Piezoelectric versus electrostatic actuation for a capacitive RF-MEMS switch

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***Abstract* --- In this paper, piezoelectric actuation is compared with electrostatic actuation for application in RF-MEMS switches with respect to actuation voltage and technological implementation. The expression for the actuation voltages of electrostatic and piezoelectric actuation are discussed and compared with respect to scaling. Calculation examples show actuation voltages for a cantilever beam of 1µm thick and 100µm long of 25.0V for electrostatic actuation and 18.9V and 2.39V for piezoelectric actuation with AlN and PZT as the piezoelectric layers respectively. From a technological point of view, the electrostatic switch is the easiest to implement, compared to piezoelectric actuation.**

***Keywords* --- piezoelectric actuation, RF-MEMS, switch**

I. INTRODUCTION

RF-MEMS (Radio Frequency MicroElectroMechanical Systems) switches offer great potential benefits over GaAs MMICs and PIN diode switches for application in wireless communication systems. However, an important drawback of the current electrostatically actuated RF-MEMS switches is their high actuation voltage, typically 30V or higher [1]. This is undesired considering their application in handheld wireless communication systems like mobile phones, in which available DC supply voltages are limited to 3-5V.

In this paper, piezoelectric actuation will be investigated as an alternative for electrostatic actuation for achieving lower actuation voltages. The expressions for the actuation voltage of a cantilever beam for both types of actuation will be compared. The cantilever beam is taken for simplicity, although a clamped-clamped beam is commonly used for RF-MEMS switches. The difference in scaling between the two types of switches will be discussed. Calculation examples for both types of switches will be given for typical designs for slender beams and open gap spacings of 3µm. Technical implementation issues will also be discussed.

II. BASIC SWITCH DESIGN

A basic sketch of an electrostatically actuated switch is shown in Figure 1 [1-3]. The voltage between the metal bridge and the CPW (CoPlanar Waveguide) signal line causes an attractive force, which pulls the bridge down and thus changes the capacitance.

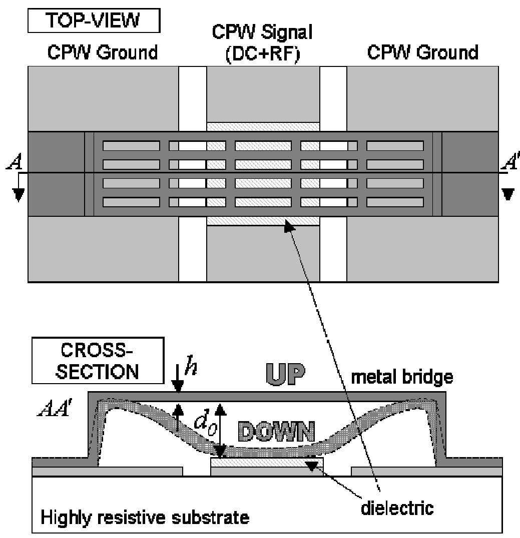

***Figure 1**: Top-view and cross-section of a capacitative RF-MEMS switch*

The design for the piezoelectric switch is based upon the design for the electrostatic switch. On top of the metal bridge, a thin piezoelectric layer and a thin metal top electrode film are deposited respectively (see Figure 2). Applying a voltage between the two metal layers induces a stress in the piezoelectric layer and thus a bending moment in the bridge, causing the beam to deflect [4].

III. CALCULATIONS

The mechanical part of the RF-switch is modelled by a cantilever beam, as shown in Figure 2.

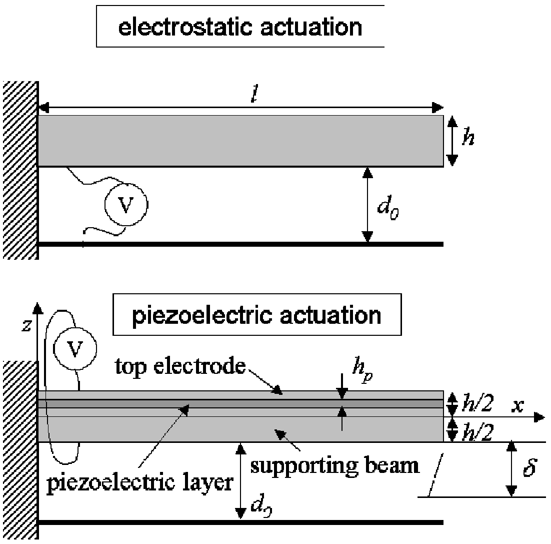

***Figure 2**: Cantilever models for electrostatic and piezoelectric actuation*

The expression for the actuation voltage (pull-in voltage) of a cantilever beam with parameters as shown in Figure 2 and assuming that the bottom electrode has a maximum overlap with the cantilever beam and $b>>d_0$, is given by [5]:

$$V_{PI} \approx \frac{0.54}{l^2}\sqrt{\frac{Eh^3 d_0{}^3}{\varepsilon_0}} \qquad (1)$$

where E is the Young's modulus.

Deflections of piezoelectric cantilevers have been studied by several people, e.g. [3,4,6,7], all of them making assumptions to make the expressions easier. In this paper, the calculations are based on the model of piezoelectric actuation as described in reference [8], where it will be indicated which assumptions have been made for the final calculations. From standard mechanics it follows that the deflection δ at the tip of the cantilever is:

$$\delta = \frac{M_p}{\overline{EI}}\frac{l^2}{2} \qquad (2)$$

where $\overline{EI}$ is the equivalent bending stiffness of the laminated beam, given by:

$$\overline{EI} = \frac{A_x D_x - B_x{}^2}{A_x} \qquad (3)$$

where A_x, B_x and D_x are given by:

$$A_x = \iint_A E(z)dA \qquad (4a)$$

$$B_x = \iint_A E(z)zdA \qquad (4b)$$

$$D_x = \iint_A E(z)z^2 dA \qquad (4c)$$

where A is the cross section of the beam ($dA = dydz$) and $E(z)$ the Youngs modulus. The piezoelectric bending moment M_p is given by:

$$M_p(x) = \iint_A E(z)(z - z_0)\varepsilon_p(x,y,z)dydz \qquad (5)$$

where $z_0 = B_x / A_x$ denotes the distance of the neutral axis to the center line and $\varepsilon_p(x,y,z)$ is the externally applied piezoelectric strain, given by:

$$\varepsilon_p(x,y,z) = \frac{d_{31}D_3(x)}{\varepsilon_{33}} \qquad (6)$$

where d_{31} is the piezoelectric coeffiecient, $D_3(x)$ the dielectric displacement in the piezoelectric layer and ε_{33} the permittivity. The dielectric displacement $D_3(x)$ is given by:

$$D_3(x) = \varepsilon_{33}(1 - k_{31}{}^2)\frac{V}{h_p} + \frac{\varepsilon_{33}k_{31}{}^2}{d_{31}h_p}\int_p S_1(x,z)dz \qquad (7)$$

where V is the applied voltage, h_p is the thickness of the piezolayer, k_{31} the piezoelectric coupling factor and $S_1(x,z)$ the strain in the x-direction. The symbol p, denoting the integration boundaries, indicates evaluation of the integral over the thickness of the piezoelectric layer.

Plane stress conditions are taken for simplicity, but this has a negligible effect on the final calculation results. The second term of equation (7), which originates from the electromechanical coupling in the piezoelectric layer, will be neglected, which is allowed for typical piezoelectric materials [8]. These approximations lead to a simplified expression for the piezoelectric bending moment:

$$M_p(x) = bd_{31}\frac{v}{h_p}\int_p E_p(z - z_0)dz \qquad (8)$$

This equation is equivalent to the equation given by [jan smits].

In order to have a deflection $\delta = d_0$, a voltage $V = V_p$ has to by applied, where V_p follows from equations (2) and (8):

$$V_p = \frac{2d_0\overline{EI}h_p}{l^2 bd_{31}\int_p E_p(z - z_0)dz} \qquad (9)$$

If the thicknesses of all the layers scale by a factor α, the actuation voltage V_p scales by α^2.

If equation (1) is compared to equation (9), one can see the difference in scaling between piezoelectric and electrostatic actuation. The actuation voltage scales proportional to d_0 for piezoelectric actuation, whereas for electrostatic actuation it scales proportional to $d_0^{3/2}$. Another difference is the dependence upon thickness of the beam. For piezoelectric actuation, the actuation voltage scales proportional to h^2, whereas for electrostatic actuation it scales proportional to $h^{3/2}$. The length of the beam appears for both types of actuation in the same form.

IV. Comparison of actuation mechanisms

A calculation example for the actuation voltage of an Al cantilever beam (E = 70 Gpa) will be given below and compared with the actuation voltage of comparable piezoelectrically actuated beams: one with AlN and one with PZT as the piezoelectric layer. These switches will be refered to as the 'AlN switch' and the 'PZT switch'. For the thickness h of the beam, a commonly used value of 1μm will be taken. Since the length l of the beam appears in the same form for both types of actuation, the absolute value is not important for the comparison, so a value of 100μm will be taken.

If for the deflection d_0 a value of 3μm is taken, which is a reasonable value for getting a good UP/DOWN capacitance ratio for the RF-switch, the actuation voltage for electrostatic actuation is 25.0V. A comparable piezoelectric switch with an Al beam (800nm thick), AlN piezoelectric layer (100nm thick, E = 320Gpa, d_{31} = 3.125pC/N), Al topelectrode (100nm thick) and identical parameters for the rest, needs 18.9V for actuation. This is 25% lower than the value for electrostatic pull-in actuation.

In order to obtain a further decrease of the actuation voltage, another piezoelectric material has to be used with a higher piezoelectric coefficient, for example PZT (E = 70Gpa, d_{31} = 90pC/N). The Al has to be replaced by another metal with a higher meltingpoint, since PZT is processed above the melting temperature of Al. If the Al for the supporting beam is for example replaced by 800nm Cu (E = 124Gpa) + 50nm Pt (E = 165Gpa) and the topelectrode by 50nm Pt, the actuation voltage is only 2.39V.

The drawback of the piezoelectric switch is the higher technological complexity [9], in particular the PZT switch processing is difficult as diffusion barriers are needed in order to prevent interdiffusion of Pb with the other materials during the high temperature curing.

V. Conclusions

The analytical expressions for electrostatically and piezoelectrically actuated cantilever beams have been compared, assuming plane stress conditions and a uniform electric field in the piezoelectric layer. The calculation example shows an actuation voltage of 25.0V for the electrostatically actuated cantilever, 18.9V for the piezoelectrically actuated cantilever with AlN as the piezoelectric material and 2.39V for the piezoelectrically actuated cantilever with PZT as the piezoelectric material. Since the processing of the AlN switch is more complex and the actuation voltage is not significantly lower, the electrostatic switch is prefered. If PZT is used as the piezoelectric material, the actuation voltage is about one order of magnitude lower. However, the realisation of a PZT switch is even more complex than for the AlN switch. From a processing point of view the electrostatic switch is the most attractive, whereas from a performance point of view the PZT switch is prefered.

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