Low voltage puzzle-like fractal MEMS variable capacitor suppressing pull-in

A.M. Elshurafa^{1,4}, P.H. Ho², A.G. Radwan³, M. H. Ouda¹, and K.N. Salama¹

¹ Electrical Engineering, Physical Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

² ASM Pacific Technology Hong Kong Limited, Kwai Chung, Hong Kong

³ Engineering Mathematics, Cairo University, Giza 12613, Egypt

⁴ Corresponding author; email: elshurafa@ieee.org

Abstract: This letter introduces an electrostatically actuated fractal MEMS variable capacitor that, by utilizing the substrate, extends the tuning range beyond the theoretical limit of 1.5 as dictated by the pull-in phenomenon. The backbone concept behind the fractal varactor is to create a suspended movable plate possessing a specific fractal geometry, and to simultaneously create a bottom fixed plate complementary in shape to the top plate. Thus, when the top plate is actuated, it moves toward the bottom plate and fills the void present within the bottom plate without touching it akin to how puzzle pieces are assembled. Further, a reasonable horizontal separation is maintained between both plates to avoid shorting. The electrostatic forces come from the capacitance formed between the top plate and bottom plate, and from the capacitance formed between the top plate and the doped substrate. The variable capacitor was fabricated in the PolyMUMPS process and provided a tuning range of 4.1 at 6V, and its resonant frequency was in excess of 40GHz.

1. Introduction

Tunable radio frequency microelectromechanical system (RF MEMS) devices are expected to be very strong contenders in future wireless handsets because of their desirable characteristics, which surpass those of their CMOS counterparts. A variable capacitor will surely be among these candidates because of its high tuning ranges and very low losses. Seamless

integration with the electronic circuitry and reasonable actuation voltage requirement however, will be among the obstacles that will hinder commercialization.

Recently, the authors in [1] presented *fixed* RF MEMS capacitors in the PolyMUMPS process (www.memscap.com) utilizing the concept of fractals [2]. The research attention in this paper is directed towards designing RF MEMS *variable* capacitors (MVC) using fractal geometries, and we focus on those that are actuated electrostatically.

Electrostatically-actuated MVCs exhibit a number of benefits including quick response and the ability of generating high energy densities, but they do suffer from the notorious pull-in, or the snap-in, effect, which limits the theoretical tuning range (TR) of MVCs to 1.5.

Efforts have been put forth to suppress the effect of pull-in and many ideas have been proposed including for example supporting beam arrays [3], separate actuation and capacitance electrodes [4], leveraged bending [5], dimples [6], the zipping motion [7], or using three plates rather than two [8]. Although these methods were successful in suppressing the effect of pull-in, they do impose other challenges. Explicitly, additional fabrication steps are required for the array(s) of supporting beams, dimples, and the three-plate methods. Similarly, high actuation voltages are required for the leveraged bending method and zipping method, whereas the strain-stiffening method is restricted for fixed-fixed beams only.

In this letter, we introduce a new method that also suppresses pull-in, and extends the TR of typical MVCs beyond 1.5, by employing fractal geometries. In the proposed method, we create the top suspended plate such that it follows a specific fractal shape, and simultaneously create the bottom fixed plate using a fractal shape complementary in shape to the top one. In other words, nowhere does the bottom plate exist under the top plate, and nowhere does the top plate exist under the bottom plate. Hence, irrespective of how far the top plate travels towards the bottom plate, there will be no threats of both plates touching each other and consequently causing a short. If a very large voltage were to be applied, then the top plate would collide with the nitride insulator layer that is above the substrate without touching the bottom plate. When this latter case

occurs, the entire void that is present within the bottom plate will be filled with the top plate similar to how a jigsaw puzzle is formed. The source of the electrostatic forces is two-fold: the fringing capacitance that is present between the top plate and the bottom plate, and the capacitance that is present between the top plate and the semiconducting substrate. The effects of substrate coupling in PolyMUMPS are significant and cannot be ignored as clearly demonstrated in [7, 9]. By using both the concept of fractals and substrate coupling, a variable capacitor with a high tuning range was attainable as will be shown.

2. Principle of operation

2.1. Basic principle

Fig. 1 shows a scanning electron microphotograph (SEM) for the proposed MVC fabricated in PolyMUMPS [10], where the top plate was created from Poly2+Metal, whereas the bottom plate was created from Poly0.

a

b

Fig. 1. The proposed capacitor

a The complete proposed variable capacitor showing the top plate along with four suspension arms carrying it, and three measurement pads on the left

b a close-up of the figure shown in *a* showing clearly the top and bottom plates

Fig. 1a shows the overall structure including the top plate, the bottom plate, the suspension arms, and the measurement pads, while Fig. 1b shows a close-up for the image shown in Fig. 1a. It is clearly visible in Fig. 1b how nowhere does Poly0 exist under Poly2+Metal. The fractal geometry shown in Fig. 1 is the fifth-order (i.e. fifth iteration) Moore's Fractal, and the rationale behind choosing the Moore's Fractal was detailed in [1].

We explain the basic principle of operation of electrostatic fractal MVCs with the aid of Fig. 2, in which a conceptual schematic is provided comprising a small portion of the Moore's Fractal similar to that shown in Fig. 1b. When a potential difference is applied, a representative

electrostatic vector force is generated between both plates due to the fringing capacitance present between these two plates, and we name this force F_F , as shown in Fig. 2. Similarly, another electrostatic force is generated between the top plate and the substrate, and we name this force F_S . However, F_F can be de-composed into two forces, namely a horizontal force (F_{FH}) and a vertical force (F_{FV}). Note that F_F shown in Fig. 2 can be in any direction, but we show a single case for illustration purposes only. Due to symmetry, all the horizontal forces would theoretically cancel each other out, and only the vertical forces would contribute to the movement of the top plate, i.e. F_{FV} and F_S . Practically nonetheless, and due to fabrication imperfections, the horizontal forces will not be exactly equal. However, these imperfections are not severe to the extent that they cause a real concern. Further, the suspension arms are designed such that they would be very stiff in the direction of these horizontal forces but not as stiff in the direction of the vertical forces, and the varactor is also designed with a horizontal separation of $2\mu\text{m}$ present between both plates. Hence, and as indicated in Fig. 2, independent of how high the actuation voltage reaches, the top plate would never touch the bottom plate.

Fig. 2. A conceptual schematic of the fractal variable capacitor. The forces present are: the force resulting from the fringing capacitance F_F , and the force resulting from substrate coupling, F_S . The electrostatic force resulting from fringing, F_F , is written in terms of its x - and y - components (i.e. horizontal, F_{FH} , and vertical, F_{FV} , components). Both F_{FH} components are equal in magnitude and opposite in direction. The remaining forces, i.e. F_{FV} and F_S , are the ones that are responsible for actuation.

By taking a close look at Fig. 2, we can expect that F_{FV} and F_S will eventually cause the top plate to collide with the nitride layer, which is on top of the substrate. The latter can be easily

understood by visualizing two puzzle pieces coming together to form one bigger piece. At a first glance, one may be tempted to ignore the effect of F_S . However, it was clearly demonstrated experimentally that the substrate effects in PolyMUMPS on actuation are significant in [7, 9], and as such, ignoring F_S is not a reasonable assumption.

It is possible to create the varactor without the bottom plate. If the latter were to happen, then the varactor would resemble the one that was previously introduced in [7, 9]. However, the presence of the bottom plates provides two important advantages. First, it creates additional fringing capacitance, which results in creating an electrostatic force and subsequently lowers the required actuation voltage. Secondly, the second plate contributes in increasing the maximum capacitance, i.e. when the top plate becomes completely in contact with the nitride.

2.2. Residual stress consideration and tuning range

Another factor to consider in this design is the upward warping that will take place due to residual stresses [11-13], which will affect the TR . Ideally, the top plate should be parallel to the bottom plate. Practically however, and due to residual stresses, the top plate will be warped upwards. We can easily deduce that the capacitance measured for the warped varactor at 0 V (i.e. before actuation) will be less than that measured for the varactor with plates that are parallel to each other. Further, we expect that, as the warping becomes more severe, the capacitance will be even smaller. Because the minimum capacitance is used to calculate the TR , then the TR is directly affected by the warping that takes place due to residual stress. Explicitly, this warping causes the initial capacitance to decrease and hence, the TR will increase.

The warping due to residual stresses has been used advantageously in several designs as in [14] for example; conversely, other papers discussed techniques to suppress it [15, 16]. By taking a close look at Fig. 1a, it is clear how the outer parts of the top plate are warped upwards more than the middle parts of the plate. To obtain more information on this warping, we present in the

following detailed optical profilometer analysis with the aid of the Zygo 7300 optical profiler (www.zygo.com).

Fig. 3a shows a 3D oblique profile plot of the proposed varactor, which clearly shows the warping that takes place. To quantify this warping, we obtain two cross sections for the varactor, i.e. AA' and BB' as shown in Fig. 3b and we provide the surface profile plot for these sections in Fig. 3c and Fig. 3d respectively. Explicitly, Fig. 3c shows the AA' surface profile and indicates that the warping distance between the outer and middle parts of the plate is $5.6\mu\text{m}$. On the other hand, Fig. 3d measures how far the outer parts of the plates are from the substrate, and this distance is $8.8\mu\text{m}$.

Fig. 3. Optical profile analysis of the proposed variable capacitor.

a 3D oblique view

b SEM showing where cross sections are taken

c cross section AA' as shown in Fig. 3b measuring the warping between the outer parts of the variable capacitor and the middle part of the variable capacitor (right next to the suspension arms)

d cross section BB' as shown in figure 3b measuring the warping between the outer part of the variable capacitor and the substrate. Note that the outer part of the capacitor is almost $9\mu\text{m}$ far from the substrate despite that the total oxide thickness is approximately $1.25\mu\text{m}$ only.

Fig. 3 affirms that, when a DC voltage is applied and the top plate starts to move towards the bottom fixed plate, the middle part of the plate will be the first to collapse onto the nitride/substrate because it will not be as warped as the outer parts of the plate. As the voltage increases further, the rest of the plate will start to flatten out, in a zipping manner, until the complete plate is fully in contact with the substrate and rests on it.

We can also deduce from the previous optical profiler images, that the middle part of the plate is $8.8\mu\text{m} - 5.6\mu\text{m} = 3.2\mu\text{m}$ above the substrate. However, note that the distance of $3.2\mu\text{m}$ accounts also for the Poly2+Metal thickness of $2\mu\text{m}$. As such, the sacrificial oxide thickness is approximately $1.2\mu\text{m}$ as expected and as detailed in the PolyMUMPS documentation [10].

2.3. Sacrificial layers consideration and tuning range

There are two sacrificial (oxide) layers in the PolyMUMPS process, i.e. Oxide1 and Oxide2, which are $2\mu\text{m}$ and $0.75\mu\text{m}$ thick, respectively, and PolyMUMPS allows some flexibility in designing structures that depend on these oxide layers.

For the cases of the MVC herein for example, it is possible to create the top plate over both oxide layers, in which case the separation between the top plate and the substrate/nitride would be $2.75\mu\text{m}$. It is also possible to partially etch Oxide1 by $0.75\mu\text{m}$ before depositing Oxide2 atop Oxide1. The latter case would result in making the top plate reside $2\mu\text{m}$ above the substrate. Another possible combination is to use the *via* step and etch the combined thickness of $2.75\mu\text{m}$ to bring it down to approximately $1.25\mu\text{m}$. Other possibilities are also achievable [10].

The effect of the sacrificial layer thickness on the *TR* follows exactly the same rationale and explanation provided in the previous section. Depending on the initial separation between the top plate and the bottom plate, the minimum capacitance changes. As such, the tuning range changes also assuming that the maximum capacitance should always, theoretically, stay constant irrespective of the oxide thickness. If the top plate is far from the bottom plate, then the minimum capacitance becomes smaller, which increases the *TR*. On the other hand, if the top plate is close

to the bottom plate, then the minimum capacitance becomes larger, which decreases the TR . However, the higher TR will be acquired at the cost of a higher actuation voltage. Clearly, a compromise must be exercised and the designer should exercise his best judgment to satisfy the stipulated design specifications. For the purposes of this paper, we opt to prioritize the actuation voltage requirement rather than the TR because the actuation voltage requirement is very compelling in wireless handheld devices. Consequently, and with the previous explanation in mind, we chose the combination that provides the minimum oxide thickness, i.e. using the via step, to achieve an oxide thickness of $1.2\mu\text{m}$ as explained in section 2.2.

2.4. Self resonant frequency enhancement

Among the important advantages of utilizing fractals in creating the MVC, is reducing the parasitics coupling between the bottom plate and the substrate due to the reduced area of the bottom plate. Subsequently, the SRF of these varactors should be higher than other varactors that utilize the typical parallel-plate structure.

The SRF of a capacitor is the frequency at which the impedance of the capacitor becomes purely resistive. In other words, it is the frequency at which the capacitor can no longer provide a capacitance because the losses of the capacitor dominate the response. As such, the SRF is an important capacitor characteristic that needs to be known to ensure that a specific capacitor can be used in the circuit or system being designed for a specific frequency range. For example, if the SRF of a capacitor is 2GHz, it cannot be used for Bluetooth applications, which operate at 2.4GHz. Ideally, it is desired that the resonant frequency of the varactor be as high as possible so that it can serve a wide range of frequency bands and applications. Further, when choosing a capacitor for an application, it is prudent that the SRF be considerably higher than the operating frequency of the system to account for fabrication imperfections, measurement tolerances, calibration inaccuracies, etc.

The SRF, or f_R , of a capacitor is generally given by: $2\pi f_R = 1/(LC_t)^{0.5}$, where L is the inherent inductance present due to the connections and the lines within the structure itself, and C_t is the total capacitance which comprises the capacitance from the structure itself (C) and the parasitic capacitance (C_p), i.e. $C_t = C + C_p$. The parasitic capacitance in our case, which is formed between the bottom plate and the substrate, can be computed using: $C_p = \epsilon_n A / d_n$, where ϵ_n is the dielectric constant of nitride, A is the area of the bottom plate, and d_n is the distance separating the plate from the substrate (i.e. the nitride thickness). Because the area of the plate is small in the case studied herein (not a typical rectangular shape), C_p decreases and hence f_R increases. Note also that because the capacitance appears in the denominator, the increase in f_R is not linear. The expression for f_R also suggests that decreasing the unwanted inductance that comes from the capacitor connections increases the SRF.

3. Experimental results

3.1. Measurements

Fig. 4a shows the return loss measurement (i.e. S_{11}) of the MVC from 1GHz up to 4GHz where Q is approximately 5 throughout the frequency band, while Fig. 4b shows the tuning characteristics. The attained TR was 4.1 and was reached at a voltage of 6V, and no change in capacitance takes place beyond this voltage.

By taking a close look at Fig. 4b, we can conclude that the first pull-in occurs at 3V. After that, multiple consequent pull-ins also occur, until the maximum capacitance is reached at approximately 6V. These measurements are inline with the expected behavior of zipping.

Fig. 5 shows the measurement that was performed in order to find the resonant frequency of the proposed varactors. The network analyzer was re-calibrated through a band of 1 GHz to 40GHz, which is the maximum operating frequency of the Agilent 8363C network analyzer available. As can be seen, the resonant frequency is not yet reached at 40 GHz, and we conclude that the SRF of this varactor is beyond 40 GHz. To the best of our knowledge, and as will be

shown in the next section, the highest previously reported SRF in PolyMUMPS was measured to be 20 GHz.

Fig. 4. Measurement results

a The return loss measurement of the proposed capacitor from 1GHz to 4 GHz.

b The tuning behavior of the capacitor shown in Fig. 1. The tuning range is 4.1 and the maximum required voltage was 6V. The zipping behavior can also be noticed from the multiple pull-in voltages between 3V and 6V.

Fig. 5. The return loss measurement for the proposed varactor showing that the SRF is beyond 40GHz.

3.2. Comparison with literature

In table 1, we compare the performance of previously reported MVCs available in the literature with the proposed varactors herein. When referring to any previous design, we include the method or technique that was used in order to extend the tuning range of the variable capacitor beyond 1.5. In fairness, we restrict this literature review to MVC designs that are actuated electrostatically and attempted to extend the TR beyond the basic TR of 1.5; tunable capacitors that do not address the pull-in limitation were not compared.

Table 1. Comparative study.

Reference	Method used to overcome pull-in	TR	DC Voltage (V)	SRF (GHz)	Process
[3] IEEE MEMS, 2006	Using supporting beams between suspended and fixed plates	4	11	10•	PolyMUMPS
[4] IEEE VLSI, 2003	Separating AC and DC actuation electrodes	5.3	10	<5	PolyMUMPS
[6] IEEE MEMS, 2001	Zippering	1.5	35	<5•	PolyMUMPS
[7] IOP JMM, 2010	Zippering and substrate parasitics	4.5	55	N/A•	PolyMUMPS
[9] IOP JMM, 2010	Substrate parasitics	3	55	N/A•	PolyMUMPS
[17] IEEE TMTT, 2000	Separating AC and DC actuation electrodes	3.4	9	4	PolyMUMPS
[18] IEEE RFIC, 2001	Using three plates	1.87	4.4	<6•	PolyMUMPS
[19] IEEE EuMW, 2007	Actuating both plates	7	90	9	MetalMUMPS
[20] IEEE MEMS, 2008	Utilizing an electrically floating plate	1.4	5.5	10	SOI+electroplating
[21] IEEE JMEMS, 2011	Moving the suspended plate away from the fixed plate	2.3	45	3.4	Electroplating
[22] IEEE JMEMS, 2009	Depositing an insulator layer between plates to avoid shorting	5	60	20	PolyMUMPS + wet etching + atomic layer deposition
<i>This Work</i>	<i>Using substrate parasitics, residual stress warping, and fractal geometries</i>	<i>4.1</i>	<i>6</i>	<i>>40</i>	<i>PolyMUMPS</i>

• Estimated from measurements.

• This work belongs to one of the authors of this letter. Although the SRF was not reported in the paper, it was measured to be 8 GHz in [7] and 6 GHz in [9].

The highest SRF previously reported in the PolyMUMPS process was 20GHz, but was acquired after significant additional post processing [22]. However, the SRF of the varactor presented herein, although not exactly detected, is surely in excess of 40 GHz, and this result is noteworthy given that no fabrication intervention or post-processing was performed. In terms of TR, the highest TR acquired in PolyMUMPS was reported in [4] and the voltage required was reasonable, but the SRF was low. On the other hand, the highest TR reported in table 1 (i.e. 7) was in the MetalMUMPS process but was acquired at voltage of 90V, which is incompatible with

wireless handheld devices. As for the variable capacitor presented in this communication, both the TR and actuation voltage measure very well compared to other designs especially when looking at the TR , required voltage, and SRF collectively. Finally, we note that table 1 shows that no capacitor possesses a high TR , low actuation voltage, and high SRF simultaneously; a cost has to be always paid.

4. Concluding Remarks

MEMS variable capacitors possessing a fractal shape were proposed, fabricated, and tested at RF frequencies, where their dynamic behavior very much resembles that of a puzzle being put together. It was found that by coupling the concept of fractals along with the zipping motion, the typical pull-in drawback, which restricts the theoretical tuning range in electrostatically actuated variable capacitors to 1.5, can be overcome. Among the very important benefits attained from using the fractal structure in creating MEMS variable capacitors, is the ability to increase the resonant frequency of the varactor due to decreasing parasitic capacitances. Further, it was shown that the fractal capacitor requires relatively low actuation voltages for tuning (in the range of 6V), yet yields high tuning ranges (in the range of 4) without any fabrication intervention or post-processing.

5. Acknowledgments

The authors thank Dr. Ali Behzad, Mr. Xiang Yu, Mr. E. Diallo, and Dr. Dongku Cha at the Advanced Nanofabrication and Imaging Laboratories in King Abdullah University of Science & Technology (KAUST) for measurement and imaging assistance.

References

- [1] Elshurafa A.M., Radwan A.G., Emira A., Salama K.N., 'RF MEMS Fractal Capacitors With High Self-Resonant Frequencies', *J. Microelectromech. Syst.*, 2012, **21**, pp. 10-12
- [2] Samavati H., Hajimiri A., Shahani A., Nasserbakht G., Lee T., 'Fractal capacitors', *IEEE J. Solid-State Circuits*, 1998, **33**, pp. 2035-2041

- [3] Bakri-Kassem M., Mansour R., 'High tuning range parallel plate MEMS variable capacitors with arrays of supporting beams'. IEEE MEMS Conf., 2006, pp. 666-669
- [4] Tsang T., El-Gamal M., 'Very wide tuning range micro-electromechanical capacitors in the MUMPS process for RF applications'. IEEE Symp. VLSI Circuits, 2003, pp. 33-36
- [5] Hung E., Senturia S., 'Extending the travel range of analog-tuned electrostatic actuators', *J. Microelectromech. Syst.*, 1997, **8**, pp. 497-505
- [6] Ionis G., Dec A., Suyama K., 'A zipper-action differential micro-mechanical tunable capacitor'. IEEE MEMS Conf., 2001, pp. 29-32
- [7] Elshurafa A.M., El-Masry E., 'MEMS variable capacitance devices utilizing the substrate: II. Zipping varactors', *J. Micromech. Microeng.*, 2010, **20**, article id 45028
- [8] Dec A., Suyama K., 'Microwave MEMS-based voltage-controlled oscillators', *IEEE Trans. Microw. Theory Tech.*, 2000, **48**, pp. 1943-1949
- [9] Elshurafa A.M., El-Masry E.I., 'MEMS variable capacitance devices utilizing the substrate: I. Novel devices with a customizable tuning range', *J. Micromech. Microeng.*, 2010, **20**, article id 045027
- [10] J. Carter, B. Hardy, R. Mahadeven, and S. Wilcenski, "PolyMUMPS Design Handbook, Rev. 13," MEMSCAP Inc., Bernin, France
- [11] Chiou J., Chou L., Lai Y., Juang Y., Huang S., 'Thermal switch design by using complementary metal oxide semiconductor MEMS fabrication process', *IET Micro & Nano Lett.*, 2011, **6**, pp. 534-536
- [12] Perdignes F., Moreno J., Luque A., Quero J., 'Characterisation of the fabrication process of freestanding SU-8 microstructures integrated in printing circuit board in microelectromechanical systems', *IET Micro & Nano Lett.*, 2010, **5**, pp. 7-13
- [13] Wang J., Gutierrez M., 'Stress-strain behaviour of carbon nanotubes under cyclic loading', *IET Micro & Nano Lett.*, 2007, **2**, pp. 111-114
- [14] Al-Dahleh R., Mansour R., 'High-Capacitance-Ratio Warped-Beam Capacitive MEMS Switch Designs', *J. Microelectromech. Syst.*, 2010, **19**, pp. 538-547
- [15] Elshurafa A.M., Salama K.N., 'Two-layer radio frequency MEMS fractal capacitors in PolyMUMPS for S-band applications', *IET Micro & Nano Lett.*, 2012, **7**, pp. 419-421
- [16] Elshurafa A.M., Salama K.N., 'Differential RF MEMS interwoven capacitor immune to residual stress warping', *IET Micro & Nano Letters*, 2012, **7**, pp. 658-661
- [17] Elshurafa A.M., El-Masry E.I., 'Finite-element modeling of low-stress suspension structures and applications in RF MEMS parallel-plate variable capacitors', *IEEE Trans. Microw. Theory Tech.*, 2006, **54**, pp. 2211-2219
- [18] Dec A., Suyama K., 'RF micromachined varactors with wide tuning range'. IEEE Radio Freq. Integ. Cir. Symp., 1998, pp. 309-312.
- [19] Bakri-Kassem M., Mansour R., 'A parallel-plate MEMS variable capacitor with vertical thin-film comb actuators'. IEEE European Microw. Integ. Cir. Conf., 2007, pp. 551-554
- [20] Suk Lee H., Yoon Y., Choi D., Yoon J., 'High-Q, tunable-gap MEMS variable capacitor actuated with an electrically floating plate', IEEE MEMS Conf., 2008, pp. 180-183
- [21] Han C., Choi D., Yoon J., 'Parallel-Plate MEMS Variable Capacitor With Superior Linearity and Large Tuning Ratio Using a Levering Structure', *J. Microelectromech. Syst.*, 2011, **20**, pp. 1345-1354
- [22] Bakri-Kassem M., Mansour R., 'Linear bilayer ALD coated MEMS varactor with high tuning capacitance ratio', *J. Microelectromech. Syst.*, 2009, **18**, pp. 147-153