**Mechanical Characterization of Electrostatic MEMS Switches**

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### ABSTRACT

This paper presents a methodology developed to characterize the mechanical properties of MEMS switches. Mechanical experiments have been performed to explain the electrostatic behavior of an ohmic electrostatic series switch made by CEA-LETI.

The mechanical properties of switches are characterized by nanoindentation experiments: membrane stiffness, gap heights and contact load. These results have been compared to the results obtained by simple analytical models: the mechanical model shows a good correlation with a membrane stiffness currently around 50-100 N/m, and the electrostatic model gives capacitance values in accordance with measurements.

Based on these results, the electrostatic behavior of switches has been analyzed: the influence of the mechanical properties on the ohmic and capacitive responses is pointed out.

**Keywords:** MEMS, switch, nanoindentation, stiffness, model

### 1 INTRODUCTION

Over the past years, CEA-LETI has been developing electrostatic MEMS switches. This paper is focused on the mechanical study that has been performed in order to explain the electrostatic behavior of an ohmic electrostatic series switch. Experimental and theoretical aspects are compared through two types of switches which are different from geometric and process flow standpoints.

### 2 ANALYTICAL MODEL

#### 2.1 Mechanical model

The switch is modeled as a fixed-fixed beam, with two vertical symmetric loads corresponding to the actuating electrostatic force, and two axial stretching forces corresponding to the effect of the residual stress (see Fig. 1).

![Mechanical model of the switch](image)

- **S**: axial force / **F₁, F₂**: vertical force

The analytical model is derived using the classic formula as described in reference [1]. (1) is the final equation used to calculate the stiffness of the MEMS switch.

\[
k = \frac{F_1 + F_2}{z(d_1) + z(d_2)}
\]

where

\[
z(d_i) = \frac{F_i \sinh p d_i}{S p \sinh p l} \sinh p x + \frac{F d_i}{S l} x + M_{i0} \frac{cosh \left( \frac{l}{2} - x \right)}{cosh \frac{pl}{2}}
\]

and

\[
M_{i0} = F_i \left( \frac{2E u}{l \ tanh} \left( \frac{\sinh p d_i}{S \sinh p l} - \frac{d_i}{S l} \right) \right)
\]

### 2.2 Electrostatic model

The actuator’s equivalent capacitor is modeled by 2 capacitors in parallel. Each capacitor between symmetric electrodes and coplanar wave guide can be considered as a parallel plate capacitor [2].

Based on these hypothesis, the capacitance of the switch is simply expressed by the following formula (4):

\[
C = \frac{2\varepsilon_0 A}{y_e + \frac{l_d}{\varepsilon_r}}
\]

where **C** is the actuator capacitance, **ε₀** is the vacuum permittivity, **εₑ** is the relative dielectric constant, **A** is the electrode surface, **l_d** is the dielectric thickness, **y_e** is the air gap between electrodes.

The capacitances for up-state position and down-state position can be easily calculated from equation (4).
3 SWITCH DESCRIPTION

3.1 Design and process flow

The ohmic electrostatic switch was designed for RF applications and implemented on a coplanar wave guide using full wave analysis [3].

The series switch (see Fig. 2) is made of a silicon nitride fixed-fixed membrane with patterned metallic contacts: 2 symmetrical electrodes located inside the membrane actuate the membrane while a center metallic contact with 2 dimples short-circuits the transmission line.

When a biasing voltage is applied between the electrodes and the coplanar wave guide ground plans, the membrane is pulled down and the transmission line is short-circuited by the metallic contact.

![Figure 2: Top view of a fabricated ohmic electrostatic series switch](image)

The main steps of the switch fabrication process are as follows (see Fig. 3):

- After a thermal oxidation on a silicon wafer, 2 etching steps are required to create a cavity with bumps,
- A gold layer is deposited and patterned to define coplanar wave guide and RF lines,
- A thick photo resist sacrificial layer is deposited by means of spin coating and then patterned,
- A first silicon nitride layer is deposited, followed by a TiN layer for electrodes. This last layer is patterned before being covered with a second silicon nitride layer,
- The switch contact is then realized by a nitride etching and a gold layer deposition. A last silicon nitride layer is deposited,
- The process ends with pads and membrane opening, and with removal of the sacrificial layer in dry oxygen plasma.

![Figure 3: Schematic stack of the ohmic electrostatic series switch](image)

3.2 Type description

Various types of switches have been designed and manufactured. Each one is different from geometric and process flow standpoints.

This paper presents the results achieved for 2 types of switches among these: A-type and B-type. The 2 types of switches come from 2 runs of fabrication with geometrical design and process flow variations. The main differences are listed below:

- A longer beam for B-type switches,
- A lower residual stress in the membrane for B-type switches,
- Different etching depths to get a bigger electrode gap and a smaller contact gap for A-type switches
- 2 different process flows to realize the switch contact, in particular to etch the silicon nitride and the sacrificial layer before the gold layer deposition.

4 EXPERIMENTAL SET-UP FOR MECHANICAL CHARACTERIZATION

The mechanical properties of the switches have been characterized by nanoindentation experiments. The experiments consist in applying a vertical concentrated load to the indenter tip and measuring the force and the displacement. More precisely, the stiffness of the contact between the indenter tip and the beam is continuously measured by superimposing simultaneously an oscillating force, and the test is automatically stopped as soon as the stiffness rises above a limit value in order to keep the switch working.

In practice, nanoindentation experiments have been performed at the membrane center and at the electrode center in order to measure the membrane stiffness and two gap heights: the contact gap between dimples and transmission line, and the electrode gap between the electrodes. The contact load required for getting the ohmic switching have been also extracted from experiments made at the membrane center.
5 RESULTS AND DISCUSSION

5.1 Mechanical behavior

The A-type switch has a usual mechanical behavior as shown in Figure 4 (effective stiffness versus the indent displacement). The membrane center stiffness presents usually a step which corresponds to the membrane free stiffness before the dimples of the metallic contact and the transmission line get into contact. The electrode center stiffness presents 2 steps: one before and another one after contact at the membrane center. The stiffness is respectively around 110 N/m at the membrane center, 130 N/m at the electrode center before the contact at the membrane center and 200 N/m after contact. As wanted, the contact gap height is very small compared to the electrode gap height: 130 nm against 650 nm.

![Figure 4: Nanoindentation measurement A-type switch](image1)

Figure 4: Nanoindentation measurement A-type switch

The B-type switch does not have the same behavior (see Fig. 5). The membrane center stiffness presents an additional step. The first step corresponds to the membrane free stiffness, the additional step could correspond to a 2 phase contact between the dimples of the metallic contact and the transmission line.

![Figure 5: Nanoindentation measurement B-type switch](image2)

Figure 5: Nanoindentation measurement B-type switch

These hypothesis have been confirmed by a failure analysis. Various investigations show that the dimples surface is significantly different between the 2 types of switches. Figures 6 and 7 present SEM observations for the 2 switches. The dimples for the A-type have a rough and quite homogeneous surface. Comparatively, B-type switches are less homogeneous with higher peaks which can explain the stiffness trend: after the first contact of the highest peak of 2 dimples on the transmission line, the membrane could twist to put the second dimple in contact. The process flows used to make the switch contact explain these differences between the dimples of the 2 switches.

![Figure 6: SEM observation of membrane dimple surface _ A-type switch](image3)

![Figure 7: SEM observation of membrane dimple surface _ B-type switch](image4)

Table 1 summarizes the mechanical experimental results obtained on the 2 types of switches where K1 is the free stiffness at the membrane center, K2a is the free stiffness at the membrane center, K2b is the free stiffness at the electrode center.
the electrode center, $K_{2b}$ the stiffness at the electrode center after contact at the membrane center, $G_c$ the contact gap height, $G_e$ the electrode gap height, $F_c$ the necessary load for contact switching.

<table>
<thead>
<tr>
<th></th>
<th>Stiffness (N/m)</th>
<th>Gap Height (nm)</th>
<th>Load (µN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_1$</td>
<td>$K_{2a}$</td>
<td>$K_{2b}$</td>
</tr>
<tr>
<td>A-type</td>
<td>110</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>B-type</td>
<td>50</td>
<td>60</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 1: Mechanical experimental results

The mechanical model detailed in 3.1 has been adapted to fit the nanoindentation experiments (one vertical concentrated load instead of 2). Table 2 presents the experimental and analytical results, and show that the stiffness calculated with the model correlates quite well with the nanoindentation data when the switch behavior is usual.

<table>
<thead>
<tr>
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<th>Experimental stiffness (N/m)</th>
<th>Analytical stiffness (N/m)</th>
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<tbody>
<tr>
<td></td>
<td>$K_1$</td>
<td>$K_{2a}$</td>
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<tr>
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<tr>
<td>B-type</td>
<td>50</td>
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Table 2: Experimental and analytical results for the membrane stiffness

5.2 Electric behavior

The behavior of the 2 switches (see Fig. 8 and 9) have been identified using a classic single sweeping test and illustrates how the 2 gap heights and the contact load manage the electrostatic behavior.

Table 3: Experimental electrostatic results

Table 4: Analytical electrostatic results

6 CONCLUSION

The paper presents nanoindentation experiments in order to characterize the mechanical properties of MEMS switches: membrane stiffness, gap heights and contact load. These results have been compared to the results given by simple analytical models: mechanical and electrostatic models show a good correlation with experimental data. Finally, the electrostatic behavior of switches are well-understood thanks to these mechanical characterizations.

REFERENCES