Impact of the variability of microfabrication process parameters on CMUTs performance

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***Abstract*—As CMUT technology moves towards the industrial phase, the robustness of the fabrication process becomes a key aspect to produce reliable and well-performing devices. CMUT arrays typically show a variability of the electromechanical and acoustic behavior among the transducer elements, which is mainly ascribed to tolerances of process-related parameters. This paper investigates the impact of process-related parameters variability on the performance of CMUT arrays, by proposing a local sensitivity analysis technique performed according to a Design of Experiments (DoE) approach based on Vertex Analysis. The sensitivity analysis is performed by simulating a Reverse-Fabricated CMUT using Finite Element Modeling (FEM), and computing the CMUT electromechanical parameters by varying the thicknesses of the front membrane layer, of the top and bottom passivation layers and of the sacrificial layer within a 10% tolerance range around the nominal set of values. The sensitivity analysis results are then compared to the variability observed in the data obtained characterizing a 256-element Reverse-Fabricated CMUT linear array for medical imaging.**

Keywords*— *CMUTs, sensitivity analysis, microfabrication, design of experiments, main factor

I. Introduction

Despite the good accuracy of microfabrication techniques, a non-uniformity exists between Capacitive Micromachined Ultrasonic Transducers (CMUTs) dice from different wafers or even from the same wafer. Further, an intrinsic variability is observed among the elements of the same array (inter-element variability) as well as between cells of the same element (intra-element variability). Consequently, the devices exhibit uneven electrical and mechanical properties, which impact on the overall performance of the CMUT arrays and on the reliability of the microfabrication process. In the case of CMUTs, a great impact on the performance unevenness is due to the tolerance of the geometrical parameters that determine the actual layout of the device [1]. The efforts for the improvement of the manufacturing process reliability can be driven by a sensitivity analysis that investigates the impact of the variability of all uncertain process-related parameters on the device performance.

In this work, we describe the sensitivity of selected indicators of the electromechanical and acoustic performance of a 256-element, Reverse-Fabricated [2] CMUT linear array for medical imaging to a 10% tolerance of the thickness of the silicon nitride (SiN) passivation layers, deposited by Dual-Frequency Plasma-Enhanced Chemical Vapor Deposition (DF-PECVD) [3], and of the evaporated chromium sacrificial layer. We propose the FEM-based simulation of the CMUT according to a 3-factors, 3-level full factorial Design of Experiments approach, that allows to compute the device sensitivity to the layout tolerances by accounting for the interactions between the input quantities variations. The finite element simulations run on a 2D axisymmetric model of the reverse-CMUT circular cell described in [4] and based on the transducer structure described in [5], by means of the FEM commercial software ANSYS (ANSYS Inc., Canonsburg, PA, USA). The simulated variability of the resonance frequency and of the static capacitance is compared to the measured distribution of the same quantities. The measured values are extracted by the electrical impedance obtained by the electrical characterization of the 256 elements of a fabricated array [6].

II. Design of Experiments approach

A. 3^3 full factorial DoE-based sensitivity analysis

A sensitivity analysis [7], [8], can validate or discard hypotheses on which, among a certain set of variables (factors), is the most influential on a chosen output quantity (performance). The first-order sensitivity, computed as the first derivative of the output with respect to the considered input, is a quantitative assessment of the dependence only in case the relation between the considered quantities is linear and not affected by the simultaneous variation of other input quantities. The classical approach based on "one-factor-at-a-time" variations does not allow to account for the interaction between the factors that affect the system behavior [9]. For this reason, we propose a full-factorial sampling of the parameter space [10] for the CMUT sensitivity analysis.

In particular, we carried out the analysis according to a 3-factors 3-level full factorial Design of Experiments approach [11]. Such technique involves the variation of three parameters $\underline{x} = [x_1, x_2, x_3] = \{x_i\}$ between a minimum, a center and a maximum value. In the case of symmetric tolerance Δ, the center value coincides with the nominal value $x_{i,n}$ and each input factor is an array $x_i = [x_i^L, x_{i,n}, x_i^U]$ with $x_i^L = x_{i,n} - \Delta$ minimum and $x_i^U = x_{i,n} + \Delta$ maximum values. The addition of the nominal

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value to the extremes of the variation range of each factor allows assessing the linearity of the dependence of the selected output quantities upon the factors. By considering $m = 3$ factors, and $l = 3$ levels for each factor, according to the expression $n_c = l^m$, this full-factorial DoE makes for $n_c = 27$ possible combinations of the input parameters, provided to the FEM model to simulate the selected performance indicators. The results computed for the 27 points allow calculating the coefficients relating the generic output y to the 3 factors, according to the equation

$$y = y_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \epsilon. \quad (1)$$

If the interaction effects can be neglected, the variation observed in the output Δy is a linear combination of the input factors variation Δx_i according to the β_i coefficients, whose computation is the goal of this analysis, by means of

$$\Delta y \approx \beta_1 \Delta x_1 + \beta_2 \Delta x_2 + \beta_3 \Delta x_3. \quad (2)$$

The relation between each simulated performance and input factor is analyzed by observing the scattered data on the dex scatter plot (DSP) and the first-order approximation of the mean performance variation on the main effect plot (MEP). In both plots, the m factors are reported on the x-axis in form of coded variables: the values [-1, 0, 1] correspond to the minimum, center and maximum value, respectively. The MEP reports the percentage variation of the performance $\Delta y = y_{avg}^U - y_{avg}^L$, with y_{avg}^U and y_{avg}^L mean values of the performance assessed in correspondence of the x_i^L and x_i^U settings of the factors, with respect to the performance computed in correspondence of the nominal input set. The MEP also reports the β_i coefficients, which are computed as

$$\beta_i = \partial y / \partial x_i \approx \Delta y / \Delta x_i = (y_{avg}^U - y_{avg}^L) / (x_i^U - x_i^L) \quad (3)$$

and represent the first-order sensitivity coefficients with respect to the input factors. The MF coefficients are the same quantity computed by using the coded variables, and quantify the sensitivity independently from the factors absolute value.

B. *Choice of input parameters and performance parameters*

The three input parameters considered are the thickness t_m of the SiN layer deposited on top of the LPCVD SiN membrane, the total thickness t_p of the SiN passivation layers deposited on top of the bottom electrode and below the top electrode, both placed along the gap between the electrodes, and the thickness t_c of the sacrificial Chromium layer that determine the cavity height. Fig. 1 shows a cross section of half the CMUT cell.

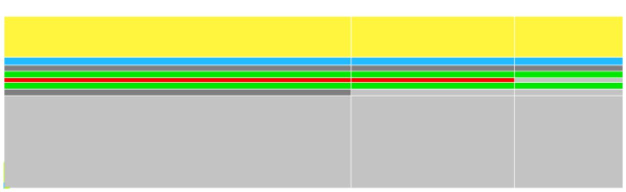

Fig. 1. Corss section of half the CMUT cell. The input parameters considered are the thickness of the SiN layer below the membrane t_m (in blue), the sum of the SiN passivation layers thicknesses t_p (in green), and the sacrificial layer thickness t_c determining the cavity height (in red).

The input parameters' nominal values are $t_{m,n} = 360$ nm, $t_{p,n} = 686$ nm, $t_{c,n} = 200$ nm. The tolerance applied to all three parameters is the 10% of their own nominal value, which is greater than the highest measured tolerance of the deposited layers thickness.

The observed output parameters are the mechanical resonance frequency f_m, the collapse voltage V_c, the biased transducer resonance frequency f_r, and static capacitance C_0, both computed by biasing the device at 80% of the nominal collapse voltage. Currently, the analysis is being performed on the water-coupled transmission sensitivity amplitude $|G_{tx}|$, phase $<G_{tx}$, and -3dB fractional bandwidth, BW_f, computed at the nominal center frequency.

III. Sensitivity analysis results

A. *Mechanical parameters*

The mechanical resonance frequency f_m of the CMUT was computed as the first mode frequency resulting from the modal analysis of the unbiased transducer FEM model. The scattered data in Fig. 1 confirm that the dependance of f_m on the membrane and passivation layers thickness t_m, t_p is linear and positive. The cavity height t_c variation is negligible, as it causes a variation of the resonance frequency smaller of 0.04% with respect to the nominal value $f_{m,n} = 14.85$ MHz, with a main factor two orders of magnitude smaller than that obtained for the other factors. The negligible influence of t_c is is the reason why, in Fig. 2, in correspondence of the three settings of each factor the points are grouped by three. As shown in Fig. 3, the first-order sensitivity coefficients relating the f_m variation to the factors t_m, t_p, t_c are $\beta_1 = 2.85$ kHz/nm, $\beta_2 = 1.48$ kHz/nm, $\beta_3 = -0.135$ kHz/nm, respectively. By comparing the main factors, we can assess that t_m and t_p are equally effective.

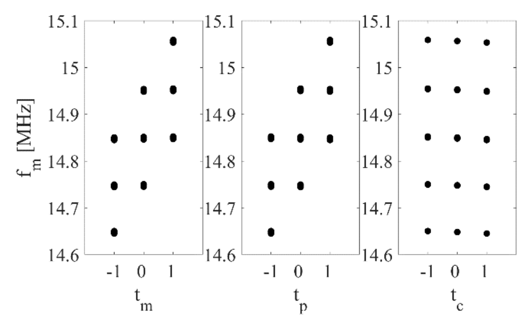

Fig. 2. DSP of the CMUT mechanical resonance frequency.

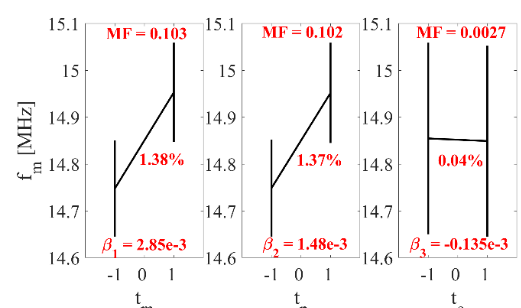

Fig. 3. MEP of the CMUT mechanical resonance frequency.

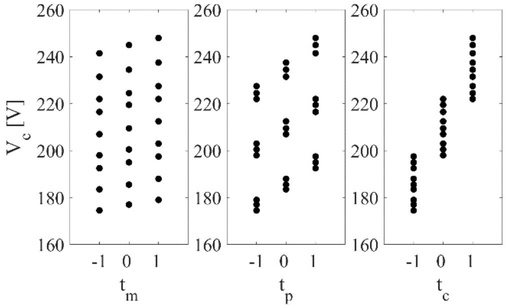

Fig. 4. DSP of the CMUT collapse voltage.

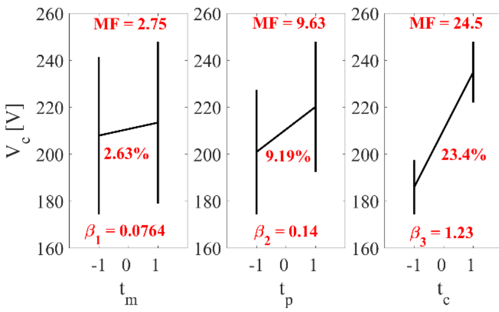

Fig. 5. MEP of the CMUT collapse voltage.

B. *Electromechanical parameters*

1) *Collapse voltage V_c sensitivity*

Due to the tolerance of the layers' thickness, the CMUT cells differ in membrane mass and stiffness and in effective gap height and dielectric constant. This causes an unevenness in the collapse voltage of the cells composing the device. The collapse voltage V_c was computed by performing a nonlinear static FEM analysis by increasing the bias voltage until the membrane collapsed. The nominal set of input parameters returned the nominal value $V_{c,n} = 210$ V. As can be seen in Fig. 4, the variation of all three factors causes a linear shift of the V_c. The sensitivity coefficients, reported in Fig. 5, are $\beta_1 = 76.4$ mV/nm, $\beta_2 = 140$ mV/nm, $\beta_3 = 1.23$ V/nm. By observing the MFs, it is clear that t_c is the most effective parameter.

2) *Biased transducer resonance frequency f_r sensitivity*

Even though the collapse voltage is non-uniform over the elements, the CMUT is biased with one voltage value, supplied to all the cells of the device. For this reason, the resonance frequency is uneven across the element. The first-mode resonance frequency f_r scattered data, computed by a FEM modal analysis run by biasing the transducer with $V_{DC} = 0.8\ V_{c,n} = 168$ V, is shown in Fig. 6. The resonance frequency variation, though monotone, is nonlinear with the input parameters variation, as can be noticed by looking at the minima obtained for the three settings of t_m, t_p, and t_c. This means that using the β-coefficients ($\beta_1 = 9.84$ kHz/nm, $\beta_2 = 10.8$ kHz/nm, $\beta_3 = 61.7$ kHz/nm) to compute the f_r variation introduces an error that can be reduced by including the interaction effects into the relation between f_r and the factors. The location shift caused by the variation of t_m, t_p, is smaller when t_c is maximum, as a consequence of the uneven difference between the applied bias and the collapse voltage.

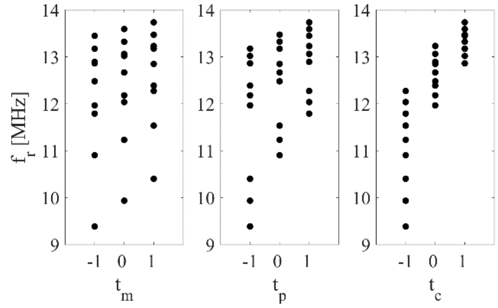

Fig. 6. DSP of the biased CMUT resonance frequency.

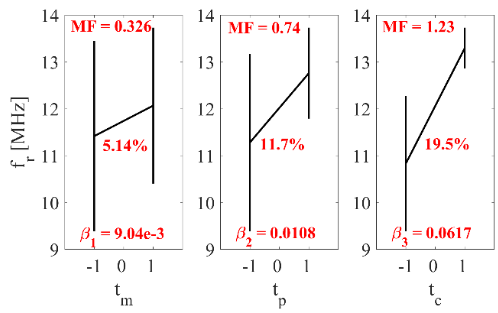

Fig. 7. MEP of the biased CMUT resonance frequency.

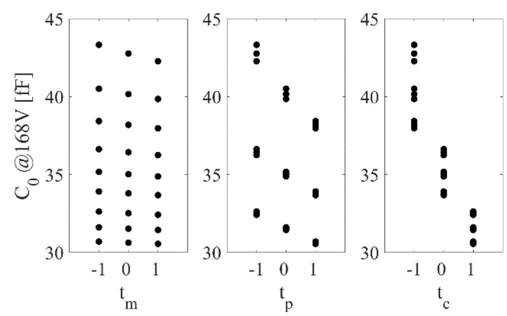

Fig. 8. DSP of the biased CMUT static capacitance.

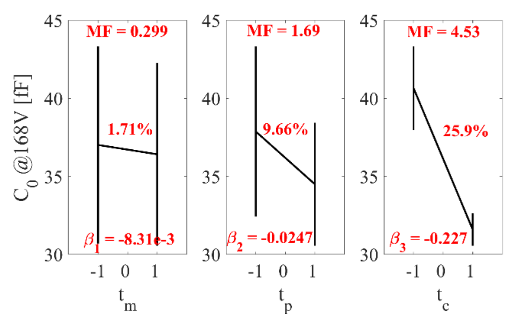

Fig. 9. MEP of the biased CMUT static capacitance.

3) *Biased transducer static capacitance C_0 sensitivity*

The non-uniformity of the equivalent gap height and dielectric constant also affects the unbiased transducer static capacitance C_0. In Fig. 8, it can be noticed that the static capacitance of the transducer biased at $V_{DC} = 0.8\ V_{c,n} = 168$ V is decreasing monotone and slightly nonlinear with respect to t_m, t_p and t_c. The static capacitance is mostly affected by t_c, whose variation causes a 25.9% shift of the mean values with respect to the nominal value $C_{0,n} = 35$ fF. The t_m effect on C_0 is negligible. From Fig. 9, the first-order approximation sensitivity coefficients relating C_0 to t_m, t_p and t_c are $\beta_1 = 8.3$ fF/pm, $\beta_2 = -24.7$ fF/pm, $\beta_3 = -227$ fF/pm.

C. Acoustic performance

The impact of the process-related parameters variation on the water-coupled transmission sensitivity amplitude ($|G_{tx}|$), phase and -3dB bandwidth (BW_3) is currently being assessed. The computation of these performance indicators' nominal values, computed at the nominal center frequency $f_{c,n} = 10.76$ MHz, are $BW_3 = 6.96$ MHz, $|G_{tx,n}| = 27.3$ dB (ref.kPa/V) and $\angle G_{tx,n} = -112°$. Preliminary results assess that the BW_3 dependence on the factors variation is strongly nonlinear and non-monotone. Therefore, it is not possible to compute the first-order sensitivity coefficient for this particular indicator.

IV. Comparison with Measurements

A 256-elements Reverse-Fabricated CMUT array for medical imaging was characterized by performing electrical impedance measurements. In order to assess the variability due to the tolerances of the microfabrication process-related parameters, the electrical impedance of the device was measured to extract the electromechanical parameters characterizing each element of the array. Measurements were performed by biasing the elements at $V_{DC} = 150$ V ≈ 0.7 $V_{c,n}$, and the comparison between simulations and experiments was performed based on the measurement data available. An initial estimate of the process parameters tolerances returns that the standard deviations for the considered parameters are $\sigma t_m = 1.6$ nm, $\sigma t_p = 5.42$ nm (computed by combining the standard deviation estimated for the two passivation layers separately), and $\sigma t_c = 2$ nm. By assuming a normal distribution of the thicknesses, almost all the measured values of the input factors fall within a $\Delta x_i = 3\sigma$ range. The spread of the mechanical resonance frequency and of the static capacitance was then computed according to (2) and compared to the variation observed in the experiments.

A. Resonance frequency

The mean value of the resonance frequency measured by biasing the 256 transducer elements with $V_{DC} = 150$ V is $f_{r,mean} = 13.67$ MHz. The difference between the highest and the lowest measured value is $\Delta f_r^{meas} = 530$ kHz. According to (3), the expected variation of the biased transducer resonance frequency is $\Delta f_r^{sim} = 589$ kHz, which is close to the measured variability. The difference between the measured and simulated variability can be ascribed to the different bias voltage applied in the simulations and in the experiment, as well as to neglecting the interaction effects.

B. Static capacitance

The static capacitance extracted from the electrical impedance measurements of the 256 array elements biased at $V_{DC} = 150$ V has a mean value of $C_{0,mean} = 26.5$ pF. The measured values spread within a range $\Delta C_0^{meas} = 3$ pF. By using (2) and the computed sensitivity coefficients β_1, β_2, β_3 reported in Fig. 8, and by considering that the element static capacitance can be calculated by multiplying the nominal static capacitance $C_{0,n}$ by the number of cells $N = 344$, the expected variation of the biased transducer static capacitance is $\Delta C_0^{sim} = 0.62$ pF. In this case, the poor fitting between the model and the experimental data is due to the parasitic capacitance of both the routing metallization layers' overlap, which depends on the measured element, and the measuring interface electronics.

V. Conclusions

In order to assess quantitatively the impact of the variability of the process parameters t_m, t_p, and t_c on a CMUT array electromechanical parameters, the mechanical resonance frequency f_m, the collapse voltage V_c, the biased device resonance frequency f_r and static capacitance C_0 were computed by FEM by varying the input parameters of 10% according to a 3-factors 3-levels full-factorial Design of Experiments. The first-order sensitivity coefficients relating the electromechanical performance variation to the three input factors variation were computed. These coefficients allow computing the expected variability of the observed output quantities in response to the process parameters variability within the simulated tolerance. The proposed analysis provides a useful method to quantify the impact of the process-related parameters tolerance on the CMUT performance non-uniformity, and the results match the measured variation of the resonance frequency well. The static capacitance variation measurement is affected by parasitic effects that impair the fairness of the comparison. Further work will improve the modeling of the selected indicators variability by including the interaction coefficients, and will assess the accuracy of the proposed method by comparing the improved model results to the experimental data. Further, the impact of process-related parameters tolerance on the acoustic performance will be analyzed by the same means.

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