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FATIGUE FAILURE ANALYSIS OF COMB-DRIVE TYPE MEMS

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Abstract. Micro Electro Mechanical Systems (MEMS) constitute nowadays a discipline of fast industrial growth due to its versatility and technical benefits. MEMS are used as sensors and actuators in numerous industrial applications like automotive (air-bags), communications (telephony), biomedical (drug dispensers), electronics (mall pillows of printers), etc. These devices, of sizes ranging from microns to millimeters are generally manufactured with fragile material like silicon in their mono or polycrystalline variants using similar techniques to those used in the production of semiconductor devices. MEMS are subjected to fatigue as a consequence of cyclic mechanical loading in many of their applications. Given the importance of establishing safe service conditions and the difficulty of testing these very diverse microstructures with experiments, it is advisable the use of numerical models to simulate their behavior. In this research, the crack propagation by fatigue of an electrostatic actuator of the Comb-Drive type is studied by using a novel technique characterizing the propagation of a simulated crack.

1 INTRODUCTION

Micro-electrical mechanical systems (MEMS) have been studied and used since the end of the past century in many technological applications. The application field of these Microsystems is continuously expanding due to the versatility of its applications (López Fernández, 2005). The major part of MEMS technology comes from technology developments carried out during the II World War to produce integrated circuits based on semiconductor material such as Silicon and Polysilicon (Van Spengen and Oosterkamp, 2007). MEMS, which are micromechanical devices fabricated using semiconductor fabrication technology, are core products for future integrated systems with advanced functionalities. Due to their compactness and portability, these devices are being employed even in mobile applications. The reliability of MEMS devices should be high because of the size effect with the miniaturization of their dimensions and the precision of micro-fabrication, which is confirmed by many commercially available devices, such as accelerometers, pressure sensors, inkjet printer heads, gas sensors, airbags, projection displays, filters and modulators; among many others. Although their high reliability has been established by the continuous development effort of researchers and engineers, numerous reliability issues and their related phenomena still remain, both in devices and materials, see Brown et al. (1997). An important new aspect, which was not as important in classic microelectronic devices as in today's MEMS development, is the mechanical reliability of materials for MEMS structures. Naturally, MEMS manufacturers try to optimize its performance in service. As a result, in many cases these devices are mechanically working at the limit of their resistance to fatigue. It is therefore essential to define their operating limits in order to be designed and implemented intelligently, as well as to characterize how a crack starts and its subsequent propagation. The aim of this work is to study the performance of a particular type of MEMS, called comb-drive, and to determine the maximum size of a crack in its structure which will allow it to operate in service conditions.

2 MEMS STRUCTURE USED IN THE STUDY

Capacitive sensors and actuators are widely used in MEMS devices. Comb-drive MEMS are very versatile devices that can be applied to sensors, attenuators, filters and modulators (Wang et al, 2003, 2004; Vidor et al., 2006). The comb-drive is a capacitive actuator, frequently made in Polysilicon, which is operated by electrostatic force. A comb-drive consists of a fixed structure and a movable one; both in the form of fingers to achieve greater capacitance (see Figure 1). When a potential difference is applied between the two sets of combs, an electrostatic force pointing in the direction of the fingers appears, and a displacement of the movable part occurs. A crack is located in one of the arms through a wedge-shaped notch, as shown in Figure 2. The degree of crack progress can be evaluated according to the variation of the total displacement of the comb-drive, as it will be detailed later on.

Linear elastic mechanics uses the stress intensity factor in opening stress mode, K_I, as a fracture parameter to assess crack behavior. Most of the K_I solutions reported in the literature correspond to regular crack geometries subjected to simple loading configurations. The parameter K_I depends on the device geometry, the applied stresses and the crack length, according to the equation:

$$K_I = Y\sigma\sqrt{\pi a} \quad (1)$$

Where Y is a dimensionless constant that depends on geometry and mode of loading.

When K_I equals a critical value K_{Ic}, which depends on the material, the crack grows catastrophically and the device breaks. As highlighted in a recent experimental study, the local fracture toughness in Polysilicon films may be substantially different (varying from 0.84 to 1.24 MPa $m^{1/2}$) from the average measured fracture toughness value (1.00 MPa $m^{1/2}$), owing to the relative orientation of the grains containing the crack tip and grain boundaries near the crack tip (Chasiotis I. et al., 2006). Then, assuming the conservative value K_{Ic} = 0.84 MPa $m^{1/2}$, it is possible to determine the critical crack length a_c for a given geometry and stress configuration, see Eq. (1).

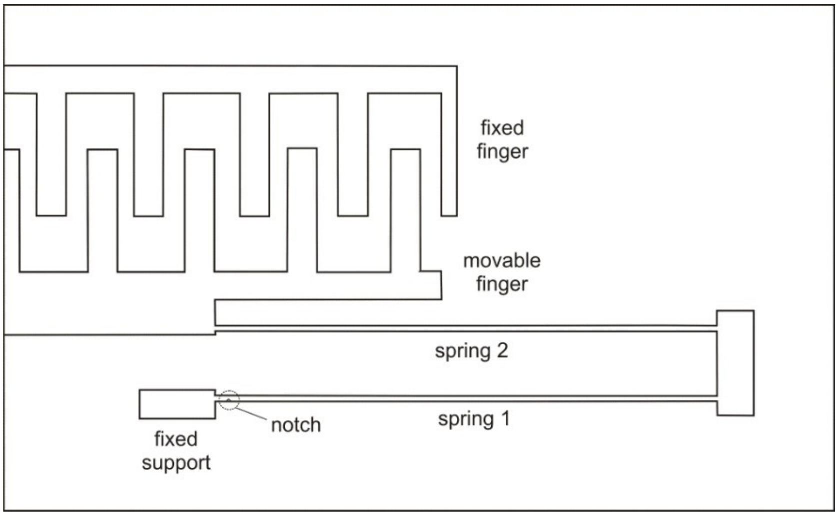

Figure 1: Simulated comb-drive structure

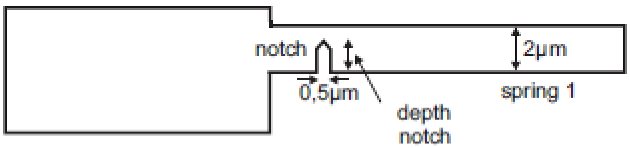

Figure 2: Simulated crack details

3 STRESS INTENSITY FACTOR DETERMINATION

The proposed comb-drive model was studied by using Comsol Multiphysics software. Due to symmetry reasons, only half of the comb-drive is studied (see Figure 1). When the bottom comb is attracted by the upper comb, the crack is subjected to opening stresses mode (mode I stress intensity factor, K_I). Between the comb-drive fingers the following identity holds:

$$-\nabla\cdot(\varepsilon \nabla V) = 0 \tag{2}$$

Where ε is the relative permittivity and V the electric potential. The electrostatic force density is expressed by:

$$F_{es} = \frac{\varepsilon E^2}{2} \tag{3}$$

Where E is the electric field produced by the potential difference between the combs. The electrostatic force attracts the upper and lower parts so that the distance between them varies, which in turn causes the variation of the electric field. This effect is addressed by the software using a mobile mesh arbitrary Lagrange-Eulerian (ALE)-method, which allows automatically following the movement of the lower comb.

The usual way to find K_I by numerical methods consists in finding first the fracture parameter known as J-integral, e.g. see Shih et al. (1986) and Moran and Shih (1987). The J-integral allows characterizing the cracks when the plastic zone size is greater than that allowed to validate K. In our case, Polysilicon being a material of low plasticity when subjected to stress, the use of J is justified by a simpler numerical treatment.

3.1 The J-integral

The J-integral is a two-dimensional line integral along a counterclockwise contour Γ, surrounding the crack tip (see Figure 3). The J-integral is defined as:

$$J = \int_{\Gamma} W\, dy - T_i \frac{\partial u}{\partial x} ds = \int_{\Gamma} \left(W\, n_x - T_i \frac{\partial u}{\partial x} \right) ds \tag{4}$$

Where W is the strain energy density:

$$W = \frac{1}{2}\left(\sigma_x \cdot \varepsilon_x + \sigma_y \cdot \varepsilon_y + 2\, \sigma_{xy} \cdot \varepsilon_{xy}\right) \tag{5}$$

And T is the traction vector defined as:

$$T = \left[\sigma_x \cdot n_x + \sigma_{xy} \cdot n_y,\ \sigma_{xy} \cdot n_x + \sigma_y \cdot n_y\right] \tag{6}$$

σ_{ij} denotes the stress components, ε_{ij} the strain components and n_i the normal vector components.

The J-integral and the stress intensity factor are related for a plane stress case and a linear elastic material by the following relation:

$$J = \frac{K_I^2}{E_Y} \tag{7}$$

Where E_Y is the Young modulus

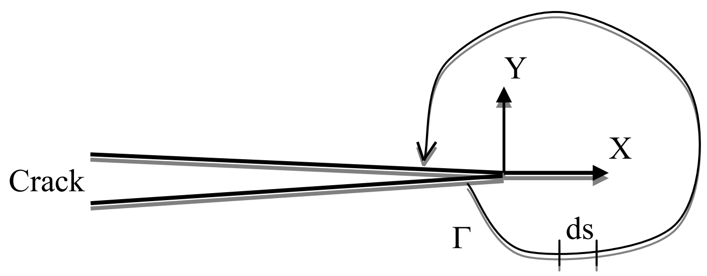

Figure 3: Arbitrary contour Γ surrounding the crack tip

3.2 Numerical resolution

The stress intensity factor solution of the problem studied was obtained by using the program Comsol Multipysics 3.5a. The region of air surrounding the comb-drive parts is also meshed to determine the resultant electric field acting when the potential is applied, ranging from 0 to 600 V in steps of 50 V. The model takes into account that the electrostatic field and the elastic field of strain and stress are coupled. The maximum load is obtained for a potential of 600 V.

The dimensions of the model shown in Figure 1 are 210 microns wide by 128 microns width. The elastic arm containing the crack in the bottom is 150 microns long by 2 microns in height. As it can be appreciated in Figure 1, the crack is located near the lower anchorage, where the momentum is maximum. The normal was defined in the program as external to each zone. The height of the zone where the crack lies, and the thickness are respectively w = B = 2 μm, and the crack length was a = 1 μm. The Young's modulus of Polysilicon is E_Y = 158.0E +9, and the Poisson's ratio is ν = 0.22

The mesh is refined in the area of the crack (see Figure 4), and the contour Γ was made surrounding this zone, as shown in Figure 5.

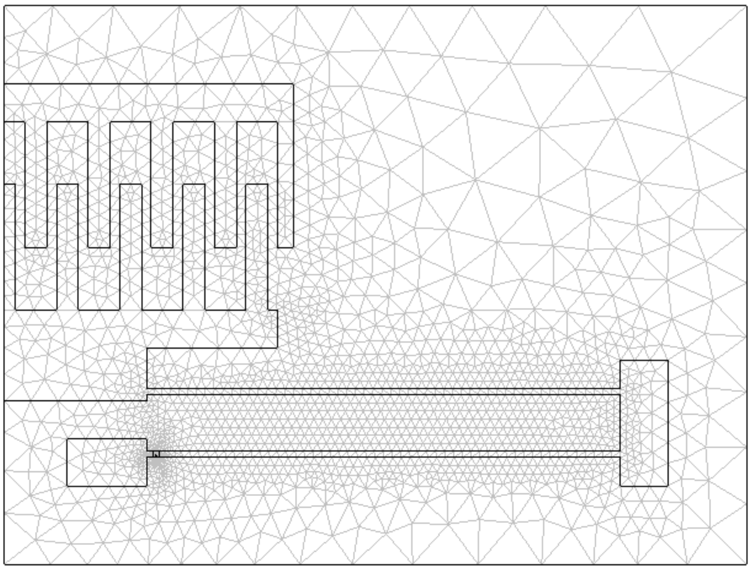

Figure 4: mesh used in the model

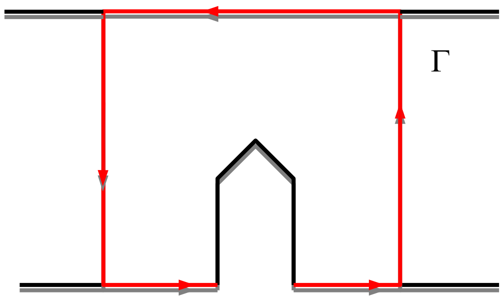

Figure 5: Contour Γ surrounding the crack, used to calculate the J-integral

Furthermore, numerical results were compared with those obtained by using K solutions existing in the literature. In the case that has been studied, the useful solution corresponds to an Edge Cracked Plate in Pure Bending, see pp. 604-606 of Anderson (1995). The dimensionless solution follows in equation (8).

$$f(a/w)=\frac{K_I B w^{3/2}}{M}=\frac{6\sqrt{2\tan\left(\frac{\pi a}{2w}\right)}}{\cos\left(\frac{\pi a}{2w}\right)}\left[0.923+0.199\left\{1-\sin\left(\frac{\pi a}{2w}\right)\right\}^4\right] \quad (8)$$

The momentum M is calculated with the Comsol software.

3.3 K results comparison and critical crack length estimation

The stress intensity factor was obtained in use of the Comsol program, using a mesh of 18672 elements. The program ran in a dual core laptop with 2 GB of RAM memory, and the solution was obtained after less than 7 minutes; K_I^{FEM} = 0.1267 MPa $m^{1/2}$. Moreover, the Handbook solution was obtained through equation (8); K_I^{H} = 0.1237 MPa $m^{1/2}$. The difference between both values is 2.37 %.

Equation (8) allows to find the critical crack length a_C, for K_{IC} = 0.84 MPa $m^{1/2}$ in Polysilicon, which results in a_C = 1.76 µm

Once estimated the critical crack length, the crack length progress by fatigue has to be studied in the comb-drive. A novel technique useful to study crack propagation by fatigue of comb-drive type MEMS is shown below.

4 MEAUSURING CRACK PROGRESS IN A CAPACITIVE COMB DRIVE

The comb-drive capacity is a function of the shape and dimension of the electrodes. One way to measure the growth of a crack is to measure the variation of displacement of the fingers of the comb-drive when a given voltage is applied. Then, the displacement can be measured by monitoring small changes in the capacity that occur between the fingers of the comb-drive. The problem that arises is that the capacitance change is masked by the large parasitic capacitance present. In fact, one way of measuring these capacitances is sending a relatively high frequency signal through the capacity formed by the fingers of the comb-drive, and measuring its impedance variation. The problem with this measurement is that the coaxial cable that connects to the MEMS has a parasitic capacitance with a magnitude near 100 *pF/m*, when the ability to measure the comb-drive may be the order of *fF*, in our case between 5 *fF* and 10 *fF*. Furthermore, this parasitic capacitance is not constant and varies with temperature.

The method proposed to measure small changes in capacity in the presence of large parasitic capacitances, is based on the work of Van Spengen and Oosterkamp (2007). The method consists in applying a high frequency signal (V_{RF}) to the circuit of the comb-drive, and varies the movement of its fingers with a low frequency signal ($V_{comb\text{-}drive}$) (see Figure 8). This produces an amplitude modulated signal (V_{AM}) whose modulation index m is proportional to the capacitance variation of the comb-drive, and therefore proportional to the displacement of the MEMS device. To counteract the effect of parasitic capacitances, capacitors and inductors are added to form a tank circuit which resonates at the frequency of the excitation signal V_{RF}. Before each measurement it is necessary to calibrate the tank circuit to compensate for possible variations in parasitic capacitance.

4.1 Measuring the capacity of a comb-drive

As we have seen in Figure 1, a comb-drive consists of a fixed structure and a movable one. When the displacement of the movable structure takes place, the capacity of the comb-drive varies, as shown in equation (9) (Seo and Shandas, 2003; Somlay et al., 2007):

$$C = 2n\frac{\varepsilon(L-y)e}{g} \quad (9)$$

Where: L is the height of the comb-drive finger and y is the displacement, g is the separation between the upper and lower fingers, e is the thickness of the finger, ε is the dielectric constant, and n is the number of fingers (see Figure 6).

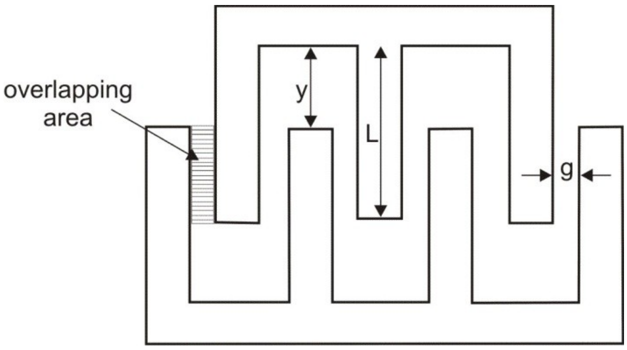

Figure 6: Parameters for measuring capacity in a comb-drive

4.2 Structure used in the model

The structure of the comb-drive used in the test was shown in Figures 1 and 2. The crack progress is evaluated according to the variation of the total displacement of the comb-drive. Cracks were generated by five notches, with respective depths of 0.5 μm, 1 μm, 1.25 μm, 1.5 μm and 1.75 μm. These different cracks were simulated using the Comsol Multiphysics 3.5a program. Figure 7 shows the variation of displacement and capacity of the comb-drive according to the applied voltage.

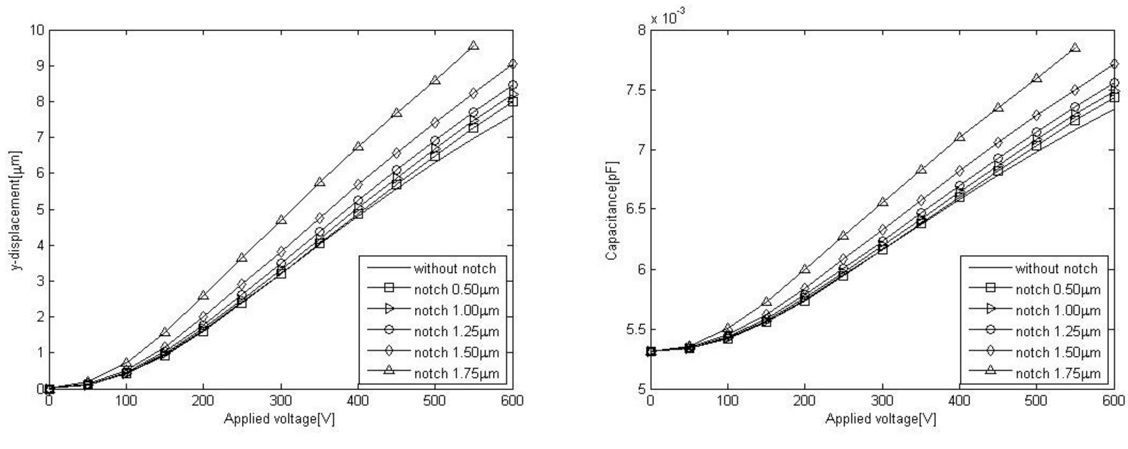

Figure 7: Displacement (left) and Capacity (right) of the comb-drive as a function of the applied voltage

5 CIRCUIT USED IN THE TEST

The circuit used in the measurement is shown in Figure 8, where:

- V_{RF} is a 100 *MHZ* generator of radio frequency.
- $V_{comb\text{-}drive}$ is the voltage applied to the actuator to produce the movement of his fingers. This voltage is applied across the inductor L_3 which functions as a radio frequency choke.
- $C_{comb\text{-}drive}$ is the capacity of the comb-drive, proportional to the separation of its fingers, as indicated by Eq. (9).

C_{cable} is the parasitic capacitance of the coaxial cables. Its value is about 170 *pF*. Because the value of C_{cable} is several orders of magnitude greater than the capacity of the actuator $C_{comb\text{-}drive}$, one way to avoid its influence is to form a parallel tank circuit introducing auxiliaries' inductor L_1 and capacity C_1, so that the resonant tank circuit and the source V_{RF} have the same frequency:

$$f_{RF} = \frac{1}{2\pi\sqrt{L_1(C_1 + C_{cable}}} \tag{10}$$

A similar tank circuit is used to offset the parasitic capacitance of the probes that are applied to the resistance R_1, when the modulated signal is measured.

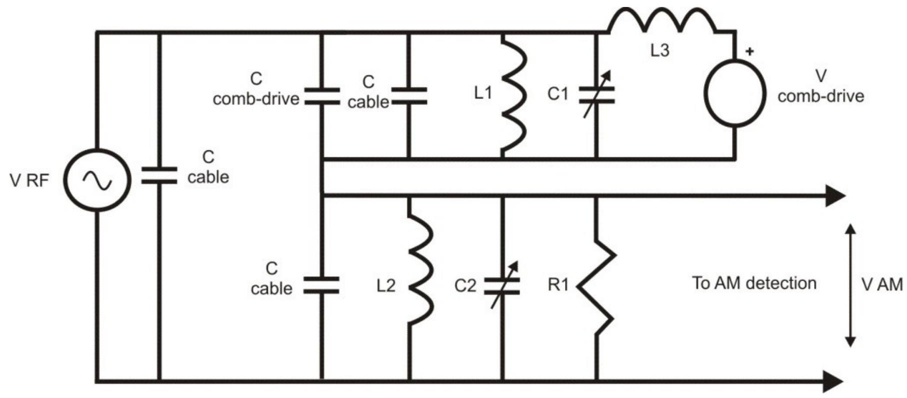

Figure 8: Circuit employed to measure the capacity of the comb-drive

Nevertheless, if in the circuit shown in Figure 8, the elements which are in resonance are eliminated (see Figure 9), the output of the modulator would be:

$$\frac{V_{AM}}{V_{RF}} = \frac{R_1}{R_1 - j\dfrac{1}{\omega_{RF} C_{comb-drive}}} \tag{11}$$

And since the magnitude of $C_{comb\text{-}drive}$ is very small, it can be expressed as:

$$\frac{V_{AM}}{V_{RF}} \cong j\omega_{RF} R_1 C_{comb-drive} \tag{12}$$

Then:

$$\left|\frac{V_{AM}}{V_{RF}}\right| \cong \omega_{RF} R_1 C_{comb-drive} \tag{13}$$

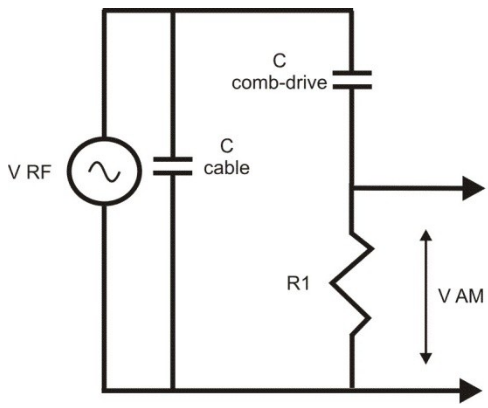

Figure 9: Simplified circuit

At the temporal level:

$$V_{AM}(t) = V_{RF}(t)\omega_{RF} R_1 C_{comb-drive}(t) \quad (14)$$

From equation (14) it can be seen that V_{AM} (t) vary linearly as a function of $C_{comb\text{-}drive}$ (t) with:

$$C_{comb-drive}(t) = \hat{C}_{comb-drive}\, sen(\omega_m t) \quad (15)$$

Therefore, this scheme produces an amplitude modulated signal (*AM*), whose amplitude variation is proportional to the capacitance variation of the comb-drive, and therefore proportional to the variation in separation of the actuator's fingers.

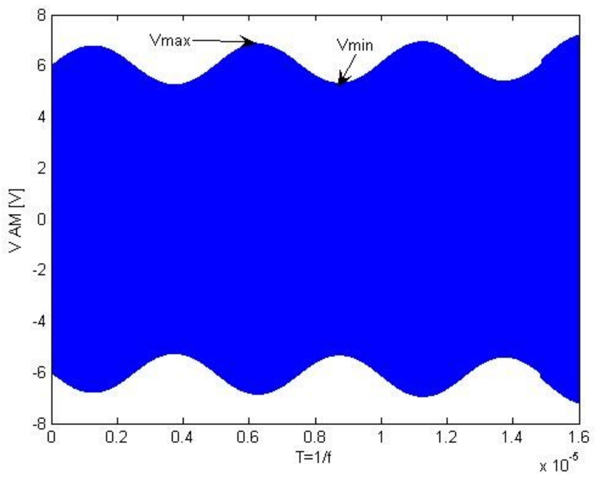

Figure 10: Amplitude modulated signal (V_{AM}) obtained at the output of the measurement circuit for a crack depth of 1.5 microns

Figure 10 shows the output obtained when $V_{comb\text{-}drive}$ is a low frequency signal, where the modulation index *m* (Malvino, 1993) is given by the equation:

$$m = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}} \quad (16)$$

From Equations (14) to (16), it can be shown that the modulation index *m* is proportional to variations of the comb-drive capacity, and therefore to variations in their displacement.

Table 1 shows the increase of the modulation index *m* as the crack depth increases.

m	Crack depth [μm]
0.1105	0.00
0.1173	0.50
0.1240	1.00
0.1315	1.25
0.1428	1.50
0.1639	1.75

Table 1: Crack depth as a function of the modulation index *m*

6 CONCLUSIONS

This work models a MEMS comb-drive with an initial crack by using a Multiphysics Finite Element package. First, the critical crack length is determined, and then a methodology is proposed for monitoring the subsequent propagation of the crack by periodically measuring the modulation index in the circuit under test.

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