Design of High Isolation Ka-band Radio Frequency MEMS Capacitive ShuntSwitch

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ABSTRACT:
Radio frequency (RF) micro electro-mechanical systems (MEMS) switches are rapidly replacing thePIN diodes and field-effect transistors (FET). Linear behavior, low power consumption, low insertion loss, high isolation, improvement power handling and etc. are benefits of MEMS switches.This paper presents a high isolation RF MEMS capacitive switchwith two shunt beams for Ka-band (27-40 GHz) applications such as in communications satellites and uplink.Simulation results using Ansoft's high frequency simulation software (HFSS) at Ka-band shows in the down-state of switch, the isolation (S_{21}) is -47 dB and return loss (S_{11}) is -0.3 dB.In the up-state, the insertion loss (S_{21}) is -0.15 dB and the return loss (S_{11}) is -18 dB. Thepulldown voltage of designed switch is 5.13 V and down-state to up-state capacitance ratio(C_d/C_u=12.11pF/0.137pF) is 88.39.Also a novel index material (*IM2*) is proposed to determine optimum material using Ashby approach. In this paper theAluminum (*Al*) is chosen for the membrane for having low pull down voltage and silicon nitride (Si_3N_4) is chosen for dielectric for having faster switching speed and largerdown-state capacitance.

KEYWORDS: Aluminum, Capacitive shunt switch, Insertion loss, Isolation, Pull down voltage, Silicon nitride.

1. INTRODUCTION

RF MEMS is an emerging technology with great promise for reducing cost and improving performance in certain microwave applications. MEMS consists of mechanical elements, sensors, actuators, and electrical and electronics devices on a common silicon substrate.Some of the advantages of MEMS devices are highly linear characteristics over a wide range of frequencies, low insertion loss, low power consumption, high isolation, moderateswitching speeds, easy to integrate into systems and very small size [1]. RF MEMS components are mainly used as inductors, tunable capacitors, switches, in VCOs, and resonators [2].

MEMS switches were first demonstrated in 1971 by Petersen [3] as electrostatically actuated cantilever armsused to switch low-frequency electrical signals. Since these switches havedemonstrated beneficial performance at microwave frequencies,different switch topologies havebeen investigated and tested. RF MEMS switches can be classified by actuation mechanism (electrostatic, thermal, electromagnetic, and piezoelectric), axis of deflection (lateral or vertical),circuit configuration (series or shunt), clamp configuration (cantilever or fixed-fixedbeam) or contact type (capacitive or metal-to-metal {DC}) [4].

A comparison of MEMS,PIN and FET switches are shown in Table 1.

Table 1. Comparison of MEMS switches with other switches [4], [5]

Characteristic	RF MEMS	PIN	FET
Size	Small	Very Small	Small
Driving Voltage (V)	10-80	3-5	3-5
Current (mA)	0	3-20	0
Power Consumption (mW)	0.05-1	5-100	0.05-1
Switching Time	1-300 μs	1-100 ns	1-100 ns
Series Resistance (Ω)	0.5-2	2-4	4-6
Cutoff Frequency (THz)	20-80	1-4	0.5-2
Isolation (1-10 GHz)	Very High	High	Medium
Isolation (10-40 GHz)	Very High	Medium	Low
Isolation (> 40 GHz)	High	Medium	None
Loss (dB)	0.05-0.2	0.3-1.2	0.4-2.5
Power Handling (W)	< 1	< 10	< 10
3rd order harmonics	Very good	Poor	Poor
Integration Capability	Very good	Very good	Very good

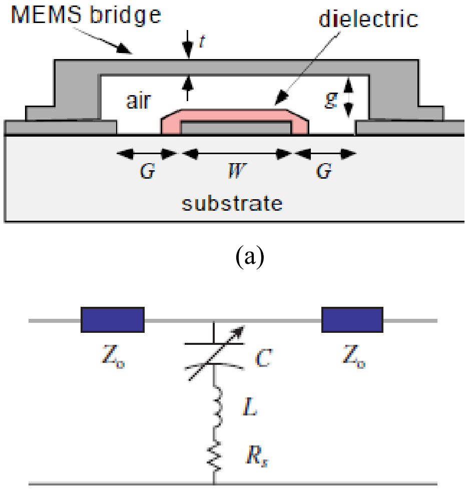
The main application areas of MEMS switches are, signal routing in transceivers applications, phase shifters in phase array antenna, impedance matching networks, wide band tuning networks, reconfigurable antennas, filters, programmable attenuators and SPNT networks [6].

RF MEMS switches have beenpresented by Rebeiz and Muldavin [7-9], Yao [10], de Los Santos [11], Brown [12] and other authors in the last fewyears[13-16].

The organization of the paper is as follows. RF MEMS capacitive shunt switch is discussed in Section 2.Ashbyapproach for material selection is explained in Section 3.In Section 4, high isolation RF MEMS capacitive shunt switch for Ka-band application is proposed. Simulation results are provided in Section 5 and finally the conclusion is given.

2. RF MEMS CAPACITIVE SHUNT SWITCH

A shunt capacitive MEMS switch consists of a thin metal membrane “bridge”suspended over the center conductor of a CPW (CoplanarWaveguide) and fixed at both ends tothe ground conductors of the CPW line. A dielectric layer is used to DC isolate the switchfrom the CPW center conductor. When the switch is up (off), the switch presents a small shunt capacitanceto ground. Also when the switch is down (on), the shunt capacitance increases. The schematic of typical shunt capacitive switch in up-state and equivalent-circuit model are shown in Fig. 1 [8].



(a)

(b)

Fig. 1. (a) Cross section of a MEMs membrane switch in the up-state [17], (b) equivalent-circuit model [8]

When a DC-bias voltageis applied between the twoconductors, charges are induced on the metal which tends to attract the two electrodes.Above a certain threshold voltage, the force of attraction is sufficient to overcomemechanical stresses in the material, and the membrane snaps down to the downposition shown in Fig. 2 [17].

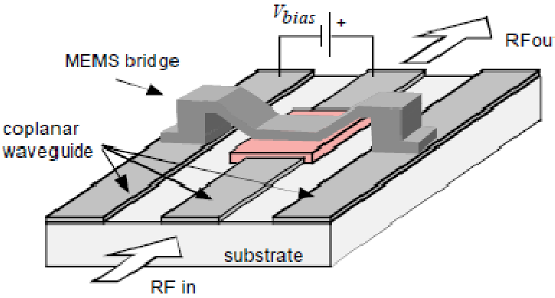


Fig. 2.Shunt capacitive switchin down-state [17]

2.1. Pulldown voltage

The MEMS bridge becomes unstable at $2g_0/3$, where g_0 is the zero-bias height. The voltage at this instability occurs in the pull down voltage and is given by [8]:

$$V_p = \sqrt{\frac{8k}{27\varepsilon_0 W w} g_0^3} \tag{1}$$

Where k is the effective spring constant of the membrane,W is the CPW center conductor width, w is the membrane width and ε_0 is the permittivity of free space. The effective springconstant of the membrane is given by [8]:

$$k = \frac{32Et^3 w}{L^3} + \frac{8\sigma(1-\upsilon)tw}{L} \tag{2}$$

Where E is Young’s modulus of the membrane material, $t$is the membrane thickness, L is the membrane length, σ is the residual tensile stress in the membrane, and υ is Poison’s ratio for the membrane material.

2.2. Hold down voltage

The voltage required to keep the membrane in the down-state is given by [18]:

$$V_h = \sqrt{\frac{2kg_0}{\varepsilon_0 W w}\left(\frac{t_d}{\varepsilon_r}\right)^2} \tag{3}$$

Where t_d is the dielectric thicknessand ε_r is the relative permittivity (dielectric constant) of dielectric.

2.3. Switching time

The switching time is calculated by [19]:

$$t_s = 3.67 \frac{V_p}{\omega_0 V_s} \tag{4}$$

Where $\omega_0 = \sqrt{k/m}$ is the mechanical resonant frequency ofthe bridge (*m*is the mass of the bridge), V_S is the source (applied) voltage. The applied voltage is 2-3 V_p for high speed switch [19].

2.4. Equivalent-circuit model

The RF capacitive switch can be modeled by two short sections of transmission line with characteristic impedance, Z_0, and a lumped series resistor–inductor–capacitor model of the bridge, as shown in Fig. 1 (b). The membrane of the switch is demonstrated mainly by the bridge resistance R_s, bridge inductance L and variable bridge capacitance *C*. The variable bridge capacitance changes according to the position of the switch. The impedance of the bridge is given by [8]:

$$Z = R_s + j(2\pi f_0 L - \frac{1}{2\pi f_0 C}) \tag{5}$$

Where $C=C_d$ or C_u and $2\pi f_0 = \omega$. The *LC* series resonant frequency of the switch is [8]:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

The impedance of the shunt switch can be approximated by [8]:

$$Z = \begin{cases} 1/2\pi f_0 C, & \text{for } f \ll f_0 \\ R_s, & \text{for } f = f_0 \\ 2\pi f_0 L, & \text{for } f \gg f_0 \end{cases} \tag{7}$$

2.5. Capacitive ratio

The parallel plate capacitance of the MEMS shunt switchis [8]:

$$C_{PP} = \frac{\varepsilon_0 A}{g_0 + \frac{t_d}{\varepsilon_r}} \tag{8}$$

The down-state/up-state capacitance ratio is:

$$C_{ratio} = \frac{C_d}{C_u} = \frac{\frac{\varepsilon_0 \varepsilon_r A}{t_d}}{\left(\frac{\varepsilon_0 A}{g_0 + t_d/\varepsilon_r}\right) + C_f} \tag{9}$$

Where C_f is the fringing field capacitance ofMEMS switches ($C_f \simeq 0.3 - 0.4\ C_{pp}$) and $A=w*W$.

2.6. S-parameters

The relationship between the capacitances and the S-parameters of the switch can be expressed as [4]:

$$S_{11} = \frac{-j\omega C_u Z_0}{2 + j\omega C_u Z_0} \tag{10}$$

$$S_{21} = \frac{1}{1 + j\omega C_d\, Z_0/2} \tag{11}$$

Where $S_{11}$and $S_{21}$are the up-state return loss and the down-state isolation, respectively. The loss of a MEMS switch is:

$$Loss = 1 - |S_{11}|^2 - |S_{21}|^2 \tag{12}$$

In other hand, in the up-state and for S_{11}< -13 dB, loss is given by [4]:

$$Loss = \omega^2 C_u^2 R_s Z_0 \tag{13}$$

And in down-state for S_{21}> -10 dB, loss is given by [4]:

$$Loss = 4R_s/Z_0 \tag{14}$$

3. ASHBY APPROACH FOR MATERIAL SELECTION

Materials selection is an important subject in micro-technology. The Ashby approach [20] is widely used for optimum selection of materials.The steps involved in the material selection using Ashby approachare illustrated in Fig. 3.

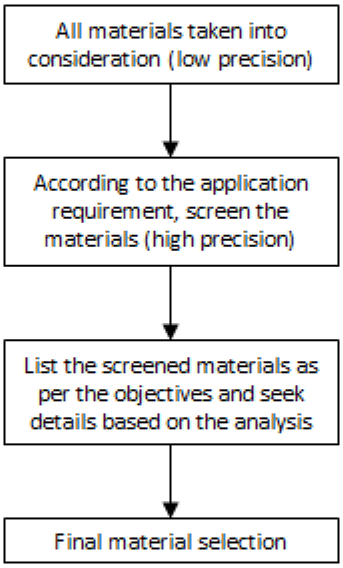


Fig. 3. Ashby approach for material selection [21]

3.1. Materials selection for a bridge

According to equation (1) pull down voltage is proportional to the square root of theYoung's modulus ($V_p \approx \sqrt{E}$). Another important parameter inRF MEMS switch is the quality factor ($Q \approx \rho^{-1}$)where ρ is the electrical resistivity of the material [22].In MEMS switch low pull down voltage, low losses and high quality factor are needed. The following index materialis defined:

$$IM\,1 = 1\big/\sqrt{E}\,\rho \qquad (15)$$

The material withhigh*IM1* value is suitable for bridge.So the material with low the electrical resistivity and low Young's modulusmust be selected. Fig. 4 is material selection chart with the electrical resistivity plotted against the Young's modulus.

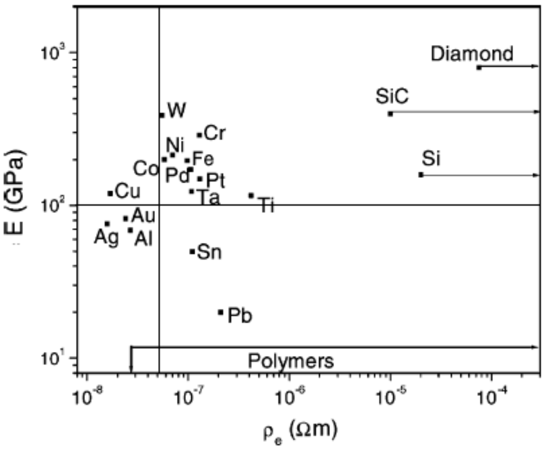


Fig. 4.Young's modulus versus electrical resistivity.The lower left corner exhibited materials with low pull down voltage, high speed and high quality factor [23]

According to Fig. 4, silver (Ag), gold (Au) and Aluminum (Al) are the best material for having high speed, low losses and low pull down voltage. Among these materials,Aluminum is the optimal choice. Notice at present polymers is not widely used in MEMS application [23].

3.2. Materials selection for a dielectric

According to equation (3) and equation (9), hold down voltage and capacitive ratio is proportional to relative permittivity (ε_r). For a low hold down voltage, high down-state capacitance and low up-state capacitance the value of ε_r must be large. Also for having minimum losses, loss tangent (tanδ) must be small. The following index materialis defined:

$$IM\,2 = \varepsilon_r \big/ \tan\delta \qquad (16)$$

Fig. 5 is material selection chart with the tanδ plotted against the relative permittivity (material with a ε_r between 3.9 and 25 have been selected). According to Fig. 5, for a low hold down voltage, high down-state capacitance, low up-state capacitance and low loss silicon nitride, Aluminum oxide, Aluminum nitride and hafnium oxide are the best dielectric layers.

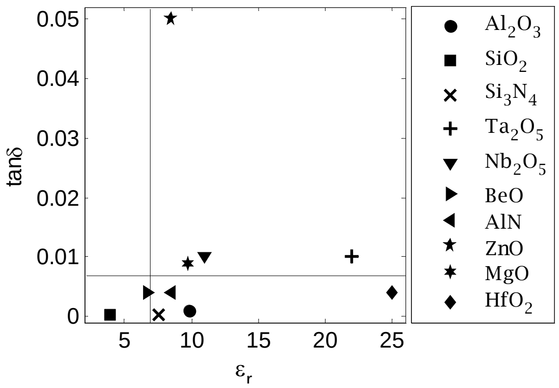
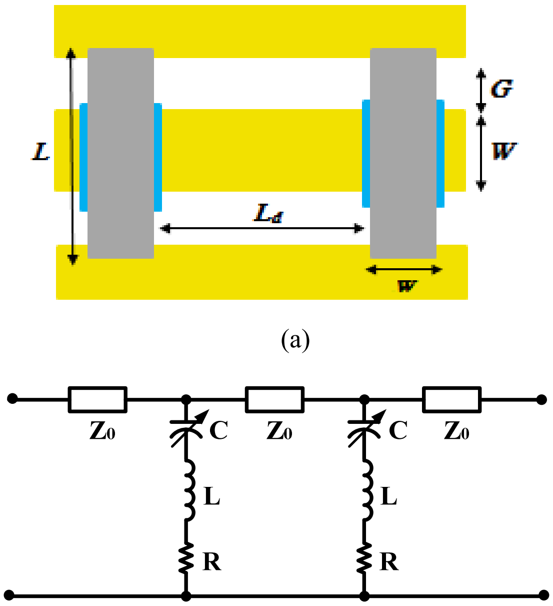


Fig. 5. Loss tangent versus relative permittivity. The lower right corner exhibited materials withhigh capacitive ratio and low loss

4. DESCREPTION THE HIGH ISOLATION TWO BEAMS K$_A$-BAND RF MEMS SWITCH

The structure of designed double bridge switch over CPW transmission line and equivalent-circuit are shown in Fig. 6. The length of midsection lineis chosen such that the reflection from the first bridge and the reflection from the second membrane cancel at theinput port when the switch is in the up-state.



(a)

(b)

Fig. 6. (a) Top view of designed switch in the up-state [17], (b) equivalent-circuit model [8]

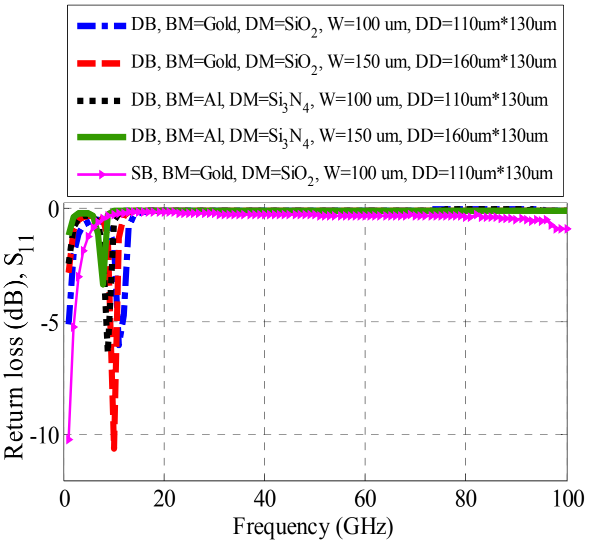
Theswitch is designed on anAluminum CPW line with dimensions *G/W/G*=100/150/100 µm (50 Ω) for low loss and highisolation for Ka-band applications. The switch has 400µm length (*L*), 120 µm width (*w*) and 1µm thickness. The anchors with 1.5µm height (air-gap height) are connected to the CPWground planes. The overlapping area between the bridge and the dielectric layer, *A*=*w***W*, is 120µm×150µm. Thesilicon nitride dielectric layer has0.1 μm thicknesswith dielectric constant of 7.6. Both bridges have the same dimensions. The separation distance between the two bridges, L_d, is 280μm. All the necessary dimensions and material of thisdesign are given in Table 2.

Table 2. Material and geometrical parameters

Parameters	Value
Al Young's modulus (GPa)	70
Al Poisson's ratio	0.33
Dielectric constant of Silicon Nitride	7.6
Length of the membrane (μm)	400
Width of the membrane (μm)	120
Thickness of the membrane (μm)	1
Dielectric thickness (μm)	0.1
Air-gap height (μm)	1.5
Width of the transmission line (μm)	150
Distance between membranes(μm)	280
Dimension of dielectric (μm)	160*130

5. SIMULATION RESULTS

The proposed switch is simulated in up and down stateusing HFSS software. The effects of various geometric dimensionalparameters (different membrane width and different dimension of dielectric) and effects of the variousmaterials (different membrane material and different dielectric material) on the switching behavior of proposed designare studied and simulated.The simulated S-parameters of the designed dual beam switch in down-state are shown in Fig. 7 and Fig. 8.



- DB: Double bridge
- BM: Bridge material
- DM: Dielectric material
- W= Width of the transmission line
- DD= Dimension of dielectric
- SB: Single bridge

Fig. 7. Return loss in down-state

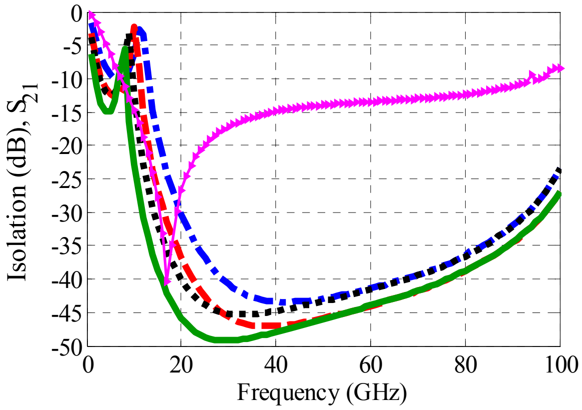
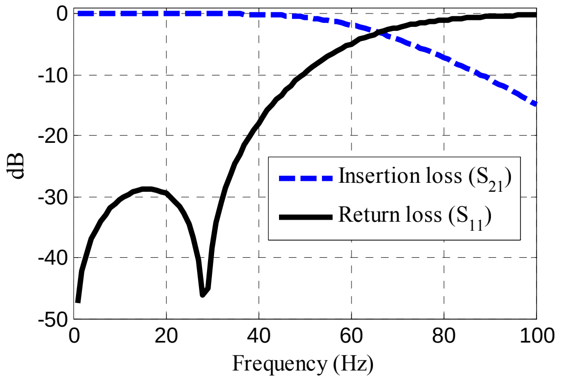


Fig. 8. Isolation in down-state

According to Fig. 7 and Fig. 8, return loss is -0.3 dB and isolation is -47 dB in ka-band.The simulated S-parameters in up-stateareshown in Fig. 9.



- DB
- BM=Al
- DM= Si_3N_4
- W=150 um
- DD=160um*130um

Fig. 9. S-parameters inup-state

The insertion loss of the switch in the up state is -0.15 dB and the return loss is -18 dB. Table 3 shows the results of the RF and DC simulation of the proposed switch and similar switches.

Table 3. Results of the designed switch and comparison with similar switches

Parameters	Proposed	[24]	[25]
S11, Up-state	-18 dB	-12 dB	-18 dB
S21, Up-state	- 0.15 dB	-0.22 dB	-0.18 dB
S11, Down-state	-0.3 dB	-0.5 dB	-0.5 dB
S21, Down-state	-47 dB	-10 dB	-13 dB
Frequency	27-40 GHz	27-40 GHz	27-40 GHz
Pull down voltage ($\sigma = 0$)	5.13 V	N/A	N/A
Capacitance (Up)	0.137 pF	N/A	N/A
Capacitance (Down)	12.11 pF	N/A	N/A

6. CONCLUSION

Highisolation dual bridges MEMS capacitive shunt switch for Ka-band applications is designed and simulated. The simulation results represent high isolation in down-state and better return loss in up-state. This switch has isolation more than -47 dB in 27-40 GHz and the pull down is 5.13 V.Aluminum and silicon nitride materials are chosen for the membrane and dielectric for having best performance respectively. The designed switch is suitable for various Ka-band applications including phased array antennas/radars, impedance matching circuits, transmitters/receivers, phase shifters and etc.

REFERENCES

[1] P. Bahmanyar, Kh. Mafinezhad and M. Bahmanyar, **"Switching Performance Analysis in RF MEMS Capacitive Shunt switches by Geometric Parameters Trade-Offs ,"***2010 IEEE Asia Pacific Conference on Circuits and Systems*, pp. 831-834, 2010.

[2] C. Christodoulou, **"RF MEMS and its applications to microwave systems, antennas and wireless communications,"** *Proceedings of the SBMO/IEEE MTT-S International Conference on Microwave and Optoelectronics*, pp. 525 -531 2003.

[3] K. E. Petersen, **"*Micromechanical membrane switches on silicon,*"***IBM Journal of Research and Development*, Vol. 23, pp. 376-385, July 1971.

[4] G. M. Rebeiz, ***RF MEMS: Theory, Design and Technology***, 2003 John Wiley & Sons, Inc.

[5] T. W. Jau, **"RF MEMS Switches: High-Frequency Performance and Hot-Switching Reliability,"** *High Frequency Electronics*, pp. 32-38, 2013.

[6] H. S. Newman, **"RF MEMS switches and applications",***Proceedings of the 40th annual Reliability Physics Symposium*, pp. 111-115, 2002.

[7] G. M. Rebeiz and J. B. Muldavin, **"RF MEMS Switches and Switch Circuits,"** *IEEE Microwave Magazine,* Vol. 2, No. 4, pp. 59-71, 2001.

[8] J. B. Muldavin and G. M. Reheir, **"High Isolation CPW MEMS Shunt Switches - Part 1: Modeling"**, *IEEE Transactions on Microwave Theory and Techniques,* Vol. 48, No. 6, pp. 1045–1052, 2000.

[9] J. B. Muldavinand G. M. Rebeiz, **"High Isolation CPW MEMS Shunt Switches - Part 2: Design"**, *IEEE Transactions on Microwave Theory and Techniques,* Vol. 48, No. 6, pp. 1053-1056, 2000.

[10] J. J. Yao, **"Topical Review: RF MEMS from A Device. Perspective,"** *Journal of Micromechanics and Micro engineerig,* Vol. 10, No. 4, pp. R9-R38, 2000.

[11] H. de Los Santos, ***Introduction to Microelectromechanical (MEM) Microwave Systems,*** Boston: Artech House, 1999.

[12] E. R. Brown, **"RF-MEMS Switches for Reconfigurable Integrated Circuits,"** *IEEE Transactionson Microwave TheoryandTechniques,* Vol. 46, No. 11, pp. 1845-1880, 1998.

[13] T. Campbell, **"MEMS Switch Technology Approaches the "Ideal Switch",** *Applied Microwave & Wireless,* Vol. 13, No. 5, pp. 100-107, 2001.

[14] D. Peroulis, S. P. Pacheco, K. Sarabandi and L. P.B. Katehi, **"Electromechanical Considerations in Developing Low- Voltage RF MEMS Switch**es,**"** *IEEE Transactions on Microwave Theory and Techniques,* Vol. 51, No. 1, pp. 259-270, 2003.

[15] D. Peroulis, S. Pacheco, K. Sarabandi and L. P. B. Katehi, **"MEMS Devices for High Isolation Switching and Tunable Filtering,"** *IEEE MTT-S International Microwave Symposium Digest*, pp. 1217-1220, 2000.

[16] J. Y. Park, G. H. Kim, K. W. Chung and J. U. Bu, **"Fully Integrated Micromachined Capacitive Switches for RF Applications,"** *IEEE MTT-S International Microwave Symposium Digest*, pp. 283-286, 2000.

[17] Y. Liu, **"MEMS and BST Technologies for Microwave Applications,"** Ph.D. Thesis, University of California, Santa Barbara, 2002.

[18] B. Jlassi and A. Merdassi, **"Design methodology of a high power RF MEMS switch for wireless applications,"** *4th AnnualCaneus Fly by Wireless Workshop*, pp. 1-4, 2011

[19] J. B. Muldavin, and G. M. Rebeiz, **"Nonlinear electro-mechanical modeling of MEMS switches,"** *IEEE MTT-S International Microwave Symposium Digest*, pp. 219-2122, 2001.

[20] M. F. Ashby, ***Material selection in mechanical design***, 2nd ed. Oxford (UK): Butterworth; 1999.

[21] O. Parateand N. Gupta, **"Material selection for electrostatic microactuators using Ashby approach,"** *Materials and Design*, Vol. 32, No. 3, pp. 1577-1581, 2011.

[22] G. Guisbiers, O. Van Overschelde and M. Wautelet, **"Materials selection for thin films for radio frequency microelectromechanical systems,"** *Materials and Design*, Vol. 28, No. 6, pp. 1994-1997, 2007.

[23] V. T. Srikar and S. M. Spearing, **"Materials selection for microfabricated electrostatic actuators,"***Sensors and Actuators A: Physical,* Vo. 102, No. 3, pp. 279–285, 2003.

[24] Y. Mafinejad, A. Z. Kouzani, K. Mafinejad and D. Izadi, **"Design and Simulation of a RF MEMS Shunt Switch for Ka and V Bands and the Impact of Varying Its Geometrical Parameters,"** *52nd IEEE International Midwest Symposium onCircuits and Systems,* pp. 823–826, 2009.

[25] Y. Mafinejad, A. Z. Kouzani, K. Mafinejad and H. Nabovati, **"Design and simulation of a low voltage wide band RF MEMS switch,"** *IEEE International Conference onSystems, Man and Cybernetics,* pp. 4623–4627, 2009