DESIGN AND SIMULATION OF ZIPPING VARIABLE CAPACITORS*

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Abstract — *Variable capacitors are essential for building tunable RF systems. We present here the design and simulation of novel zipping variable capacitors with a high permittivity dielectric layer. Two modelling techniques are presented: finite element simulation and variational analysis. A capacitance ratio greater than 40 can be obtained for a $100\mu m \times 25\mu m$ device which has a high permittivity dielectric layer ($\varepsilon_r = 200$). By shaping either the top electrode beam or the bottom electrode, continuously variable capacitance is achieved at low bias voltages.*

Key Words: zipper tunable capacitor, stable zipping, RF MEMS, high-k dielectric

I   INTRODUCTION

Variable capacitors are key components in the implementation of tunable filters, phase shifters and voltage-controlled oscillators (VCO). In the last ten years, MEMS variable capacitors have emerged as viable alternatives to semiconductor varactor diodes mainly due to the higher quality (Q) factors and extended tuning ranges that can be achieved [1]. Despite the lower tuning speeds of MEMS variable capacitors relative to varactors, typical operation speeds (on the order of microseconds) are sufficient for many RF applications [2].

MEMS variable capacitor designs can be broadly categorised into gap-tuning devices, where the gap between the capacitor electrodes is changed to achieve tuning, and area-tuning devices, where the electrode overlap area is adjusted [1]. The majority of these designs are electrostatically actuated due to the low power consumption and ease of implementation.

Electrostatic zipping structures have been employed in MEMS actuators [3,4] but have remained relatively unexplored for variable capacitor applications. Hung et al have previously fabricated zipping variable capacitors with a straight cantilever design [5]. In addition, Lincoln Lab has also produced a zipping capacitive switch [6]. This paper presents the design and modelling of a new type of zipping variable capacitor with a high permittivity dielectric layer.

II   CAPACITOR DESIGN

II.1 ZIPPING VARIABLE CAPACITOR

Figure 1 below shows a schematic cross-section of a zipping variable capacitor. By applying a control voltage V_b, a curved top electrode is pulled down onto a dielectric layer, hence increasing capacitance. In the absence of a DC bias voltage, the capacitance (C_0) of the device is dominated by the air gap underneath the top electrode, resulting in low capacitance. Once the top electrode is pulled down, the presence of the high permittivity dielectric allows a large capacitance ratio (C_{max}/C_0) to be obtained for a given device size.
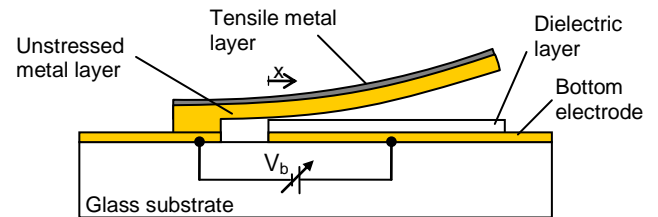

Figure 1. Schematic of a zipping capacitor.

The curved top electrode can be fabricated using a bi-layered structure with a thin top layer which is in biaxial tension prior to release, and a relatively stress-free bottom layer. This creates a bending moment when the structure is released, and thus an upward curvature. Figure 2 shows the cross-section of the bi-layered top electrode where the subscripts 1 and 2 refer to the bottom and top layers respectively; h is the thickness, b is the width and d denotes the distance from the surface to the neutral plane.
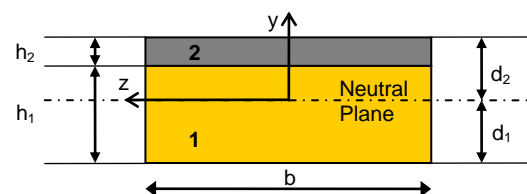

Figure 2. Cross-section of bi-layered top electrode.

Using plate theory, the released shape of the top electrode may be determined by

$$s_r(x) = \frac{\sigma_2}{2(\bar{E}_1 I_1' + \bar{E}_2 I_2')}\left(h_2 d_2 - \frac{h_2^2}{2}\right)x^2 \qquad (1)$$

where σ_2 is the is the biaxial (in x and z directions) tension in the top layer, $\bar{E}$ is the biaxial modulus defined as $\bar{E} = E/(1-v)$, E is the Young's modulus, v is Poisson's ratio and I' is the moment of inertia per unit width about the neutral axis. This expression is valid for small deflections where the radius of curvature is much greater than the electrode thickness.

II.2 PULL-IN INSTABILITY

The curved top electrode is susceptible to the well-known electrostatic pull-in instability that affects gap-tuning parallel plate capacitors. As the control voltage is increased from 0, the capacitance increases from C_0 until the critical pull-in voltage is reached when the entire curved beam is straightened out onto the dielectric. This results in a large sudden increase in capacitance and essentially the device functions as a capacitive switch, alternating between a low nominal value and a high switched value. Figure 3 shows an example of the simulated C-V characteristic of one such device with a dielectric relative permittivity of 4 (SiO_2). The closure of the air gap at pull-in results in a highly non-linear capacitance variation and this effect will be magnified when a high permittivity dielectric is used.
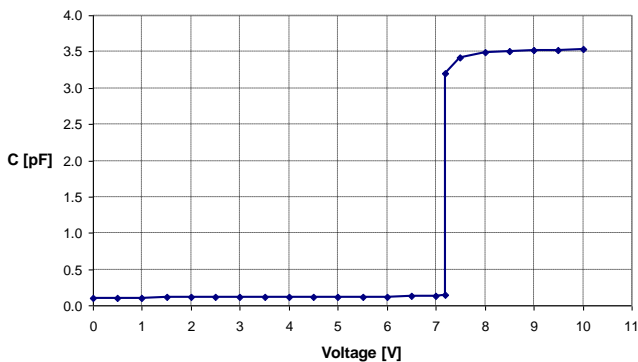
Figure 3. C-V characteristic of zipping capacitor with constant electrode widths.

In order to achieve continuously variable capacitance, we propose two different strategies for allowing stable zipping of the top electrode as the bias voltage is increased. The first method is to vary the stiffness of the beam, increasing its width from the fixed end to the free end. Hence, as the top electrode is pulled onto the dielectric increasingly larger voltages are required to zip the electrode further. The second method for achieving controlled zipping is by varying the width of the bottom electrode [5] and hence controlling the electrostatic force per unit length along the device. The width is made largest at the end nearer to the fixed anchor and smallest at the free end. Figure 4(a) shows a zipping variable capacitor with a shaped top electrode and figure 4(b) shows one with a shaped bottom electrode.
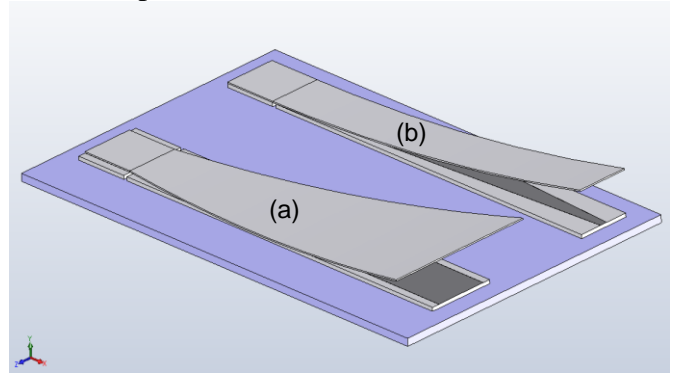
Figure 4. Achieving controlled zipping with (a) shaped top electrode (b) shaped bottom electrode.

III MODELLING AND RESULTS

Two different modelling techniques were applied in the design of the zipping variable capacitors. An electromechanical finite element model was used to evaluate designs with variable top electrode width. In addition, a semi-analytical variational approach [7] was used to evaluate both types of designs.

III.1 ANSYS FINITE ELEMENT MODEL

Due to the geometry of the device, 3D modelling is required. However, the computation times are extremely long and hence a simplified 2D model was created which approximates the beam width function using an equivalent elastic modulus function. Treating the bi-layered top electrode as a beam when loaded electrostatically, the moment-curvature relationship is given by

$$\frac{1}{R_x(x)} = \frac{M(x)}{b(x)(E_1 I_1' + E_2 I_2')} \qquad (2)$$

where $b(x)$ is the width function, M is the bending moment and R_x is the radius of curvature. Next, we

consider a simplified 2D (unit beam width) model consisting of a single layered beam in which the actual beam width function $b(x)$ is modelled using an equivalent Young's modulus function $E_m(x)$. The moment-curvature relationship of this 2D model is then

$$\frac{1}{R_x(x)} = \frac{12M(x)}{E_m(x)h_m^{\,3}b_e} \qquad (3)$$

where the subscript m denotes the parameters of the model and b_e is the actual width of the bottom electrode. By equating (2) and (3) and imposing M and R_x to be equal we can obtain an expression for E_m

$$E_m(x) = \frac{12b(x)(E_1 I_1' + E_2 I_2')}{h_m^{\,3}b_e} \qquad (4)$$

The Young's modulus of each element along the 2D beam is then specified using equation (4).

III.2   VARIATIONAL ANALYSIS

A second, semi-analytical method was used to solve for the C-V characteristic of the zipping capacitors. The released curvature of the top electrode may be expressed as

$$s_r(x) = \alpha x^2 \qquad (5)$$

where α is a function of the stress in the tensile layer, the thickness of the two layers and their elastic properties. When the top electrode is deflected and zipping, its shape is approximated by

$$\begin{aligned} s_d(x) &= 0 & 0 \le x \le a \\ s_d(x) &= c(x-a)^2 & a \le x \le L \end{aligned} \qquad (6)$$

where a and c are variational shape parameters. Figure 5 shows the released and deflected shapes of a zipping capacitor.
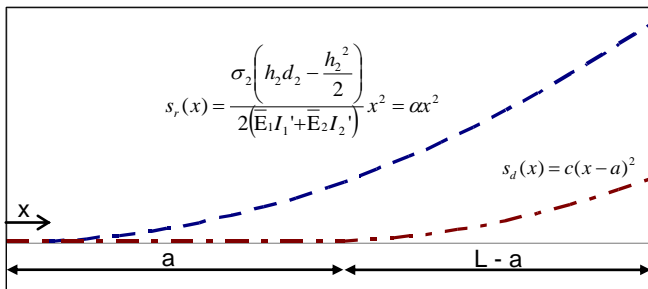

Figure 5. Released and deflected top electrode shapes.

The top electrode is modelled as a single layered beam and its mechanical strain energy can be expressed as

$$U_m = \int_0^a \frac{EI}{2}\left[\frac{d^2 s_r}{dx^2}\right]^2 dx + \int_a^L \frac{EI}{2}\left[\frac{d^2(s_r - s_d)}{dx^2}\right]^2 dx \qquad (7)$$

where I is a function of x for the case where the top electrode width b is a function of x. The electrostatic energy can be expressed as

$$U_e = \int_0^a \frac{1}{2}\left(\frac{b_e \varepsilon_d V^2}{t_d}\right) dx + \int_a^L \frac{1}{2}\left(\frac{b_e \varepsilon_0 V^2}{t_d/\varepsilon_r + s_d}\right) dx \qquad (8)$$

where t_d is the dielectric thickness, ε_0 is the permittivity of free space and the dielectric permittivity $\varepsilon_d = \varepsilon_r \varepsilon_0$ (b_e is a function of x for the case where the bottom electrode is shaped). According to the principle of virtual work, the equilibrium shape of the top electrode can be determined by minimising an appropriate energy function. Assuming the capacitor is actuated by a variable voltage source, the required function is

$$\Pi(a,c) = U_m - U_e \qquad (9)$$

Differentiating (9) with respect to a and c, and setting the derivatives to zero yields two equations in a and c. Since no closed-form solution has been found, the equations are solved numerically giving the deformed shape, s_d. The capacitance can then be calculated from the shape.

III.3   RESULTS FOR TOP ELECTRODE SHAPING

Figure 6 shows the simulated C-V characteristic of a zipping capacitor with a linear beam width function, $b(x)=0.18x+20$ (µm) for $0 \le x \le 400$. The bottom electrode width is 20µm and the dielectric has a thickness of 0.1µm and a relative permittivity of 4.
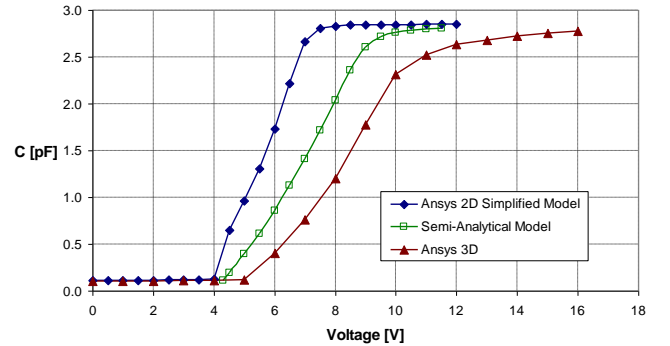

Figure 6. C-V characteristic of a zipping capacitor with linear beam shape.

The results from the different simulation methods show similar characteristics qualitatively but differ

in actual values of zipping voltages. Nevertheless, the results all indicate that controlled zipping can be achieved by shaping the top electrode and the increase in capacitance with voltage is now much more gradual relative to that in figure 3. For this design, the achieved capacitance ratio exceeds 20.

Figure 7 shows the C-V characteristic of a zipping capacitor with a high permittivity dielectric ($\varepsilon_r = 200$). The dielectric thickness is 0.1μm and the bottom electrode width is 5μm. The width function is $b(x)=0.18x+5$ (μm) for $0 \leq x \leq 100$. The high permittivity of the dielectric allows a much larger capacitance ratio (>40) to be obtained for a smaller device size.
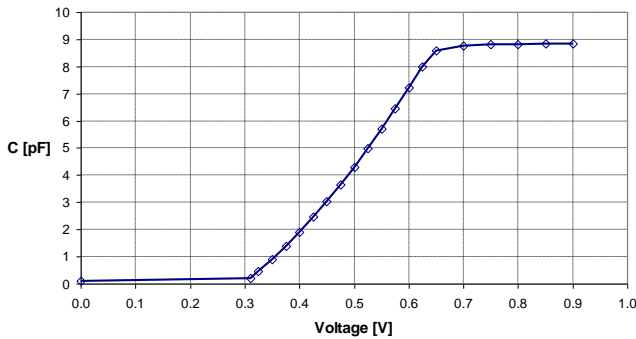

Figure 7. C-V characteristic of a zipping capacitor with a linear beam shape and a high permittivity dielectric.

III.4 RESULTS FOR BOTTOM ELECTRODE SHAPING

Results from the semi-analytical model for capacitors with shaped bottom electrodes are shown in figure 8. Three different bottom electrode shapes have been modelled for a capacitor of length $L = 480$μm. The top electrode width is 70μm and the dielectric is 0.3μm thick with a relative permittivity of 4. As expected, the results indicate that controlled zipping with gradual increase in capacitance is possible. Capacitance ratios larger than 9 were obtained based on these designs.

IV CONCLUSIONS

Zipping MEMS variable capacitors with large tuning ranges have been presented. The use of a high permittivity dielectric layer gives a large capacitance ratio for a compact device size. Stable

zipping, and hence gradual increase in capacitance is achieved by shaping either the top electrode beam or the bottom electrode. Two different modelling methods have been discussed which allow the C-V characteristics of various design options to be simulated quickly.
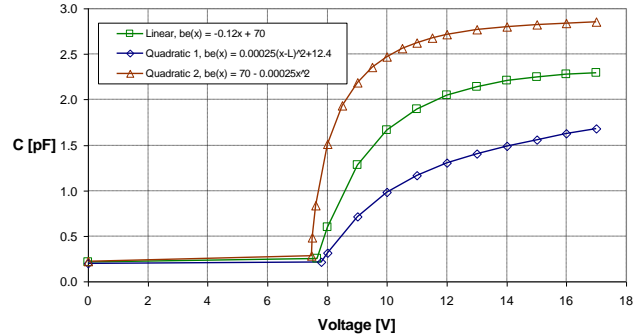

Figure 8. C-V characteristics of capacitors with shaped bottom electrodes.

Further work is needed to develop fabrication processes for making the zipping capacitors. As a first step, devices with a SiO$_2$ dielectric layer will be fabricated. Subsequently, high permittivity dielectric materials such as lead zirconate titanate or barium strontium titanate will be integrated into high tuning range devices.

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