical curve and measurements.

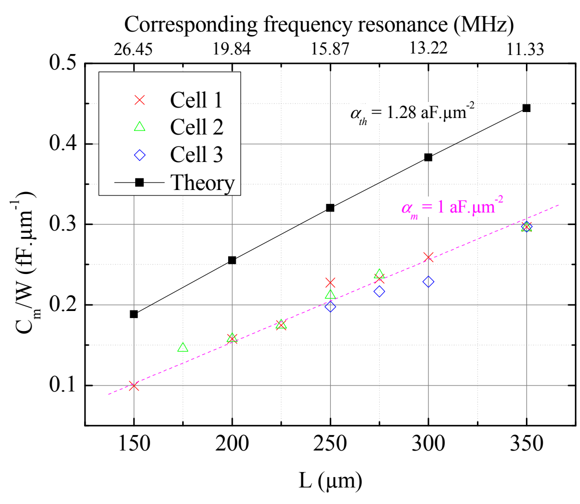

Figure 8. Motional capacitance variation versus length of the TFEAR beam. α_{th} and α_m are theoretical and measured curve slopes, respectively.

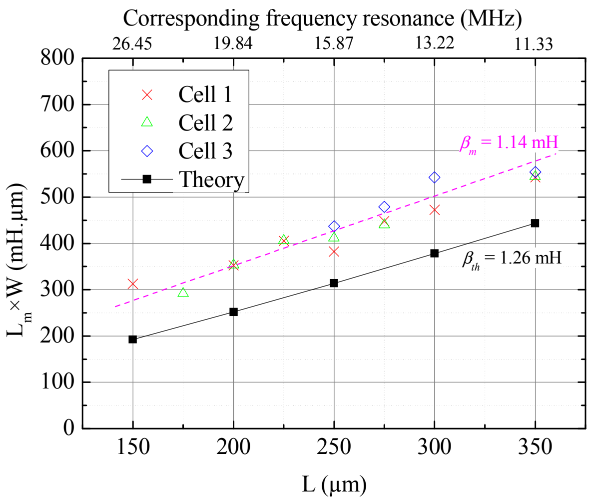

Figure 9. Motional inductance variation versus length of the TFEAR beam. β_{th} and β_m are theoretical and measured curve slopes, respectively

PERFORMANCES AND OSCILLATOR INTEGRATION

Fabricated resonator presents free beam length which varies from 75 µm to 350 µm. It permits to obtain resonance frequencies f_r between 10 MHz to 50 MHz according to the equation 1. Quality factor Q as high as 2500 was measured [4] with motional resistance (R_m) of about 400 Ω. In uncompensated temperature mode (without SiO_2 layer), we recorded a frequency resonance accuracy of about 30 ppm/°C for 25 °C to 100 °C temperature range (*Cf.* Fig .10). Study is in progress to optimized SiO_2 layer under the beam to decrease this value.

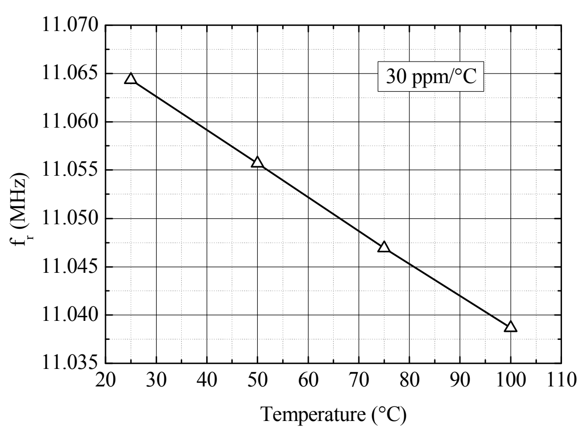

Figure 10. Frequency shift versus temperature in uncompensated temperature mode (f_{r0} = 11.06435 MHz)

TFEAR was embedded in a simple oscillator circuit based on non-inverting operational amplifier circuit. The figure 11 shows the oscillogram obtained for a 325 µm length and 50 µm width TFEAR. Expected theoretical resonance frequency of this resonator is about f_r = 14.11 MHz. It is in good agreement with measured value ($f_{osc} \approx$ 14.13 MHz).

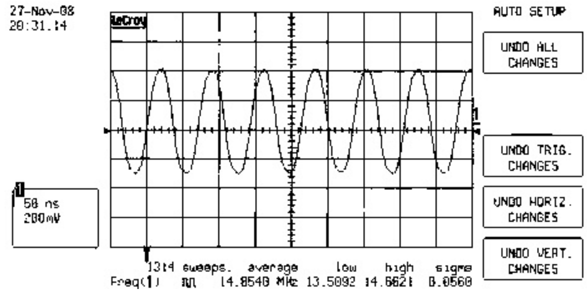

Figure 11. Oscillogram of an oscillator output based on TFEAR.

CONCLUSION

In this work, we have presented and characterized an in-plane extensional TFEAR. Resonance frequencies ranging from 10 MHz to 50 MHz have been observed as expected. They are linked to TFEAR beam size, *L,* ranging from 75 µm to 350 µm, in our study. Simulation and measurement show a good agreement with the theoretical model, which easily explains the electrical behavior of the resonator. More, basic relationships can be extracted from model and data. Q factor as high as 2500 and motional resistance below 400 Ω have allowed designing a first oscillator. This is the first step to specify the capability of the TFEAR to be embedded in industrial applications without significant change in classical existing oscillator circuits. Improvements on the process will allow obtaining smaller motional resistance (< 100 Ω) and higher quality factor (> 10 000) to extend the compatibility of TFEAR in RF applications.

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