MEMS Varactor Modeling Methodology for interactive Electromechanical Simulation with High Accuracy

GERHARD KAHMEN[1], MATTHIAS WIETSTRUCK[2]
and HERMANN SCHUMACHER[3]

[1]Rohde & Schwarz GmbH, Muehldorfstrasse 15, 81671 Munich, Germany
[2]IHP, Im Technologiepark 25, 15236 Frankfurt (Oder), Germany
[3]Institute of Electron Devices and Circuits, Ulm University, 89069 Ulm, Germany

Abstract. MEMS varactor devices integrated into the *Backend-of-Line* (BEOL) metal stack of a semiconductor process offer an attractive alternative to PN junction or FET gate-channel varactors for monolithic integration of RF-VCOs. Typically the design of MEMS varactors is based on finite element solvers (FEM) and EM field solvers to optimize the electromechanical and RF properties of the devices, which is time consuming and tedious. This paper introduces a methodology for an interactive MEMS varactor design with high accuracy based on a generalized mechanical approach. Additional to the ideal MEMS membrane a composite membrane layer system and the inherent membrane deflection due to residual stress are considered. The good agreement between measurements and predicted results proofs the validity of the presented methodology.

1. Introduction

For frequency tuning of monolithically integrated VCOs, PN junctions or FET gate-channel capacitors are widely used as varactors since most semiconductor processes do not offer dedicated varactor devices. These varactors show significant nonlinearities of the CV characteristic, low RF power handling capability, low tuning voltage range and moderate 1/f noise performance limiting their application to narrow band RF VCOs with moderate phase noise performance. MEMS varactors monolithically integrated into the BEOL metal stack offer an attractive alternative to overcome the above drawbacks [1].

Typically the design of MEMS-varactors is based on finite element (FEM) solvers and electromagnetic (EM) field solvers which is a computationally resource-hungry and time consuming approach. In the literature [2] simple electromechanical approximations for dedicated topologies can be found which are sufficient to get a general understanding for the MEMS operation, but which cannot be used for an actual MEMS design with given specifications. This paper introduces a modeling methodology based on a generalized electromechanical approach which allows the interactive design of MEMS varactors with high accuracy. As a basis this model considers an ideal single layer planar MEMS membrane. Subsequently the impact of a composite MEMS membrane layer system and an inherent deflection of the MEMS membrane due to residual stress are added. This modeling methodology is demonstrated and verified on a fabricated fixed-fixed MEMS varactor design and can be applied for any kind of MEMS varactor topology.

2. Analytical Calculation of the MEMS Membrane Displacement

The basis for the interactive electromechanical simulation is the analytical calculation of the MEMS membrane displacement *w(x)* when a point force *F* is applied. Figure 1 shows the sectioned model of the MEMS membrane and a photo of the fabricated device.

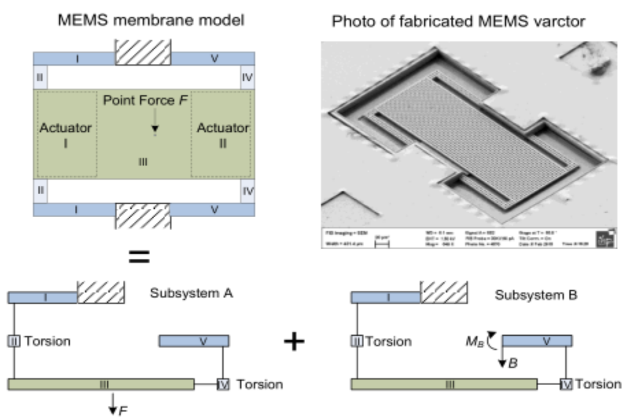

Fig. 1. (Color on line). Model of MEMS membrane and photo of the fabricated MEMS varactor.

The actuators are placed below the MEMS membrane as indicated in Fig. 1. When a force is applied, sections I, V and the MEMS membrane III act as bar springs while sections II and IV act as torsion springs. Since the MEMS membrane as shown in Fig. 1 represents a statically indetermined system it has to be subdivided into two statically determined subsystems with the introduction of the unknown force *B* and moment *MB* as indicated in Fig. 1. In a first step the displacement *w(x,F)* is calculated for subsystem A and *w(x,B, MB)* for subsystem B making use of the differential equations [3] for the beam displacement with Young's module E, the moment of inertia I, the acting moments M.

$$w'' = -\frac{M}{EI} \tag{1}$$

and the equation for a torsion spring with the shear module G, torsion moment M_T, torsion moment of inertia I_T and length l

$$\vartheta' = \frac{M_{Tdl}}{I_T G} \tag{2}$$

The displacement of the complete membrane is calculated by the superposition of subsystems A and B. The two boundary conditions at the right side of the anchor

$w_A + w_B = 0$ (no displacement at the anchor)
$w'_A + w'_B = 0$ (slope of membrane at anchor is zero)

are applied to calculate the force B and the moment M_B.

3. Electromechanical Simulation of MEMS Membrane Displacement

The electrostatic force which is acting on the MEMS membrane is given by [4]

$$F = \frac{1}{2}\frac{\epsilon_0 A}{d^2} V^2 \tag{3}$$

The MEMS beam represents a linear mechanical system. To consider the distributed geometry of the actuator, the electrodes are subdivided into infinitesimal sub-actuator areas acting as point forces on the MEMS membrane. For each of these point forces the membrane displacement is calculated based on the analytical approach described in section II and then superposed to result in the total displacement of the membrane.

The actual calculation of the displacement, resulting in the equilibrium between the electrostatic force ($F \sim 1/d^2$) and the spring restoring force ($F \sim d$) requires a numerical approach, which is shown in Fig. 2.

Based on the initial gap d_0 and (3) the point forces of the infinitesimal sub-actuators and the resulting superposed displacement of the membrane are calculated giving the updated gap d_1. For this updated gap the infinitesimal point forces and the new gap d_N are repeatedly calculated again until an equilibrium between electrostatic and restoring force is achieved. This equilibrium is reached if the difference between gap d_n and d_{n+1} is smaller than a predefined error value. Once the equilibrium is reached the capacity of the MEMS varactor is calculated by summing up the infinitesimal capacitor values of the sub-actuator areas applying the parallel plate capacitor equation.

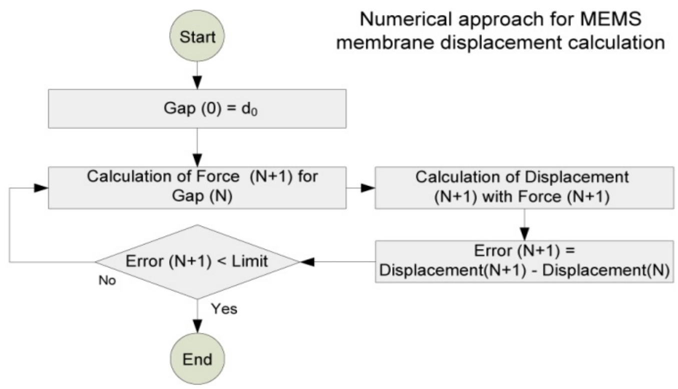

Fig. 2. Numerical approach of the MEMS membrane displacement calculation.

4. Impact of Composite MEMS Membrane Layer

In practice MEMS membranes are realized as multilayer composite systems to compensate the residual layer stress. As an example the MEMS membrane realized within this work is a triple layer TiN-AlCu-TiN stack.

The TiN layers on top and bottom of the AlCu layer are considered by assigning a modified moment of inertia to their cross section applying Steiner's equation [5]

$$I_{\bar{y}} = I_y + \bar{Z}^2 A \tag{4}$$

The modified moment of inertial of the complete composite MEMS membrane is given by with n_{TiN} being the ratio of the Young's moduli of AlCu and TiN.

$$\bar{I} = I_{\bar{y}\mathrm{AlCu}} + n_{\mathrm{TiN}} I_{\bar{y}\mathrm{TiN}} + n_{\mathrm{TiN}} I_{\bar{y}\mathrm{TiN\_u}} \tag{5}$$

The modified stiffness of the composite MEMS membrane is finally given by

$$\overline{EI} = \sum_i E_i I_{\overline{Yi}}^{\;-} = E_{\text{AlCu}} \overline{I} \tag{6}$$

5. Impact of Inherent MEMS Membrane Deflection

Residual layer stress within the MEMS membrane can lead to an inherent deflection of the MEMS beam resulting in a significant increase of the MEMS varactors spring constant. Since the practical deflection is small compared to the dimension of the MEMS membrane the triangle approximation shown in Fig. 3 can be applied. The MEMS membrane will be compressed by $2v$ in x-direction if a force F displaces the membrane by a distance of u in z-direction. Due to the law of energy conservation, the spring energy stored in the compressed membrane equals the energy used to displace the membrane by the distance u with the applied force F_z.

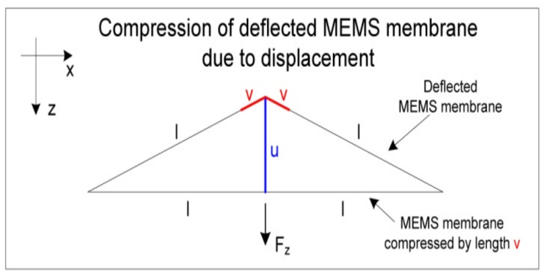

Fig. 3. Compression of deflected MEMS membrane when displaced by a distance *u* and a force *F*.

Equalizing these two energies and applying the law of elasticity results in the spring constant for the compressed MEMS membrane

$$k_S = \frac{F_Z}{u} = \frac{EA}{l}\frac{\left(\sqrt{u^2+l^2}-l^2\right)^2}{u^2} \tag{7}$$

6. Semiconductor Technology

The MEMS varactor developed within this work is embedded in the BEOL metallization stack of the IHP 0.13 µm Si/SiGe BiCMOS technology. This state-of-the-art process offers high speed and high voltage active devices with a BV_{CEO} / f_T combination of 1.7 V / 250 GHz and 3.7 V / 45 GHz, respectively, and a metal stack of 7 layers. The cross section of the fabricated MEMS varactor is shown in Fig. 4.

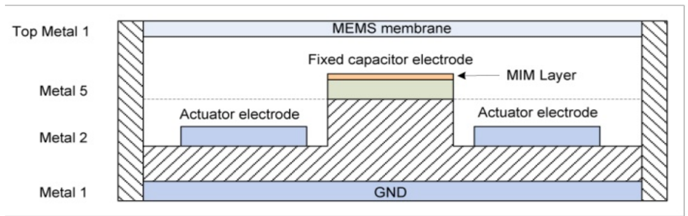

Fig. 4. (Color on line). MEMS varactor configuration within the IHP SG13 BEOL metal stack.

7. Results

Fig. 5 shows measured and simulated CV curves of the realized MEMS varactor. In the varactor CV simulation the effect of the composite MEMS membrane is considered by applying the modified stiffness (6). The inherent deflection due to residual layer stress is accounted for by the additional spring constant (7) acting “in parallel” to the non-deflected ideal MEMS membrane. The simulated pull-in voltage for the ideal single layer AlCu membrane with a Young's module of 70 GPa is 22 V. Taking the triple composite layer stack with ~50 nm and ~100 nm TiN layers (E = 410 Gpa) on top and bottom of the AlCu layer into account results in a pull-in voltage of 32 V.

Adding the effect of the 910 nm inherent membrane deflection due to residual stress leads to an increased distance between the actuators and the MEMS membrane which results in a pull-in voltage of 43 V and a reduced capacitance as expected. The compression of the MEMS membrane due to the deflection in z-direction finally leads to a pull-in voltage of 53 V, which is in good agreement with the CV measurements.

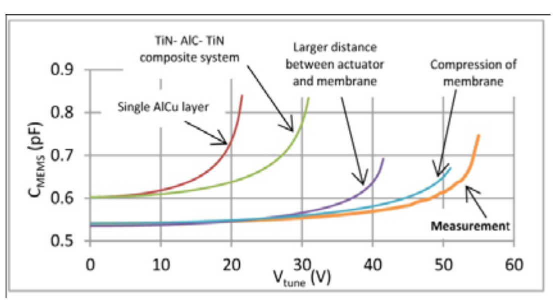

Fig. 5. (Color on line). Measured and simulated CV curves successively including the composite MEMS membrane layer system and the inherent deflection of the membrane.

The time required to simulate each of the CV curves shown in fig. 5 takes less than 20 seconds on a state of the art notebook computer compared to FEM simulations lasting from several minutes to hours depending on the details considered.

8. Conclusion

This work presents an interactive methodology for the electromechanical simulation of MEMS varactors with high accuracy. In addition to the ideal MEMS membrane effects such as a composite membrane layer system and the inherent membrane deflection due to residual stress are considered and can be separated from each other. Due to its high accuracy this methodology can be successfully applied for practical MEMS varactor design and BEOL process optimization.

References

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