Material Properties Characterization of BiCMOS BEOL Metal Stacks for RF-MEMS Applications

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Abstract. The mechanical material parameters of complex metal layer stacks embedded inside a BiCMOS process have been analyzed. Finite-Element-Method simulations (FEM) with a combination of statistical calculation methods have been used to accurately determine the material properties. The Young's modulus of AlCu and TiN have been found to be 65 GPa and 410 GPa. The residual stress values have been extracted as -514 MPa (compressive), 494 MPa (tensile) and -964 MPa (compressive) for the TiN Top-layer, AlCu and the TiN Bottom-layer which is in good agreement to in-line wafer curvature measurement. Intrinsic stress was found to play an important role for the reason that it partly compensates temperature-induced stress and offers a reliable RF-MEMS switch operation. The extracted material parameters are very useful to perform accurate FEM simulations and help to reduce the design/modeling time of new BiCMOS embedded MEMS components.

Index Terms: FEM analysis, material characterization, residual stress, RF-MEMS switch, monolithic integration.

1. Introduction

The knowledge of mechanical material parameters is mandatory for the development of MEMS due to their influence on device performance and reliability [1]. One of the most important MEMS components for RF applications are electromechanical switches [2].

Electromechanical switches are considered as a key component for multi-band circuits due to their low insertion loss, high isolation and low power consumption [3, 4]. Recently a BiCMOS embedded RF-MEMS switch was demonstrated with an excellent performance and a very good reliability [5, 6]. The specific switch consists of electrodes in Metal 1, the signal line in Metal 2 and a TiN/AlCu/TiN stack in Metal 3 which is used as a movable membrane (Fig. 1).

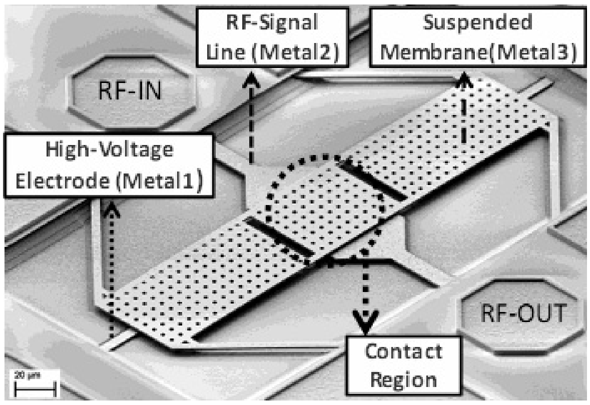

Fig. 1. SEM of the BiCMOS embedded RF-MEMS switch.

For a cost-efficient development and fabrication, the mechanical and electrical performance has to be simulated/modeled with accurate material parameters which strongly depend on deposition conditions [7], determine the stiffness of the system and therefore define the actuation voltage, switching time and reliability which need to be optimized before fabrication. In this work we have demonstrated the characterization of a complex metal layer stack of a BiCMOS BEOL metallization based on optical measurements and FEM simulations. The developed method provides mechanical material properties of the suspended Metal 3 layer and is very promising to perform accurate mechanical simulations of MEMS structures.

2. Material Parameter Estimation

Different material characterization methods like mechanical resonance, pull-down voltage and load-deflection method have been proposed in literature to estimate mechanical material properties [8, 9]. In this work, the determination of the specific mechanical material properties is based on mechanical resonance and load-deflection method combined with FEM simulations and statistical methods (Fig. 2).

The mechanical resonance frequency or load-dependent deflection of a mechanical system strongly depends on the material parameters. These two main properties of the specific test structures are simulated using CoventorWare ®. A multivariate linear regression (MLI) is used to determine a dependency between measurement value and the important material parameters. The “coefficient-of-determination” shows if the linear regression is sufficient or a higher-order polynomial function is required. The method is resulting in different sets of material parameters which show the lowest deviation to measurement results. The shown method is universal for different types of static and dynamic behavior and can be adapted to several applications.

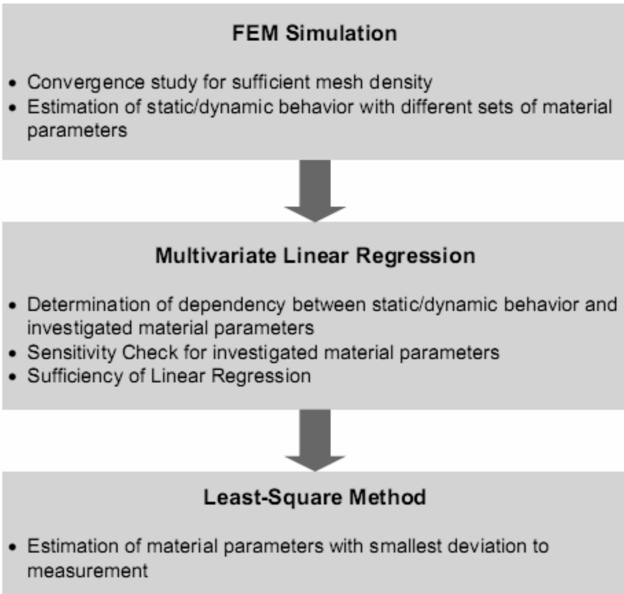

Fig. 2. Material parameter estimation method.

3. Experimental Results

The movable part of the RF-MEMS switch is realized using the Metal 3 layer of the BiCMOS BEOL stack. Metal 3 consists of three different layers: TiN/AlCu/TiN. TiN layers are used as a barrier layer between AlCu and the BEOL oxide whereas AlCu (99.5% Al) is used as the main conductive part of Metal 3. Typically, the TiN layer has a thickness of ~200 nm while the AlCu layer has a thickness of ~700 nm. The mechanics are mainly dominated by the Young's modulus of TiN, AlCu and the residual stresses of these layers. Residual stress is a combination of temperature-induced stress and intrinsic stress [10]. Temperature-induced stress is a result of cooling down process from deposition temperature (~500K) to room temperature due to the different thermal expansion coefficients of AlCu and TiN. Intrinsic stress is caused by crystallographic defects, grain boundaries and further deposition effects [11]. The material parameters are strongly affected by the type of deposition and the deposition conditions like temperature and pressure. The estimation of Young's modulus and residual stress is done with different types of structures and the aforementioned estimation method.

A. Determination of Young's modulus

To determine the Young's modulus, clamped beams with different lengths and widths have been fabricated and measured (Fig. 3).

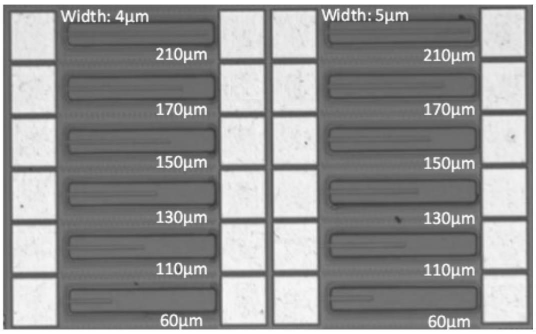

Fig. 3. Clamped beams for estimation of Young's modulus.

The frequency-response-function (FRF) of simple clamped beams depends on the Young's modulus. The first eigenfrequency can be calculated by (1) and shows a dependency on the length, the thickness, the material density and the Young's modulus E.

$$f_r = \frac{1}{2\pi \cdot l^2} \cdot \sqrt{\frac{4 \cdot E \cdot t^2}{\rho}} \tag{1}$$

The geometry was investigated by Focused-Ion Beam Milling (FIB) to consider process-specific characteristics like under-etching of the cavity mask (lateral etch of SiO_2) and unwanted etching of AlCu to take these effects into account during FEM simulation (Fig. 4).

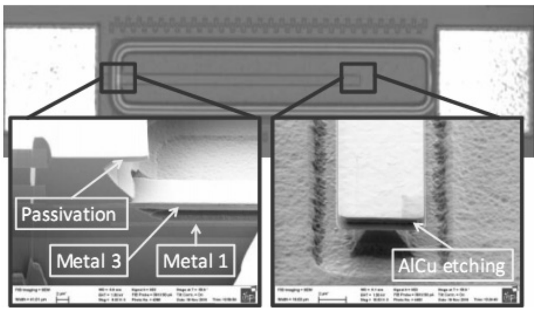

Fig. 4. FIB analysis of clamped beam.

The MLI has shown that the FRF is independent from residual stress and therefore it is only defined by geometry and the effective Young's modulus of the metal stack. The FRF was detected by electrostatic actuation with a broadband signal and observing the mechanical response with the Laser-Doppler Vibrometer (LDV) MSA-500 from Polytec®. The FRF of a 210 µm beam is shown in Fig. 5. It provides 6 detectable eigenfrequencies in the maximum frequency range of 2.5 MHz.

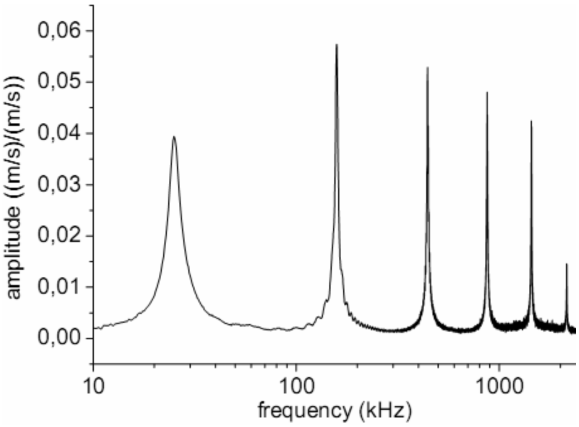

Fig. 5. Frequency-response-function of 210 µm beam.

The “coefficient-of-determination” is higher than 0.998 for every eigenfrequency and therefore the linear type of multivariate regression is suitable. The most accurate result of the least-square method with lowest deviation tomeasurement is shown in Table 1.

Table 1. Results for determination of Young’s modulus

E_{AlCu}	E_{TiN}	Maximum deviation $f_{1\text{-}6}$
65 GPa	410 GPa	3.0%

The Young’s modulus of 65 GPa for AlCu and 410 GPa for TiN are in a very good agreement with literature [12, 13] and the simulated FRF with the estimated material properties shows a small deviation of 3% compared to the measured FRF. For further analysis of residual stress, the estimated Young’s moduli are applied to RF-MEMS switch structure to analyze the residual stress characteristics of the AlCu and TiN layers.

B. Determination of Residual Stress

Residual stress in suspended structures results in an up or down bended membrane and strongly influences the performance of the switch. Residual stress is not only limiting the reliability performance by affecting the restoring force and therefore the risk for stiction, but also results in poor electrical and RF performance.

By the help of this analysis, optimal switch structures can be selected in design-level. This helps to decrease the design optimization time and to improve the yield of the process.

To perform the residual stress analysis, the surface topology of the RF-MEMS switch has been observed using White-Light-Interferometer (WLI) shown in Fig. 6.

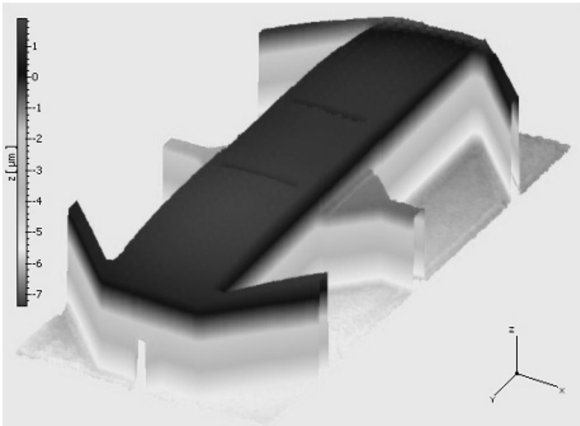

Fig. 6. WLI of RF-MEMS switch.

The aforementioned calculation method is used to estimate the residual stress. An initial deflection of the suspended membrane is achieved by adding residual stress to the different layers. Different tensile and compressive stress cases have been applied and the surface topology was extracted along the black line shown in Fig. 7.

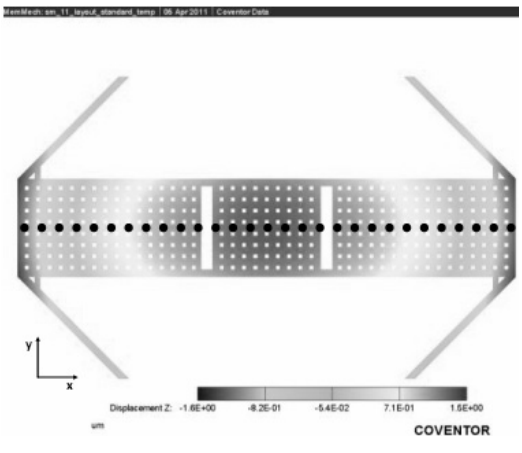

Fig. 7. Extraction of initial deflection.

The MLI shows a high sensitivity to residual stress but it has to be considered that the “coefficient-of-determination” varies for different locations in x-direction. Only points with a high “coefficient-of-determination” have been taken into account. The most accurate result of the least-square method is shown in Table 2. The results are in good agreement to in-line stress measurements using wafer curvature method. Characterization of stand-alone layers was only possible for the Bottom TiN and AlCu layers.

Table 2. Results of residual stress for different layer

Layer	TiN-Top [MPa]	AlCu [MPa]	TiN-Bottom [MPa]
Calculation	-514 (comp.)	494 (tensile)	-964 (comp.)
Wafer Curvature	---	432 (tensile)	-860 (comp.)

The initial deflection of the switch has been simulated with the resultin residual stress and shows an excellent agreement to the real surface topology of the investigated RF-MEMS switch (Fig. 8). The zero-level of initial deflection shows the position of the clamped anchors.

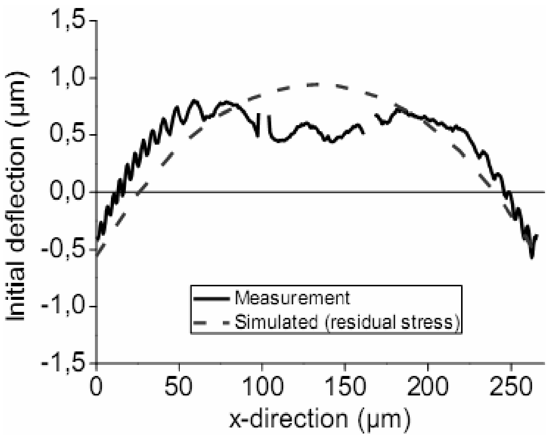

Fig. 8. Initial deflection due to residual stress.

In fact, the initial deflection is caused by two effects: temperature-induced stress and intrinsic stress. To distinguish between these two effects, firstly the temperature-induced stress is simulated by the thermal expansion coefficients taken from [14, 15] and a constant zero-stress temperature option which is provided by CoventorWare®. The initial deflection of the switch after applying the temperature-induced stress is shown in Fig. 9.

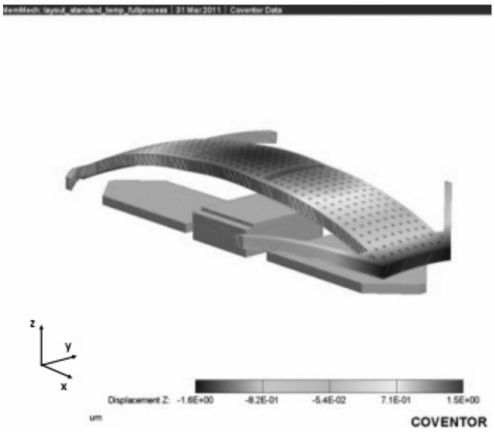

Fig. 9. Initial deflection due to temperature-induced stress.

As can be seen from Fig. 9, the center of the suspended membrane is up-bended compared to the anchors whereas the edges are strongly down-bended. Temperature-induced stress leads to a deflection status higher than measured which shows that intrinsic stress partly compensates the temperature-induced stress and has a primary importance. Without any compensating intrinsic stress, the distance between the grounded membrane in Metal 3 and the high-voltage electrodes in Metal 1 is about 1.5µm which increases the risk for a short between Metal 1 and Metal 3.

The estimation of stress compensating intrinsic stress is achieved by adding intrinsic compressive and tensile stress combinations to the different layers. The initial deflection of the switch has been simulated with the resulting temperature-induced stress and intrinsic stress and shows again a good accuracy to the real surface topology of the switch (Fig. 10).

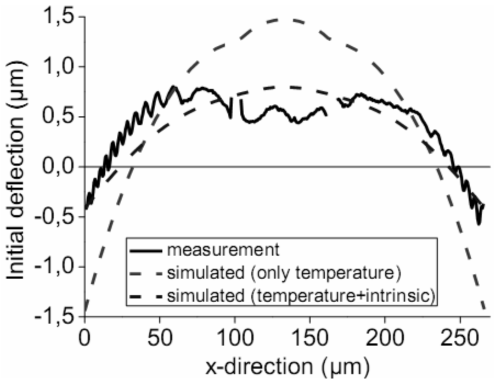

Fig. 10. Initial deflection due to temperature-induced stress and intrinsic stress.

The estimated intrinsic stress parameters are shown in Table 3. The stress compensating intrinsic stress has a crucial importance to prevent from device failure.

Table 3. Results for determination of intrinsic stress

Layer	TiN-Top [MPa]	AlCu [MPa]	TiN-Bottom [MPa]
Calculation	-1240 (comp.)	-240 (comp.)	-1460 (comp.)

4. Conclusion

The mechanical material properties of a complex three-layer metal stack have been characterized using the FRF of clamped beams and the surface topology of current RF-MEMS switch structure. The Young's moduli of AlCu and TiN have been found to be 65 GPa and 410 GPa which are in good agreement with literature. The residual stress values have been extracted as -514 MPa (compressive), 494 MPa (tensile) and -964 MPa (compressive) for the TiN Top-layer, AlCu and the TiN Bottom-layer. Intrinsic stress partly compensates temperature-induced stress and therefore plays an important role by enabling a stable and reliable RF-MEMS switch operation.

The developed technique can be applied for different process conditions and provide precise material properties which help the modeling of various MEMS structures. Furthermore, understanding the stress non-uniformity over the wafer using the developed technique helps to enhance the yield of the MEMS process.

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