Received 13 March 2016; revised 10 May 2016; accepted 14 June 2016. Date of publication 7 July 2016; date of current version 24 October 2016.
The review of this paper was arranged by Editor C. C. McAndrew.

Digital Object Identifier 10.1109/JEDS.2016.2582833

Study of the Effect of Surface Roughness on the Performance of RF MEMS Capacitive Switches Through 3-D Geometric Modeling

SARATH GOPALAKRISHNAN, AMITAVA DASGUPTA (Member, IEEE), AND DELEEP R. NAIR (Member, IEEE)

Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
CORRESPONDING AUTHOR: SARATH G (e-mail: sarathgopalakrishnan@gmail.com)

ABSTRACT Surface roughness is an important factor that influences the reliability and performance of radio frequency microelectromechanical systems switches. The presence of surface roughness impedes a perfect contact in the down-state condition of the switch which in turn affects the following parameters—resonant frequency, down-state capacitance, and isolation at resonance. The result is a significant deviation from the electromagnetic characteristics simulated by assuming flat surfaces making a perfect contact. However, creating a rough topography manually is cumbersome. A Visual Basic Script code for generating rough surfaces of any average value and standard deviation has been developed. The code runs on High Frequency Structure Simulator platform. This paper focuses on the simulations that include the effect of surface roughness on both the beam and the dielectric layer using a 3-D geometric model by representing surface asperities as an array of pyramids, the heights of which follow a Gaussian distribution. This assumption takes into account of the statistical nature of surface roughness. The results of simulation indicate that the presence of surface roughness reduces down-state capacitance and isolation and shifts the resonant frequency from the X-band (8–12 GHz) for which it was originally designed.

INDEX TERMS Down-state capacitance, isolation, RF MEMS capacitive switch, surface asperities, surface roughness, X-band.

I. INTRODUCTION

Radio Frequency (RF) Microelectromechanical Systems (MEMS) switches designed to operate in RF-to-millimetre-wave frequencies (0.1-100 GHz) provide near-zero power consumption, very high isolation, very low insertion loss and low cost which enable them to be a potential replacement for electronic switches in high frequency applications [1]. RF MEMS capacitive switches operating in shunt configuration can be designed to resonate at a desired frequency and to provide high isolation. Nevertheless, reliability poses a main challenge for their industrial implementation [2]. Among the several factors studied from the point of view of the reliability of RF MEMS switches, surface roughness is one of the important phenomena [2], [3]. This is because, on the one hand surface roughness leads to some failure mechanisms, but on the other hand it can be used as a solution to certain failure mechanisms [4], [5].

Surface roughness can lead to a reduction in the down-state capacitance thereby changing the high frequency parameters such as isolation [6] of the switch. This is an important concern from the perspective of time-zero reliability of the switch. Surface roughness can cause abrasive wear [7] and dielectric breakdown [8] leading to device failure. Surface roughness influences the nature of charge injection in dielectric films [9]. Dielectric charging is an important reliability concern which can lead to a shift in the pull in voltage of the switch [10], [11]. This adversely affects the long term reliability of the switch. At the same time, it has been used as a solution to other failure mechanisms such as stiction which can lead to long-term reliability issues in switches. Various adhesion models and studies on stiction show that the higher the roughness the lesser the adhesion [12]–[14]. Therefore, the surfaces of the contacting faces are intentionally roughened to avoid stiction [5], [15]. This topological modification to improve reliability varies the down-state capacitance and the associated high frequency parameters of RF MEMS switches. Since surface roughness influences the down-state capacitance and the high frequency parameters of the switch when it is a reliability problem and a solution to a reliability problem the impact of surface roughness on the characteristics of RF MEMS switches needs to be investigated.

An RF MEMS capacitive switch consists of a Coplanar Waveguide (CPW) and a beam suspended above the signal line of the Coplanar Waveguide as shown in figure 1(a) and 1(b). The signal line transmits the radio frequency signal and helps in actuating the suspended beam. The beam is anchored at the ground planes and acts like a bridge. A dielectric layer is deposited and patterned on the signal line. The two metal electrodes, namely the beam and the signal line, separated by the air gap and the dielectric layer, introduce two capacitors in series resulting in a low capacitance (C_{up}) in the up-state condition of the beam. In this state of the switch, the signal is transmitted with low loss (ON-state). A DC voltage is applied on the signal line to actuate the beam. In the down-state condition of the beam, as the air gap is eliminated, the capacitance increases. The switch resonates at the frequency corresponding to the down-state capacitance (C_d) isolating the output port from the input port. A high value of C_d is possible only if the beam makes a perfect contact with the dielectric layer on actuation. However, the rough interface between the beam and the dielectric layer prevents a perfect contact. This affects the values of C_d and thereby the electrical parameters dependent on it, such as resonant frequency and isolation.

The randomness in surface roughness was explained using a statistical method in [16]. An analytical solution is derived by assuming a surface topography that consists of asperities that are spherical with uniform radii near the summit [16]. However, only the up-state capacitance can be calculated by this method. Another method was explained in [17]. It was based on the assumption that the effective area of contact in the down-state condition of the switch is half the total area of overlap and does not consider the statistical nature of surface roughness. The effect of surface roughness on C_d is statistically examined in [18]. The capacitance contributed by the dielectric layer ($C_{dielectric}$) is neglected in the up-state condition of the switch and C_{up} is equated to the capacitance due to the air gap (C_{air}). Although this assumption is applicable for large air gaps, the equation becomes invalid when the air gap is small enough to make C_{air} comparable with $C_{dielectric}$. Therefore, this equation cannot be used to find the capacitance between the beam and the signal line when beam is in the proximity of the dielectric layer. Moreover, C_d is calculated after quantifying the normalized contact area between the two surfaces. Since the roughness of the bottom surface of the beam is not taken into account in this study, the normalized contact area will be smaller than the value obtained from this equation.

This paper aims to study the influence of surface roughness on the high frequency characteristics of an RF MEMS capacitive switch using a 3-dimensional (3-D) geometric model that takes into account the roughness on both the beam and the dielectric layer. This geometric model is applicable to both up-state and down-state condition of the switch. It can also be used to find the capacitance in any intermediate state of the beam. The capacitance along the path traversed by the beam upon actuation is quantified with the help of simulations. The design and specifications of the RF MEMS capacitive switch employed for simulation are presented in Section II. The general methodology adopted in simulation is explained in Section III. Section IV demonstrates the results followed by the discussion. The study is concluded in Section V.

II. DESIGN OF RF MEMS CAPACITIVE SWITCH

An RF MEMS capacitive switch can be represented as a series RLC circuit [17] as shown in figure 1(c). The capacitance is a function of the area of overlap between the beam and the signal line, the air gap between the dielectric layer and beam and the thickness and relative permittivity of the dielectric material used. The inductance depends on the geometry of the beam. The switch can be designed to operate in a frequency band based on the values of the capacitance and inductance.

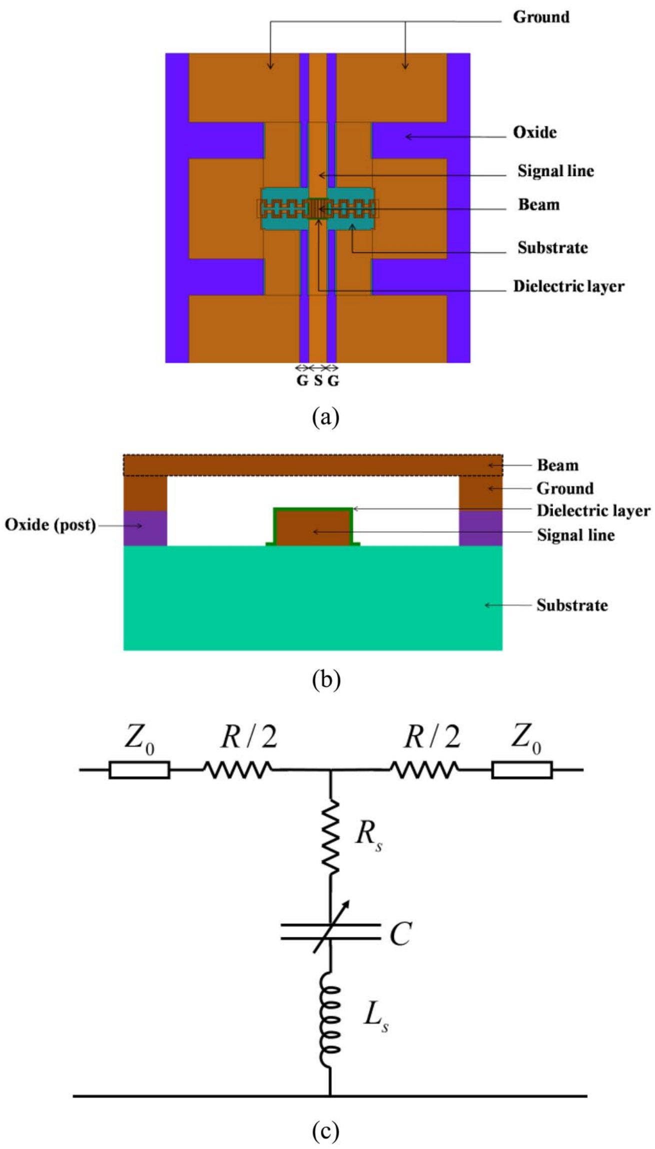
The RF MEMS capacitive switch shown in figure 1(a) and 1(b) is designed to operate in the X-band (8-12 GHz). The CPW transmission line is of gold and has the dimensions $G/S/G = 60/120/60$ μm, where G stands for the separation between the signal line and the ground plane near the ports and S stands for the width of signal line. The mechanical design of the beam consists of meander structures that increase the effective length and hence provide the required inductance.

The thickness of the signal line and the beam are 2 μm and 1.2 μm, respectively. The width of the meander is 20 μm. Silicon nitride is chosen as the material for the dielectric layer. It has a thickness of 0.1 μm. The dielectric constant is taken to be 7. The area of the overlap contributing to the capacitance is 120 μm x 120 μm. The air gap in the up-state condition of the beam is 2 μm. The electrical performance of this switch has been reported earlier [19].

III. METHODOLOGY

A. 3-D MODELING

Surface roughness can be considered as an indiscriminate and non-uniform distribution of protrusions and cavities along the mean plane of a surface. The asperities are assumed to be an array of square pyramids of uniform base size and randomly varying peak height (figure 2). This geometric approximation is advantageous from the point of view of simulations. Square pyramids can be meshed by the simulator with ease. Since the base of the pyramid is a square, the entire surface can be divided into a square grid. The pyramids can be placed on each cell. This leads to the assumption that the pyramids are independent of each other. The protrusions are modelled as vertical pyramids added to



(a)

(b)

(c)

FIGURE 1. (a) Simple structure of an RF MEMS capacitive switch (top view). (b) Simple structure of an RF MEMS capacitive switch (side view). (c) RLC equivalent circuit of an RF MEMS capacitive switch.

the mean plane of the surface and the cavities are modelled as inverted pyramids removed from the mean plane of the surface.

A Gaussian distribution function is used to describe the randomness of surface roughness. The heights of the vertical pyramids provide a positive deviation and that of the inverted pyramids provide a negative deviation from the mean plane. In order to simulate the structure, it is assumed that the mean of the heights of the pyramids, calculated after assigning a positive value to the height of a vertical pyramid and a negative value to the height of an inverted pyramid, is zero. Therefore, the root-mean-square (RMS) value of roughness, hereafter represented as R_q, equals the standard deviation (σ_s) of the height distribution. For the ease of simulation, the maximum height of the pyramid is restricted to $\pm\, 3\sigma_s$ with respect to the mean plane. Therefore, the height of the tallest pyramid is three times the RMS roughness.

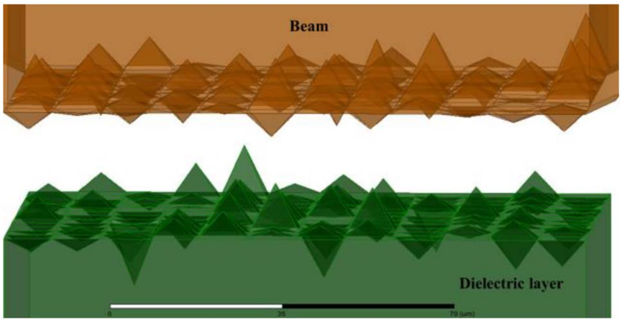


FIGURE 2. Array of vertical and inverted pyramids illustrating protrusions and cavities on a rough surface.

B. GENERATION OF ROUGH SURFACES

The asperities are generated with the help of High Frequency Structure Simulator (HFSS) [20]. In order to generate a pyramid in HFSS, two triangles, the coordinates of whose base fall on the corners of the base of the pyramid, are to be drawn in such a way that they share the third vertex. The two triangles are connected to each other so that they fill up the space between them forming a solid pyramid. This pyramid is placed on one of the cells of the grid. Since a large number of pyramids with randomly varying height distribution are to be drawn and placed on each cell of the grid, this manual method is cumbersome. Therefore, a Visual Basic Script (VBS) code is written alongside the random number generator from MATLAB [21]. A file containing a collection of random numbers that forms a Gaussian distribution is generated. The random numbers stand for the heights of the pyramids. The file is referred to in the VBS code and each random number is assigned to the shared vertex of the triangles. The code generates a pyramid on each cell filling up the entire grid in such a way that it forms a rough surface following a Gaussian distribution. Subsequently, the group of vertical pyramids are added to the surface to obtain protrusions and the group of inverted pyramids are subtracted from the layer to obtain cavities.

C. MINIMUM PEAK-TO-PEAK AIR GAP

The minimum peak-to-peak air gap (g_0) is defined as separation between the plane where the crest of the surface asperity with maximum height on the beam and the plane where that on the dielectric layer lies.

In figure 3, *A-A'* is the plane touching the peak of the beam asperity with maximum height lies and *B-B'* is the plane touching the peak of the dielectric asperity with maximum height lies. The separation between these planes is g_0 which varies from zero when the switch is pulled down, to the air gap in the up-state condition of the beam. Please note that since the surface roughness is statistical in nature, $g_0 = 0$ need not mean the establishment of a contact but it only

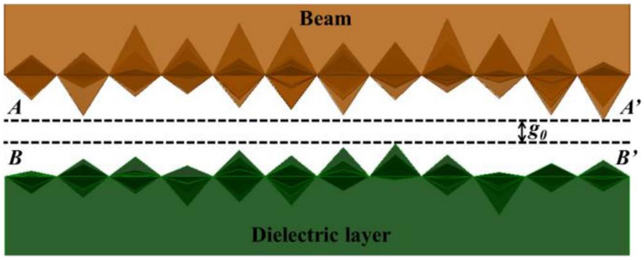


FIGURE 3. **Schematic of a beam-dielectric interface depicting surface roughness.**

represents the “possibility of first contact”. C_d is calculated in this limiting case, where the asperity on the beam’s surface with maximum height is likely to establish a contact with the asperity on the dielectric layer with maximum height. In other words, C_d is the capacitance calculated when g_0 tends to zero, and represents its lowest possible value. This is a reasonable assumption considering the fact that in the case of RF MEMS switches only a few asperities are expected to make contact [22].

D. SIMULATION

The electromagnetic characteristics are simulated with the help of HFSS. The following cases are considered for the simulations: 1. Only the dielectric layer has a rough surface and the beam has a flat surface 2. Both the beam and the dielectric layer have rough surfaces. In this case, the roughness of the beam (R_{qb}) is considered to be less than, equal to and greater than the roughness of the dielectric layer (R_{qd}).

The pull-in simulations performed in CoventorWare MEMS simulator [23] is used to extract the geometry of the beam in the down state condition (figure 4). The down-state geometry extracted from CoventorWare is recreated in HFSS with the help of a VBS code. The radiation boundary condition is applied to the structure. The frequency is swept from 1 GHz to 40 GHz and the scattering parameters are obtained.

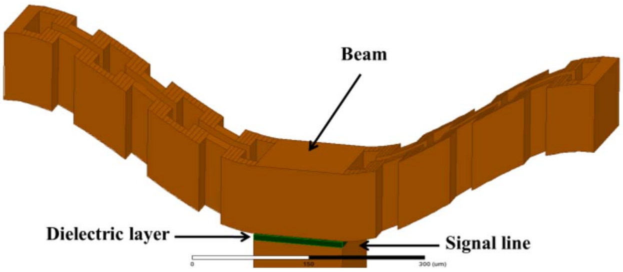


FIGURE 4. **Down-state condition of the capacitive switch (thickness is scaled 100 times the actual value).**

The scattering parameter, S_{21}, obtained using the simulations performed in HFSS is used for extracting C_d based on the following equation [17].

$$S_{21} = \frac{1}{1 + j\omega C_d \frac{Z_0}{2}} \tag{1}$$

For $\omega C_d Z_0 \gg 2$ which corresponds to $|S_{21}| \ll 10dB$

$$|S_{21}|^2 \cong \frac{4}{\omega^2 C_d^2 Z_0^2} \tag{2}$$

The switch is capacitive in nature for the frequencies much less than the LC resonant frequency. C_d is extracted from this region of frequencies where $|S_{21}| \ll 10dB$.

The capacitance between the beam and the signal line can also be found using simulations performed in COMSOL Multiphysics [24]. The outer fringing fields are neglected in the simulations performed in COMSOL Multiphysics. The capacitance at various positions of the beam as it actuates down is evaluated by changing the separation between the beam and the dielectric layer. The values of C_d obtained from COMSOL Multiphysics and HFSS are to be compared.

IV. RESULTS AND DISCUSSION

A. HIGH FREQUENCY CHARACTERISTICS

In order to take into account the statistical nature of the 3–D surface profiles, multiple runs are done with different topographies having the same roughness parameters. The results of the simulations performed to verify the statistical nature of the problem are presented in figure 5. The roughness of the beam (R_{qb}) is 2 nm and that of the dielectric layer (R_{qd}) is 5 nm. Near identical results for multiple runs support the assumption of a statistical distribution.

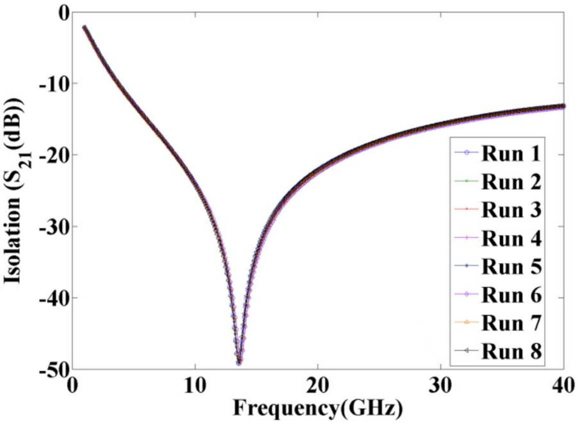


FIGURE 5. **Isolation versus frequency for multiple runs: RMS roughness on the beam, R_{qb} = 2 nm and RMS roughness on the dielectric layer R_{qd} = 5 nm.**

Case 1 of the study where the beam is assumed to be flat (R_{qb}= 0) is illustrated in figure 6. The isolation characteristics for various values of surface roughness on the dielectric layer (R_{qd}) are also shown. The plots are compared with the case where both the beam and dielectric layer have flat surfaces ($R_{qb} = 0$, $R_{qd} = 0$).

A higher resonant frequency is observed in the electrical characteristics of the structures with a rough dielectric layer as compared to the structures with flat surfaces. The reason for this variation is the reduction in C_d which leads to an increase in the resonant frequency. The resonant frequency increases drastically and the isolation at resonance reduces as the roughness on the dielectric layer increases. Even for a roughness of 15 nm, the resonant frequency changes from 9.1 GHz (X-band) in the flat-interface case to 15.1 GHz (Ku-band) and the isolation reduces from −62.72 dB to −45.62 dB. This shows the importance of surface roughness on the dielectric layer.

Case 2 is demonstrated in figure 7. The roughness on the dielectric layer is fixed at 5 nm. As the roughness on the beam is increased, the resonant frequency increases because the gap between the mean planes of the dielectric layer and the beam widens with increasing roughness. For a fixed R_{qd}, when R_{qb} changes from 0 nm to 8 nm, the resonant frequency increases by 33.33% and the isolation reduces by 4.65 dB. This signifies that the roughness of the dielectric layer alone is not sufficient to analyse the influence of the interface topography on the characteristics.

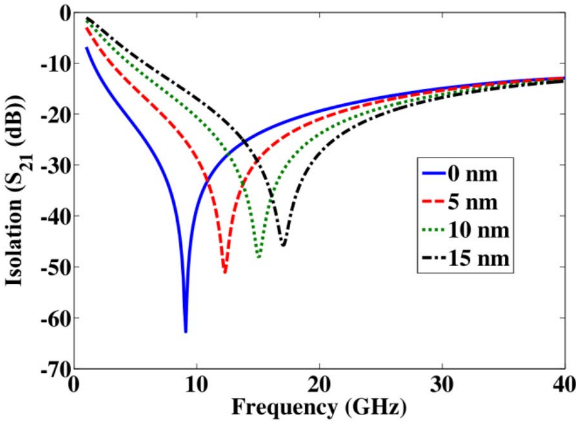


FIGURE 6. Isolation versus frequency for various values of RMS roughness on the dielectric layer (R_{qd}) and a flat beam with no roughness ($R_{qb} = 0$).

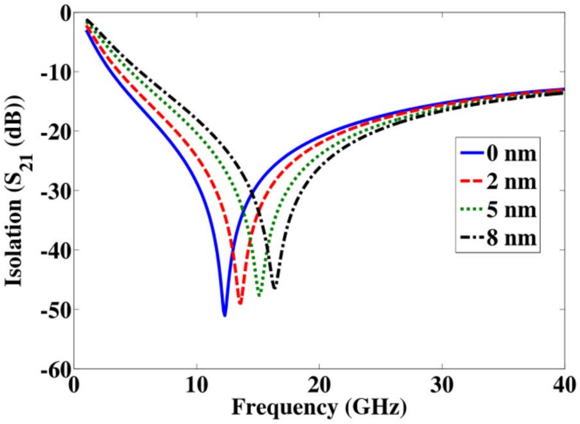


FIGURE 7. Isolation versus frequency for various values of RMS roughness on the beam (R_{qb}) and a fixed value of RMS roughness on the dielectric layer ($R_{qd} = 5$ nm).

Aforesaid cases are summarized in figure 8. The characteristics of the flat interface have been compared with the rough interface. It is inferred that the high frequency characteristics of an RF MEMS capacitive switch could be predicted if the roughness is known. The lowest possible value of resonant frequency and the highest possible value of isolation can be obtained by simulating the case where both the surfaces are flat. The highest possible value of resonant frequency and the lowest possible value of isolation can be calculated by simulating the case with rough surfaces. This gives the bounds of the characteristics. It could be asserted that the actual characteristics will fall within the calculated bounds.

Table 1 lists the values of resonant frequency and isolation at resonance for various cases. It is observed that the resonant frequency falls within the X-band only for the case where both surfaces are flat. In all other cases, the resonant frequency falls beyond the X-band for which the switch was designed.

The reduction in the isolation at resonance with the increase in the resonant frequency is due to the increase in the series resistance. The series resistance (R_s) is contributed by the conductor loss in the signal line and ground planes of the coplanar waveguide and the resistance of the beam that connects the proof-mass to the anchor [17].

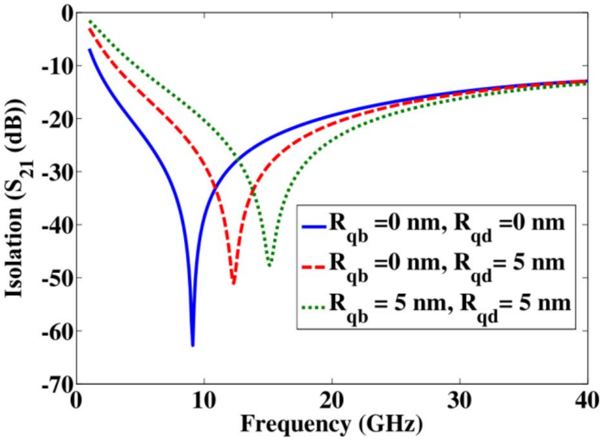


FIGURE 8. Comparison of isolation versus frequency for the three cases considered. 1. No roughness on beam and dielectric 2. Flat beam and rough surface 3. Rough beam and rough surface.

As frequency increases, the current becomes more confined to the surface of the beam. This leads to an increase in R_s and therefore the isolation at resonance reduces as per the following equation [25].

$$S_{21}|_{\omega=\omega_0} \approx 20\log\left(\frac{2R_s}{Z_0}\right) \tag{3}$$

Since a quantitative analysis of the relation between the series resistance and the frequency is difficult because of the intricate nature of the current density plot, a study has been done by replacing the 20 μm wide meanders with thin rectangular conductors of cross section 0.5 μm x 0.5 μm. This value is chosen to make sure that R_s is constant until the sweep-end frequency, 40 GHz, at which the skin depth is 0.393 μm. The switch resistance is independent of the frequency if the thickness of the beam is smaller than twice the skin depth [26]. The isolation versus frequency plot is illustrated in figure 9.

Since the thin beam is not influenced by the skin effect, the series resistance is unaffected and therefore the isolation at resonance remains the same even as the resonant frequency changes. In the case of the structures with thicker beams, the reduced isolation at increased resonant frequency is not directly related to the increased roughness but is due to the increased series resistance caused by the skin effect at higher frequencies.

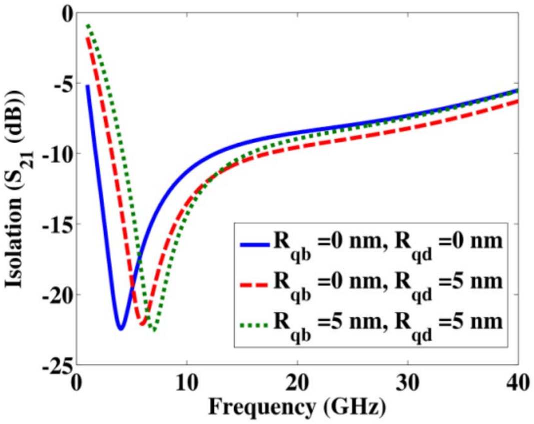


FIGURE 9. Comparison of isolation versus frequency in a thin beam for the following cases 1. No roughness on beam and dielectric 2. Flat beam and rough surface 3. Rough beam and rough surface.

B. CAPACITANCE

Simulations performed in COMSOL Multiphysics are used to plot the capacitance versus minimum peak-to-peak air gap (g_0) characteristics. A comparison of capacitance, where the dielectric thickness is changed assuming a flat beam ($R_{qb} = 0$), simulated for Case 1 is illustrated in figure 10. The results are compared with the case where the roughness of the surfaces of beam and dielectric layer is zero ($R_{qb} = 0$, $R_{qd} = 0$).

Figure 11 demonstrates Case 2. R_{qd} is fixed at 5 nm and R_{qb} is varied. The capacitance versus minimum peak-to-peak air gap (g_0) characteristics for a flat-flat interface is also plotted in figure 11 for comparison.

The minimum peak-to-peak air gap (g_0) is swept from zero to the value corresponding to the up-state condition of the switch. A significant variation is observed in the down-state condition of the switch, i.e., when g_0 is zero. This indicates that C_d is influenced by the variation in the surface roughness of the dielectric layer.

C_d decreases with the increase in the surface roughness of the dielectric layer. For a fixed value of surface roughness of the dielectric layer, C_d decreases with increase in the beam roughness. As the minimum peak-to-peak air gap increases, the deviation in capacitance reduces indicating that the influence of surface roughness is not highly pronounced in the up-state condition of the switch. The results are validated by comparing the capacitance values extracted from the isolation plots obtained from HFSS based on equation (2) with the capacitance values obtained from COMSOL Multiphysics.

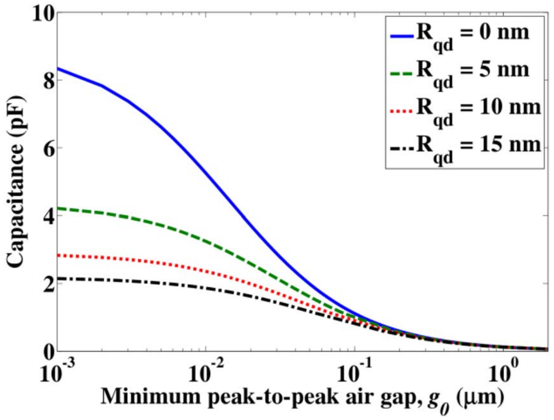


FIGURE 10. Capacitance versus minimum peak-to-peak air gap (g_0) for various values of RMS roughness on the dielectric layer (R_{qd}) and a flat beam with no roughness ($R_{qb} = 0$).

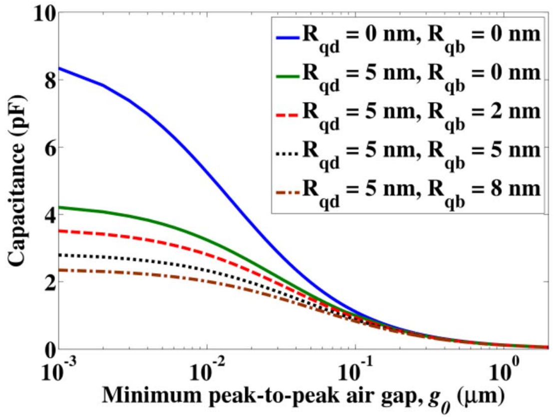


FIGURE 11. Capacitance versus minimum peak-to-peak air gap (g_0) for various values of RMS roughness on the beam (R_{qb}) and a fixed value of RMS roughness on the dielectric layer (R_{qd} = 5 nm).

The values of down-state capacitance (C_d) are listed in table 1. Even for an R_{qd} as low as 5 nm, the C_d reduces to half of its value for a flat-flat interface case. The introduction of R_{qb} = 5 nm to the case with R_{qd} = 5nm reduces the capacitance by approximately 36%. This remarkable deviation in C_d indicates how important surface roughness can be in RF switches.

It can also be noted from the table that the electrical parameters are almost similar for the case where R_{qd} and R_{qb} are 5 nm each and R_{qb} = 0 nm and R_{qd} = 10 nm. This means that the one can lump the total roughness on the beam and the dielectric layer to either beam or dielectric layer, in which case the analytical modeling would be easier. It also shows we cannot neglect roughness at either of the surfaces and what matters is the combined roughness.

COMSOL Multiphysics results underestimate the value of capacitance due to the fact that the outer fringing fields are neglected in the simulation. The table underlines the fact that the electrical parameters are influenced by the topography of the beam as well as the dielectric layer.

C. COMPARISON WITH ANALYTICAL AND MEASUREMENT RESULTS

This study has been compared with the analytical and measurement results reported in [18]. The normalized down state capacitance (C_d^*) is obtained by calculating the ratio of C_d on a rough interface to that on the perfect interface. The normalized capacitance at the first point of contact can be obtained when the hold-down voltage (d-c bias required to balance the mechanical restoring force and hold the metal bridge at the down-state position) is zero. The analytical results in [18], for $R_{qb} = 0$ nm, $R_{qb} = 10$ nm and hold-down voltage = 0 V, gives $C_d^* = 0.36$. Our results given in Table 1 shows that when $R_{qb} = 0$ nm and $R_{qb} = 10$ nm, $C_d^* = 2.293/9.018 = 0.3275$.

TABLE 1. **Surface roughness and electrical parameters.**

R_{qb} (nm)	R_{qd} (nm)	f_0 (GHz)	S_{21max} (dB)	C_d (pF) from HFSS	C_d (pF) from COMSOL
0	0	9.1	-62.72	9.018	8.925
0	5	12.3	-51.02	4.501	4.355
0	10	15.1	-47.91	2.953	2.9
0	15	17.1	-45.65	2.258	2.184
2	5	13.6	-48.94	3.683	3.626
5	5	15.1	-47.63	2.885	2.869
8	5	16.4	-46.37	2.427	2.394

The measurement results from [18], shows that when $R_{qb} = 0$ nm, $R_{qb} = 14.81$ nm and hold-down voltage = 30 V, $C_d^* = 0.22$. It can be calculated that when the hold-down voltage is 0V, C_d^* reduces by 1.5-2% and will be between 0.2 and 0.205. Table 1 shows that when $R_{qb} = 0$ nm and $R_{qb} = 15$ nm, $C_d^* = 2.258/9.018 = 0.25$. The small difference in the results is because only the effect of surface effects has been considered and the other factors have not been taken into account for calculating C_d in [18].

The isolation in the capacitive region of the high frequency characteristics is dependent on C_d. Therefore, the isolation must follow the same trend as C_d. However, the isolation at resonance is not reported in [18]. Therefore, S_{21max} cannot be directly compared. Nevertheless, the simulation results reported in this paper and the measurement result reported in [18], follow a matching trend and comes to the same conclusion.

V. CONCLUSION

A new method for analyzing the effect of surface roughness on the electrical parameters of RF MEMS switches is presented. The 3-D geometric model considers the roughness on both the beam and the dielectric layer and can be used to study any state of the beam. This eliminates the need of separate models for the up-state and the down-state condition of the switch. The results indicate that the influence of surface roughness is not prominent in the up-state capacitance while it reduces the down-state capacitance of the switch. The latter effect causes the high frequency parameters, such as resonant frequency and isolation to change from the expected values which might lead the design to fall out of specifications. The simulation results have been validated with the measurement results reported in [18]. This model provides a clear understanding of how the topological modifications introduced to improve the reliability of RF MEMS switches impacts its performance. Therefore, the effect of surface roughness must be incorporated while designing an RF MEMS capacitive switch.

ACKNOWLEDGMENT

The authors would like to acknowledge the NPMASS (National Program on Micro and Smart Systems) project being carried out at the Centre for NEMS and Nano Photonics (CNNP), Indian Institute of Technology, Madras, for funding the simulation software—CoventorWare, COMSOL Multiphysics and ANSYS HFSS.

REFERENCES

[1] G. M. Rebeiz and J. B. Muldavin, “RF MEMS switches and switch circuits,” *IEEE Microwave Mag.*, vol. 2, no. 4, pp. 59–71, Dec. 2001.

[2] S. Melle *et al.*, “Reliability behavior of RF MEMS,” in *Proc. Int. Semicond. Conf. (CAS)*, vol. 1. Sinaia, Romania, 2003, p. 26.

[3] J. Iannacci, “Reliability of MEMS: A perspective on failure mechanisms, improvement solutions and best practices at development level,” *Displays*, vol. 37, pp. 62–71, Apr. 2015.

[4] W. M. van Spengen, “MEMS reliability from a failure mechanisms perspective,” *Microelectron. Rel.*, vol. 43, no. 7, pp. 1049–1060, Jul. 2003.

[5] K. Komvopoulos, “Surface engineering and microtribology for microelectromechanical systems,” *Wear*, vol. 200, nos. 1–2, pp. 305–327, Dec. 1996.

[6] S. Mellé *et al.*, “Failure predictive model of capacitive RF-MEMS,” *Microelectron. Rel.*, vol. 45, nos. 9–11, pp. 1770–1775, Sep./Nov. 2005.

[7] Y. Huang, A. S. S. Vasan, R. Doraiswami, M. Osterman, and M. Pecht, “MEMS reliability review,” *IEEE Trans. Device Mater. Rel.*, vol. 12, no. 2, pp. 482–493, Jun. 2012.

[8] Z. Hou, Z. Liu, G. Hu, L. Liu, and Z. Li, “Study on the nanotopography of the electrode surface and the breakdown voltage in RF MEMS switches,” in *Proc. 1st IEEE Int. Conf. Nano/Micro Eng. Molecular Syst.*, Zhuhai, China, 2006, pp. 395–398.

[9] U. Zaghloul *et al.*, “Nanotribology-based novel characterization techniques for the dielectric charging failure mechanism in electrostatically actuated NEMS/MEMS devices using force-distance curve measurements,” *J. Colloid Interf. Sci.*, vol. 365, no. 1, pp. 236–253, Jan. 2012.

[10] S. Palit, X. Xin, A. Raman, and M. A. Alam, “Implications of rough dielectric surfaces on charging-adjusted actuation of RF-MEMS,” *IEEE Electron Device Lett.*, vol. 35, no. 9, pp. 948–950, Sep. 2014.

[11] G. Palasantzas, “Self-affine roughness influence on the pull-in voltage in capacitive electromechanical devices,” *J. Appl. Phys.*, vol. 98, no. 3, pp. 034505-1–034505-4, Aug. 2005.

[12] L. Wu, L. Noels, V. Rochus, M. Pustan, and J.-C. Golinval, “A micro–macroapproach to predict stiction due to surface contact in microelectromechanical systems,” *J. Microelectromech. Syst.*, vol. 20, no. 4, pp. 976–990, Aug. 2011.

[13] I. De Wolf and W. M. van Spengen, "Techniques to study the reliability of metal RF MEMS capacitive switches," *Microelectron. Rel.*, vol. 42, nos. 9–11, pp. 1789–1794, Sep./Nov. 2002.

[14] B. Bhushan, "Adhesion and stiction: Mechanisms, measurement techniques, and methods for reduction," *J. Vac. Sci. Technol. B*, vol. 21, no. 6, pp. 2262–2296, 2003.

[15] R. Maboudian and R. T. Howe, "Critical review: Adhesion in surface micromechanical structures," *J. Vac. Sci. Technol. B*, vol. 15, no. 1, pp. 1–20, Jan. 1997.

[16] L. Kogut, "The influence of surface topography on the electromechanical characteristics of parallel-plate MEMS capacitors," *J. Micromech. Microeng.*, vol. 15, no. 5, pp. 1068–1075, May 2005.

[17] J. B. Muldavin and G. M. Rebeiz, "High-isolation CPW MEMS shunt switches. 1. Modeling," *IEEE Trans. Microw. Theory Techn.*, vol. 48, no. 6, pp. 1045–1052, Jun. 2000.

[18] A. B. Yu, A. Q. Liu, Q. X. Zhang, and H. M. Hosseini, "Effects of surface roughness on electromagnetic characteristics of capacitive switches," *J. Micromech. Microeng.*, vol. 16, no. 10, pp. 2157–2166, Oct. 2006.

[19] J. Sharma, "Fabrication and study of low pull-in voltage structures for RF MEMS shunt switches," Ph.D. dissertation, Dept. Elect. Eng., Indian Inst. Technol. Madras, Chennai, India, 2010.

[20] *High Frequency Structure Simulator (HFSS)*. Accessed on Jul. 25, 2016. [Online]. Available: http://www.ansys.com/Products/Electronics/ANSYS-HFSS

[21] *MATLAB—The Technical Computing Software*. Accessed on Jul. 25, 2016. [Online]. Available: http://www.mathworks.com/products/matlab/

[22] D. Berman and J. Krim, "Surface science, MEMS and NEMS: Progress and opportunities for surface science research performed on, or by, microdevices," *Progr. Surface Sci.*, vol. 88, no. 2, pp. 171–211, May 2013.

[23] *CoventorWare MEMS Design and Simulation Software*. Accessed on Jul. 25, 2016. [Online]. Available: http://www.coventor.com/mems-solutions/products/coventorware/

[24] *COMSOL Multiphysics*. Accessed on Jul. 25, 2016. [Online]. Available: http://www.comsol.com

[25] G. M. Rebeiz, *RF MEMS: Theory, Design and Technology*. Hoboken, NJ, USA: Wiley, 2003.

[26] R. N. Simons, *Coplanar Waveguide Circuits, Components, and Systems*. New York, NY, USA: Wiley, 2001.

SARATH GOPALAKRISHNAN is currently pursuing the M.S. degree with the Department of Electrical Engineering, IIT Madras, Chennai, India. His current research interests include the study of RF MEMS switches, including their simulation, design, fabrication and characterization.

AMITAVA DASGUPTA (M'88) received the B.E. degree in electronics and telecommunication engineering from Jadavpur University, Kolkata, India, in 1982, the M.Tech. degree in electrical engineering from IIT Madras, Chennai, India, in 1984, and the Ph.D. degree from IIT Kharagpur, Kharagpur, India, in 1988. He has been a Faculty Member with the Department of Electrical Engineering, IIT Madras, since 1993, where he is currently a Professor.

DELEEP R. NAIR (M'98) received the Ph.D. degree in electrical engineering from IIT Bombay, Mumbai, India, in 2005. He was a Senior Engineer with IBM SRDC, Hopewell Junction, NY, USA, involved in low-power logic technology development. He has been an Assistant Professor with the Department of Electrical Engineering, IIT Madras, Chennai, India, since 2012.