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Investigation and Comparison of Two Movable Plates Electrostatic MEMS Tunable Capacitors

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***Abstract* – Two movable plates MEMS tunable capacitors are investigated and compared in this paper. Moveability of two plates enforce the tunable capacitor to have some interest advantages such as high tuning range, high quality factor, low actuation voltage and a simple tuning mechanism. However, the pull-in effect of the electrostatic actuation is caused a nonlinear behavior which is a major challenge and nonlinear capacitance change is its effect. Employing only one-third displacement of movable plates can solve this challenge. The design approaches and fabrication techniques of these type capacitors and their electrical and mechanical characteristics are finally investigated.**

***Keywords* – MEMS, Tunable Capacitor, Two Movable Plates, Pull-In, Quality Factor, Tuning Range.**

I. Introduction

Dramatically developments of micro-electro-mechanical systems (MEMS) technology has been affected the sensor, actuators and integrated circuit worlds. Batch fabrication process, low production cost, IC fabrication compatible, possibility of 3-D movable structures construction in micron and submicron sizes and so on, has been entered the MEMS technology into the telecommunication systems and devices [1]. Today, the demand for the high linearity, low actuation voltage (and hence low power consumption), high quality factor and high frequency tuning range telecommunication systems such as voltage controlled oscillators (VCOs) and tunable filters has been increased. Passive circuit elements such as capacitor and inductor as the essential elements of the radio frequency integrated circuits (RFICs) systems have main duty in these systems. MEMS Tunable capacitors are the key elements in phase shifters [2], VCOs [3], tunable filters [4] and wireless communication systems [5], which have the potential to replace the conventional IC technology variable capacitor known by varicap (a reverse-biased semiconductor diode).

There are several methods to achieve the capacitance tuning which is reported in the literature. Gap tuning [6], area tuning [7] and dielectric displacement [8] are the main methods of the parallel plate tunable capacitors. Also a number of actuations such as electrostatic [9], piezoelectric [10] and thermal actuators [11] are used in the parallel plate tunable capacitors. Because of the tuning simplicity, high tuning ratio, standard fabrication process availability, high quality factor and low actuation voltage, the gap tuning method is enormously employed. However, the nonlinearity of the capacitance change in the electrostatic actuation is one challenge.

This paper includes the design and analysis parameters about two parallel movable plate tunable capacitors in section 2 and a full comparison of the designed and implemented structures in section3.

II. Gap Tuning Capacitor

For the parallel plate capacitors, it is well known that the capacitance (C) is calculated as:

$$C = \varepsilon \frac{A}{d} \tag{1}$$

Where, ε, *A* and *d* are the dielectric permittivity, the overlap area and the gap between two plates, respectively. Figure 1 shows the schematic of the parallel plate capacitor.

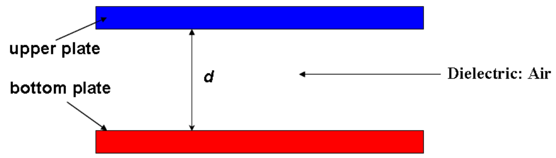
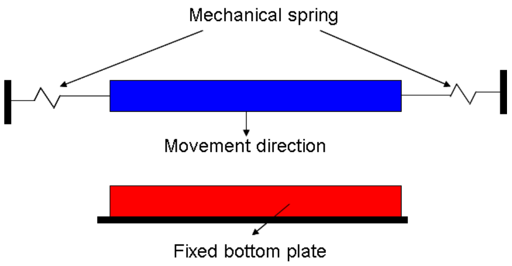


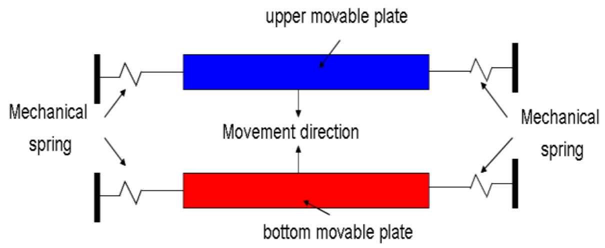
Fig.1. The schematic of the parallel plate capacitor

As mentioned, for the capacitance change, the gap (*d*), overlap area (*A*) and dielectric permittivity (ε) can be changed individually or altogether. The gap tuning method has been used almost in the high performance tunable capacitors. MEMS technology has been realized techniques to achieve the simple and high reliable gap tunable capacitors. Because of the fabrication simplicity and low power consumption, the electrostatic actuation is usually employed for the upper and (or) bottom plates. Figure 2 depicts the one-plate and two-plate displacement tunable capacitor schematically.

When the voltage is applied across the bottom and upper electrodes, electrostatic force move the upper plates (figure 2a) toward the fixed bottom plate and the two movlable upper and bottom plates (figure 2b) toward together, hence the gap between two plates is decreased and based on the Eq.1 the capacitance is increased and the tuning is achieved.



(a)



(b)

Fig.2. Tunable capacitor using gap tuning method a) one movable and b) two movable plates

A. Two movable plates versus one movable plate varactors

The first parallel plate MEMS tunable capacitor is introduced by Young and Bose in 1996 [12] which consists of two plate with dimensions of the 200 × 200 µm^2, a height of 1.5µm and a top plate thickness of 1µm. Their structure is one plate movable varactor. After this, a number of the one plate movable and two movable plate tunable capacitors are designed, simulated, analyzed and fabricated. In both of these varactors, the tuning range of the electrostatic capacitor is limited due to the nonlinear nature of electrostatic force and pull-in phenomenon. Based on the pull-in effect, as the applied voltage is increased or the initial gap between two plates is decreased, the electrostatic force is increased much faster than the linear spring force, hence the equilibrium is broken, the movable plate is moved toward the fixed plate in nonlinear mechanism and the pull-in effect is occurred. Because of the pull-in effect, the theoretical maximum tuning range of the parallel plate capacitors is limited to 50%. This effect in two parallel plates, because of the movability of two plates, is twice. However, the voltage required for a desired tuning range in the two movable plate tunable capacitors is less the one plate counterpart.

Figures 3, 4 and 5 shows the electrostatic simulation of a 200 × 200 µm^2 plate and a thickness of 2 µm, which has four supports with dimension of 15 × 100 µm^2. The gap between two plates is 2µm. To accurate comparison, assume that we have only one-third displacement to prevent the nonlinear pull-in phenomenon. The voltage required for 0.75 µm displacement of the one movable plate is about 10.3V, while the two movable plates require only 6.8V to have the same displacement (0.7µm). In this case, each movable plate is moved only 0.35µm.

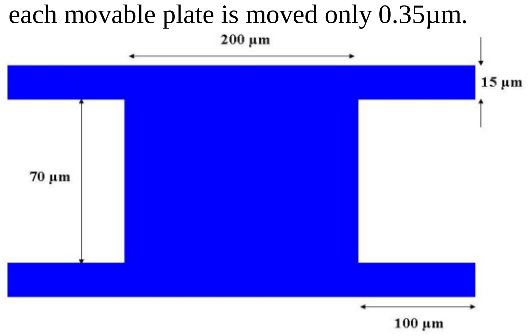


Fig.3. The schematic of a 4-support plate designed for a tunable capacitor

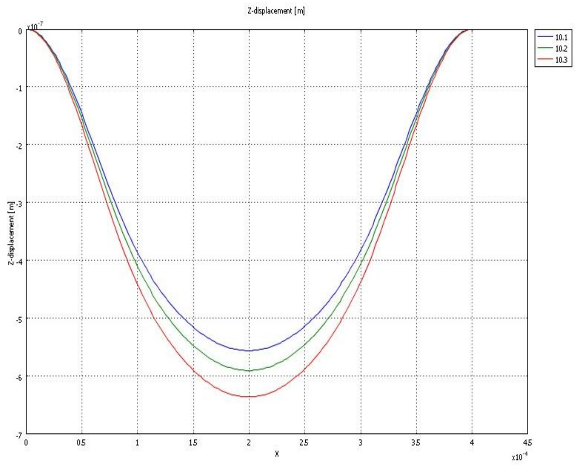


Fig.4. The electrostatic simulation of a 4-support plate designed for a tunable capacitor (voltage required for 0.7µm displacement of the one movable plate)

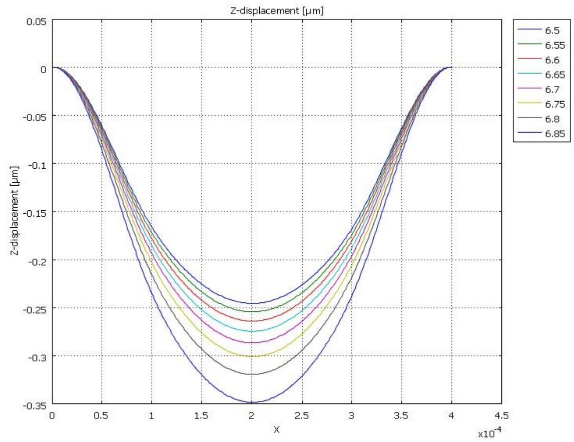


Fig.5. The electrostatic simulation of a 4-support plate designed for a tunable capacitor (voltage required for 0.35µm displacement of the two movable plates)

B. Gap tuning capacitors parameters

The tunable capacitors are investigated based on the some important parameters and a number of researchers have been found special designs to reach the ideal tunable capacitor.

1) *Tuning Range:* Large-value tuning range of the tunable capacitors is required in a variety of applications such as frequency tunable filters, electrostatic energy harvesting devices and so on. Several designs for the high tuning range MEMS varactors are reported in literature. Yongduk Kim [13] introduced a two plate tunable structure with 8 beam and 4 anchors in 2002. The Capacitance of the designed tunable capacitor is changed from 1.0pF to 1.48pF when the applied voltage is varied from 0.5V to 2.52V. This means that a tuning range of approximately 50% is achievable.

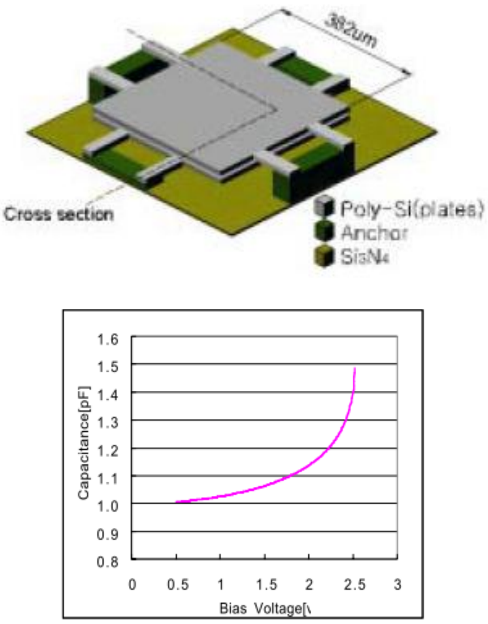


Fig.6. Schematic of two port tunable capacitor (up) and the capacitance tuning (down) [13]

In the other design, Xiuhan [14] proposed a two movable plate structure which has 4 T-shaped beams to suspend the top plate. The bottom plate is also movable (Figure 7). His designed capacitor has the tuning range of 320% with actuation voltage of 13V.

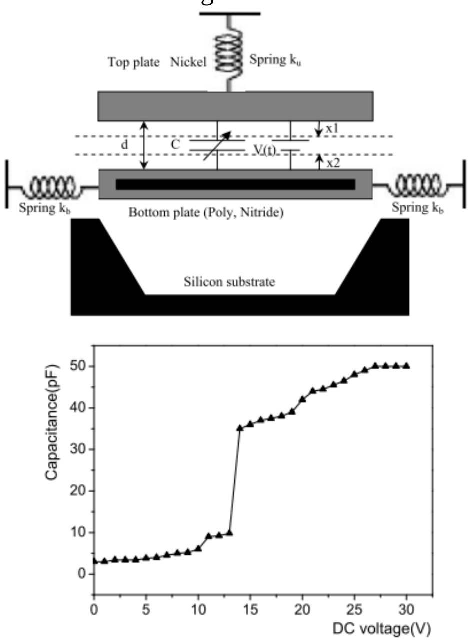


Fig.7. The schematic of the two-movable pate with 4 T-shaped beam tunable capacitor (up) and its capacitance tuning result (down) [14]

In 2004, Maher Bakri-Kaseem [15] designed a tunable capacitor which consists of two movable plates loaded with a nitride layer (Figure 8). The use of the dielectric layer on the bottom plate increases the total capacitance tuning and decreased the two plate sticktion. Tuning range of the 250% with applied voltage of 21V is reported in the [15].

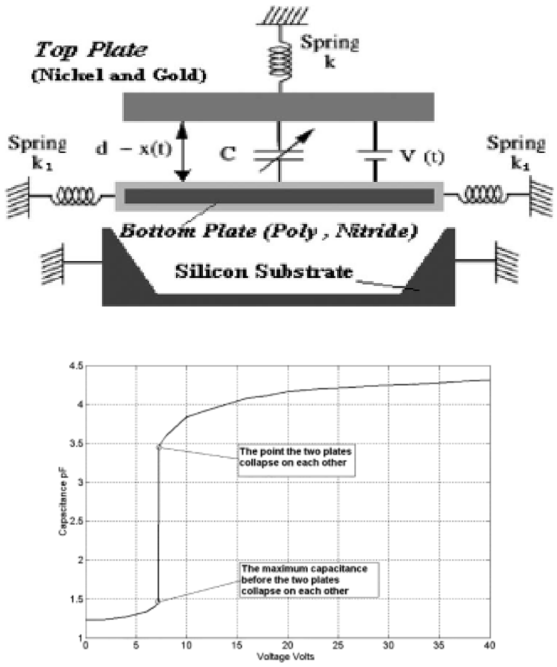


Fig.8. Schematic of the two movable capacitor (up) and the capacitance tuning (down) [15]

Ashoori [16] is reported a new three plate tunable capacitor with two movable plates in 2014 (Figure 9). Her designed capacitor has a wide tuning range about 300% which is 6 times greater than the conventional two movable plates.

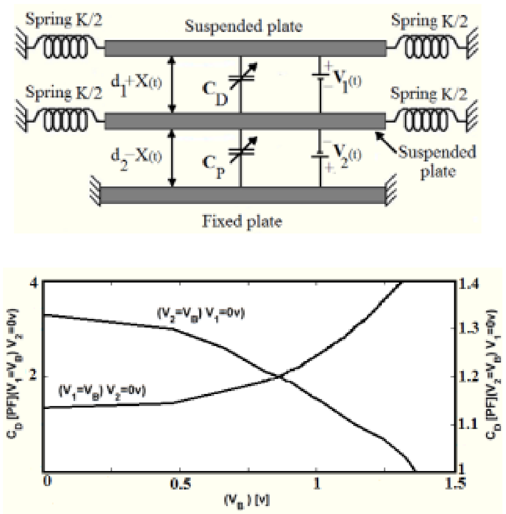


Fig.9. A three plate tunable capacitor with two movable plates (up) and the capacitance tuning (down) [16]

Some other researchers are reported the two movable plates tunable capacitors [17]. The other types of the high tuning range tunable capacitors has been also reported which are based on the one plate movable plates [18-20].

2) *Quality factor*: Each RF communication system provides multiple services such as multi-band RF front-end for the future wireless cellular phones. Tunability of the antennas, filters and amplifiers in these systems is one of the important challenges. Because these elements and devices need to deal with in each RF band, an impedance

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device with high quality factor is necessary. Tunable MEMS capacitors introduce the best quality factor for this purpose. These requirements enforce the researchers to realize the high quality factor tunable capacitors. Employing the dielectric layer between two movable plates [15] and reducing the series-resistance by the elimination of the spring constant of the movable plate in the RF signal pathway [7] are the conventional ways to increase the quality factor.

3) *Actuation voltage*: The need for low power wireless communication devices and systems is satisfied with their low actuation voltage. The pull-in voltage which is expressed as:

$$V_{pull-in} = \sqrt{\frac{8Kg^3}{27\varepsilon_0 A}} \quad (2)$$

Where, ε, A, K *and* g are the air permittivity, overlap area, mechanical spring constant, and electrode gap, respectively. Based on the Eq.2, an approach to reduce the pull-in voltage is the mechanical spring constant elimination. There are several ways for this purpose. Reducing the Young's modulus of the structure and employing free end structures, are some ways to reduce the spring constant. Several structures are proposed in the literature which is shown in Figure 10.

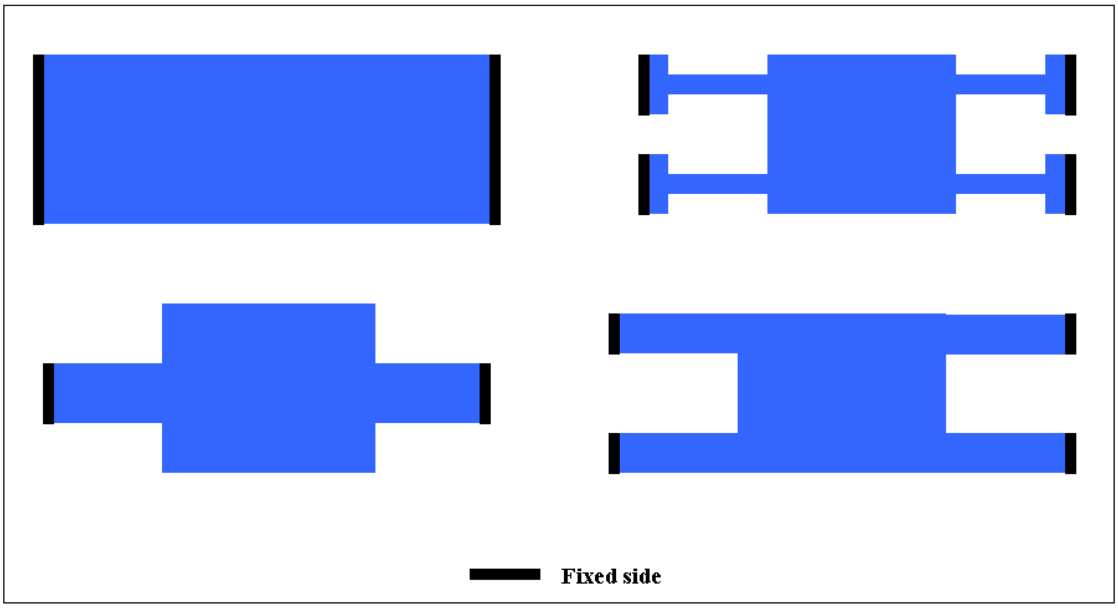

Fig.10. Proposed structures for spring constant reduction

4) *Frequency*: RF communication applications of MEMS devices are extremely growing. This characteristic enforces the MEMS device designer to realize high frequency passive and active elements. The high frequency characteristics of the MEMS tunable capacitors can be obtained through the substrate etching technique. The majority of two movable plate capacitors are fabricated using surface micromachining technology, however the substrate etching is a bulk micromachined process, hence a trade off between them should be accomplished. Employing the insulation substrate such as glass or SOI (silicon on insulator) wafers can be another approach.

III. Comparison

Table I summarizes the comparison between the electrostatic two movable plate tunable capacitors and the one plate moveable counterpart. This comparison is based on some important specifications such as tuning range, quality factor, initial capacitance, work frequency, actuation voltage and the effective capacitor size. It mention that the initial capacitance is the capacitance when no actuation voltage is applied and the work frequency is the frequency of the high amount of the capacitor quality factor.

IV. Conclusion

Two movable plates tunable capacitors are investigated and compare in this paper. Base on this comparison, two movable plates tunable capacitor introduce some advantages such as low actuation voltage due to movability of two plates and high tuning range with respect to the one movable plate counterpart. Due to rapid growing of RF communication wireless devices, the need to high tuning range and high quality factor tunable devices is inevitable.

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Table I: Comparison of the two movable plates and one movable plate tunable capacitors (TMP: Two Movable Plates (OMP: One Movable Plate NR: Not Reported)

Reference No.	Type of capacitor	Tuning range	Work frequency	Quality factor	Initial capacitance	Actuation voltage	Effective capacitance size (μm^2)
[13]	TMP	48 %	1-7 GHz	NR	1 pF	2.52 V	335 × 335
[14]	TMP	320 %	2-10 GHz	NR	3 pF	13 V	700 × 700
[15]	TMP	280 %	1 GHz	8.78	4.6 pF	39 V	500 × 520
[16]	TMP	300 %	1 GHz	300	1.33 pF	1.36 V	400 × 400
[17]	TMP	42 %	1 GHz	40	1 pF	3.6 V	340 × 200
[5]	OMP	69.8 %	NR	NR	NR	20 V	500 × 500
[6]	OMP	41 %	5 GHz	34.9	0.3 pF	5.5 V	400 × 400
[18]	OMP	30 %	NR	NR	1.18 pF	6 V	150 × 50
[19]	OMP	410 %	1 GHz	NR	10 pF	9.2 V	NR
[20]	OMP	240 %	NR	17	15 pF	3.5 V	NR

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