Progress In Electromagnetics Research Letters, Vol. 31, 147–157, 2012

MATERIAL SELECTION OF RF-MEMS SWITCH USED FOR RECONFIGURABLE ANTENNA USING ASHBY'S METHODOLOGY

A. K. Sharma and N. Gupta*

Department of Electrical and Electronics Engineering, Birla Institute of Technology and Science Pilani, Rajasthan 333 031, India

Abstract—This paper reports material selection methodology for radio frequency — micro electro mechanical systems (RF-MEMS) switches used for reconfigurable antennas. As there are variety of materials available to design engineer, a proper technique to select the best possible material is needed. Three primary performance indices, pull-in voltage, RF-loss, and thermal residual stress, are used to obtain the desired performance. The selection chart shows that aluminum is the most suitable material for being used as bridge material in RF-MEMS switches to provide the best performance in reconfigurable antenna.

1. INTRODUCTION

With tremendous advancement in the field of wireless communication, the need for reconfigurable communication devices is always felt. Therefore, the reconfigurable antennas (RA) have received significant attention in recent communication systems because a single RA can be used to change the operating frequency, radiation pattern and directivity based on different application requirements. RF-MEMS switches can be equipped with antenna design to make an antenna reconfigurable by changing its geometrical structure for different resonance frequencies.

MEMS technology has significant impact on communication applications [1, 2]. An RF-MEMS switch utilizes mechanical movement of switch beam to achieve a short or an open circuit in transmission line. Cheng et al. [3] demonstrated RF-MEMS capacitive switch based electrically switchable beam steering antenna by integrating two Quasi-Yagi antenna element with Single Pole Double Throw (SPDT) MEMS

Received 11 February 2012, Accepted 14 April 2012, Scheduled 20 April 2012
* Corresponding author: Navneet Gupta (dr.guptanavneet@gmail.com).

switch. Cheng et al. [4] described a reconfigurable millimeter-wave lens-array antenna based on dc contact MEMS switches with cantilever design and concluded that MEMS bridge resistance and up-state capacitance have the greatest impact on the frequency response of the antenna. Jung and Lee [5] achieved RF switching for a reconfigurable rectangular spiral antenna with a set of capacitive MEMS switches having low power consumption, high Q and low RF loss, to provide scan-beam capability. These RF-MEMS switches are used to change spiral overall arm length for different directions of beam radiation with low RF loss.

So it is shown that the performance of an antenna depends vastly on RF-MEMS switches which in turn depend on suitable material to be used for the switch. Though several material selection strategies [6–9] have been developed in the past, the methodology for selecting the bridge material used in RF-MEMS switches particularly for reconfigurable antenna has never been proposed. Ashby provides a comprehensive material selection strategy with less computation [10]. So the Ashby approach is used in the work to choose suitable material for RF-MEMS switch.

Through literature review [11–14] it has been observed that the possible materials used for bridge material for fixed-fixed beam capacitive shunt switch are gold, aluminum, platinum, molybdenum, copper, nickel, alumina, and silicon nitride. In this study, the key material indices considered for MEMS capacitive switch are Young's modulus, electrical resistivity, Poisson's ratio, thermal expansion coefficient, and thermal conductivity.

The purpose of this paper is to present the results of our study on material selection issue. First, in Section 2, we focus on a brief description of Ashby material selection approach. Section 3 discusses RF-MEMS switch bridge design and performance. Section 4 discusses the performance indices required in Ashby's approach. Section 5 explains results and discussion, and finally Section 6 concludes our study by giving the conclusion of the paper.

2. ASHBY MATERIAL SELECTION APPROACH

Ashby material selection strategy is used to characterize the appropriate material for desired performance depending upon its attributes (mechanical, electrical and thermal properties of the material). The steps involved in Ashby material selection are explained by Reddy and Gupta [15]. Material selection using performance indices is best achieved by plotting one material property on each axis of material selection chart [10]. The design of a component is specified by three parameters: functional requirements, geometrical properties, and material properties. The performance of an element is described by

$$P = f[(F\,G\,M)] \tag{1}$$

Here P describes the performance of the element, and f describes the functions of the functional requirement (F), geometrical properties (G) and material properties (M), respectively.

$$P = f_1(F)f_2(G)f_3(M) \tag{2}$$

Here element performance is described by individual functions of F, G and M. So the optimum subset of material can be identified by single functional requirement. For F and G, the performance can be optimized by optimizing the appropriate material indices. This optimization is conventionally performed using graphs with axes corresponding to different material indices or material properties [15].

3. RF-MEMS SWITCH BRIDGE DESIGN AND PERFORMANCE

The most common design of switch is fixed-fixed beam capacitive shunt switch. This switch beam is suspended at a height of g above the dielectric layer on the transmission line. A suspended micro-machined bridge structure, with a length L, width w, thickness t, and an actuation electrode of a length W as shown in Figure 1(a), can be approximately modeled as a fixed-fixed beam with these parameters as illustrated in Figure 1(b).

The switch operates as a digitally tunable capacitor with two states. When a voltage is applied between a switch beam and the pull-down electrode, an electrostatic force is induced on the beam. The beam over the electrode acts as a parallel plate capacitor. When

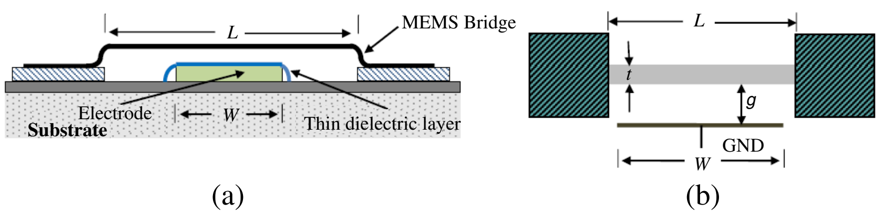

Figure 1. (a) Sketch of a typical RF-MEMS bridge structure. (b) Sketch of a fixed-fixed beam model used to model the structure shown in Figure 2.

the switch beam is in upstate, the transmission line experiences a small capacitance, and when it is in down state, transmission line experiences a high capacitance [12].

But these switches have their limitations however. By using a proper material in the switch beam, these limitations can be removed, and device performance can be optimized.

4. ASHBY APPROACH TO THE BRIDGE MATERIAL SELECTION

The various material properties, such as Young's modulus (E), Poisson's ratio (ν), thermal expansion coefficient (α), thermal conductivity (K), and electrical resistivity (ρ), for MEMS bridge material have been chosen for Ashby approach. Table 1 shows the material properties related to the considered materials.

Table 1. Material Properties of the considered materials [17].

Material	**Young's Modulus E (GPa)**	**Poisson's Ratio (ν)**	**Electrical Resistivity ρ (Ω-m)**
Aluminum	69	0.33	2.90×10^{-8}
Gold	77	0.42	2.35×10^{-8}
Copper	115	0.33	1.72×10^{-8}
Platinum	171	0.39	10.60×10^{-8}
Nickel	204	0.31	9.50×10^{-8}
Silicon Nitride	304	0.3	$> 10^{12}$
Molybdenum	320	0.32	5.20×10^{-8}
Aluminum oxide	380	0.22	$> 10^{12}$
Material	**Thermal Conductivity K (W/m-K)**	**Thermal Expansion Coefficient α (10^{-6} ($^\circ$C)$^{-1}$)**	-
Aluminum	222	23.6	-
Gold	388	14.2	-
Copper	315	17	-
Platinum	71	9.1	-
Nickel	70	13.3	-
Silicon Nitride	29	2.7	-
Molybdenum	142	4.9	-
Aluminum oxide	39	7.4	-

Performance Indices:

(i) Pull-in voltage

Pull-in voltage is an important parameter for RF-MEMS switches. The mechanical design of MEMS switch consists of two parallel plates. At the time of actuation, the sufficient pull-in voltage is applied between the electrode and MEMS Bridge. This pull-in voltage is given by [16].

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

Here k is spring constant; ε_0 is permittivity of free space; W, w, and g are the length of the pull down electrode, width of beam, and gap between the electrode and beam, respectively.

From Equation (3), it is clear that the pull-in voltage can be reduced in three different ways: first by decreasing the height between the bridge and the electrode, secondly by increasing the area of the bridge and lastly diminishing the bridge structure with low spring constant. Out of these possibilities, the third possibility depends on bridge material parameter, so this is an appropriate way to minimize the pull-in voltage.

Now spring constant depends on Young's modulus of bridge material, which is given as [16].

$$k = 4E\left(\frac{t}{L}\right)^3 \tag{4}$$

where E is the Young's modulus, and t and L are the thickness and length of the beam, respectively. So from Equations (3) and (4) it is clear that pull-in voltage is directly proportional to the square root of the Young's modulus. So, the first material index (MI) related to the pull-in voltage is

$$MI_1 = \sqrt{E} \tag{5}$$

Spring constant also depends on the thermal residual stress and Poisson's ratio of the beam material which is given by [13].

$$k = \frac{8\gamma(1-\nu)(\sigma_0 - \Delta\sigma)tw}{L} \tag{6}$$

where γ is geometric factor; σ_0 is thermal residual stress at reference temperature; ν is Poisson's ratio; $\Delta\sigma$ is the change in thermal residual stress. So from Equations (3) and (6) it is clear that the second material index related to the pull-in voltage is

$$MI_2 = \nu \tag{7}$$

Now temperature variation results in the change in thermal residual stress of the beam which is given by [13].

$$\Delta\sigma = E\Delta\alpha\Delta T \tag{8}$$

where $\Delta\alpha$ is the difference in thermal expansion coefficient between the beam and substrate, and ΔT is the temperature change of the beam. Equation (8) shows that thermal residual stress is directly proportional to the thermal expansion coefficient. From Equations (6) and (8), we can infer that a higher value of thermal expansion coefficient provides a lower spring constant. So the third material index related to the pull-in voltage is

$$MI_3 = \alpha \tag{9}$$

Therefore, the first performance indices related to the pull-in voltage is;

$$PI_1 = f(E, \nu, \alpha) \tag{10}$$

(ii) RF Loss

Second performance index is related to the RF loss which can be reduced significantly by choosing suitable bridge material having good conductivity. RF power dissipated in the beam is given by [16].

$$P_{loss} = I^2 \cdot R \tag{11}$$

where I is the current in the switch beam, and R is the beam resistance which is given by [13]

$$R = \frac{\beta\rho L}{4tw} \tag{12}$$

where β is a constant and related to the current crowding into the membrane, and ρ is electrical resistivity of the beam. From the Equations (11) and (12), we can conclude that power loss in beam structure is directly proportional to the electrical resistivity of the bridge material. Therefore, the fourth material index related to the power loss is

$$MI_4 = \rho \tag{13}$$

Therefore, the second performance index related to the RF loss in beam structure is

$$PI_2 = f(\rho) \tag{14}$$

(iii) Thermal residual stress

For large RF signals, the MEMS bridge experiences the temperature change due to self heating which further causes the change in thermal residual stress which is given by [13].

$$\Delta\sigma = E\Delta\alpha P_{loss} R_{TH} \tag{15}$$

where P_{loss} is RF power loss, and R_{TH} is thermal resistance which is given as [13].

$$R_{TH} = \frac{\varepsilon L}{4Ktw} \tag{16}$$

where K is thermal conductivity, and ε is non-uniform temperature distribution. The product of electrical and thermal resistances of the bridge material $(R \cdot R_{TH})$ produces the self heating in the MEMS bridge. From Equations (16) and (11) we therefore conclude that the fifth material index is;

$$MI_5 = R_{TH} R = \frac{1}{K} \cdot \rho \tag{17}$$

Therefore, third performance index related to the thermal residual stress in beam structure is

$$PI_3 = f\left(\frac{1}{K} \cdot \rho\right) \tag{18}$$

5. RESULTS AND DISCUSSION

The optimal performance of MEMS bridge material varies with different performance indices. The material selection graphs are used to select the optimal candidate for MEMS bridge material and also used to identify the trade-offs between the conflicting material indices.

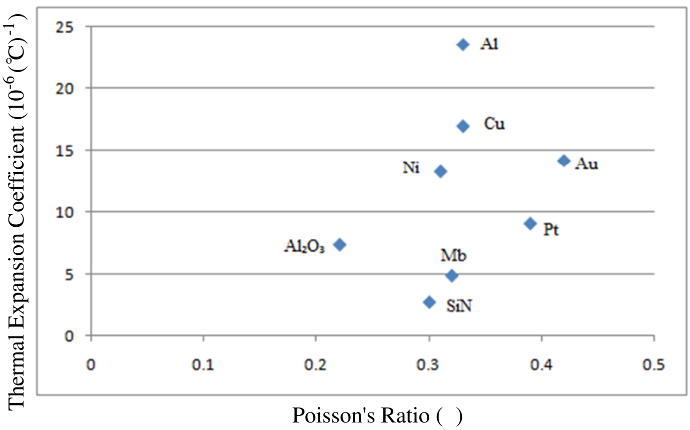

Figure 2. Thermal expansion coefficient (α) versus Poisson's ratio (ν) for considered materials.

Figure 2 shows the variation between thermal expansion coefficient (α) and Poisson's ratio (ν) for all possible bridge materials. It is considered that a material with high values of Poisson's ratio (ν) and thermal expansion coefficient (α) is suitable to minimize the pull-in voltage. From the plot, it is observed that there is a trade-off between gold and aluminum. Because gold shows a higher value of ν with a lower value of α, but aluminum shows a higher value of α with a lower value of ν.

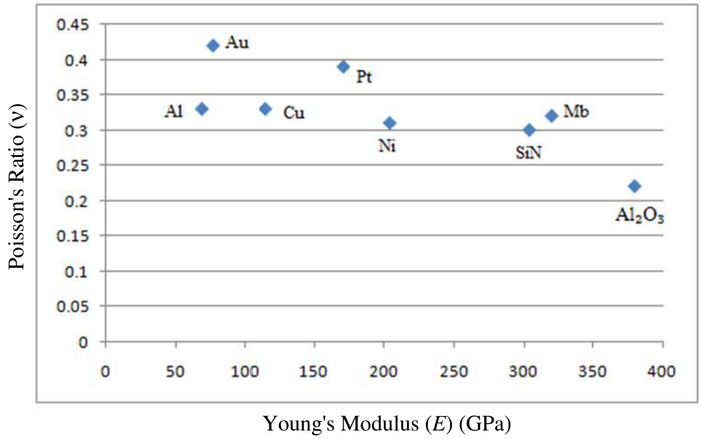

Figure 3. Poisson's ratio (ν) versus Young's modulus (E) for considered materials.

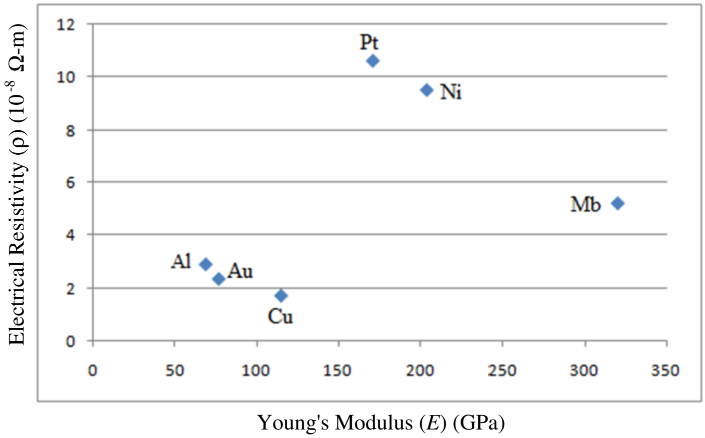

Figure 4. Electrical resistivity (ρ) versus Young's modulus (E) for considered materials.

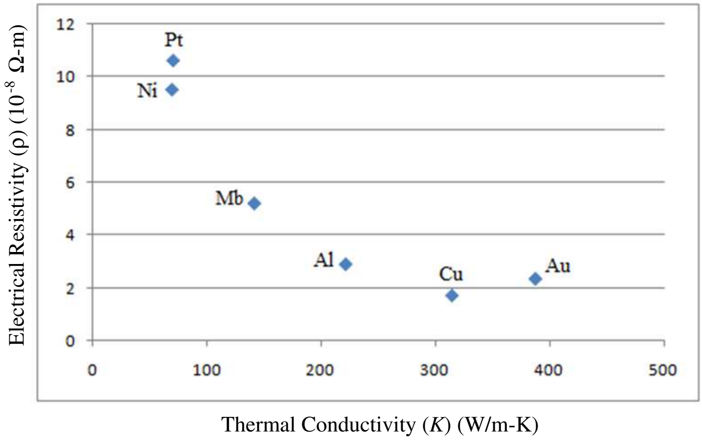

Figure 5. Electrical resistivity (ρ) thermal conductivity (K) for considered materials.

Figure 3 shows the plot of Poisson's ratio (ν) versus Young's modulus (E). From Equations (5) and (7), we can suggest a material with a low value of Young's modulus (E) and a high value of Poisson's ratio (ν) reduces the pull-in voltage. From the plot we can conclude that gold and aluminum are the best materials to reduce the pull-in voltage.

Figure 4 describes the plot of electrical resistivity (ρ) versus Young's modulus (E) to reduce the RF loss for considered materials. Here we found that aluminum and gold show the minimum value of Young's modulus (E) and electrical resistivity (ρ) to provide the minimum RF loss.

Figure 5 shows the plot of electrical resistivity (ρ) versus thermal conductivity (K). From the plot we can suggest that gold and copper followed by aluminum provide the minimum thermal residual stress for a low value of electrical resistivity (ρ) and a high value of thermal conductivity (K) of the bridge material.

So in order to fulfill the desirable criteria of bridge material for RF-MEMS switches, the results show that aluminum (Al) is the best possible material out of all the materials taken into consideration. Gold also shows the desired property but is a very expensive material. In order to validate the outcome of this paper, the results were compared with experimental results of various researchers [18–20] and found confirmation for this study.

6. CONCLUSION

Material selection for RF-MEMS capacitive shunt switch with the help of Ashby approach has been discussed in this paper. Three performance indices based on different material indices to enhance the performance of the MEMS Bridge were optimized. Based on material selection charts, we observed that gold and aluminum are the appropriate materials to be used as bridge material in RF-MEMS switch to obtain the desire properties to give the best performance of the switch in reconfigurable antenna. As gold is very expensive material as compared to aluminum, so if we have to go for mass production of switch, we propose aluminum as the best material to be used as bridge material for RF-MEMS switch.

REFERENCES

1. Cetiner, B. A., G. R. Crusats, L. Jofre, and N. Bıyıklı, "RF MEMS integrated frequency reconfigurable annular slot antenna," *IEEE Trans. Antennas Propag.*, Vol. 58, No. 3, 626–632, 2010.
2. Jung, C. W., M. J. Lee, and F. D. Flaviis, "Reconfigurable dual-band antenna with high frequency ratio (1.6 : 1) using MEMS switches," *Electronics Letters*, Vol. 44, No. 2, 76–77, 2008.
3. Cheng, S., P. Rantakari, R. Malmqvist, C. Samuelsson, T. Vaha-Heikkila, A. Rydberg, and J. Varis, "Switched beam antenna based on RF MEMS SPDT switch on quartz substrate," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 383–386, 2009.
4. Cheng, C. C., B. Lakshminarayanan, and A. Abbaspour-Tamijani, "A programmable lens-array antenna with monolithically integrated MEMS switches," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 8, 1874–1884, 2009.
5. Jung, C. W. and M. J. Lee, "Reconfigurable scan-beam single-arm spiral antenna integrated with RF-MEMS switches," *IEEE Trans. Antennas Propag.*, Vol. 54, No. 2, 455–463, 2006.
6. Srikar, V. T. and S. M. Spearing, "Material selection for microfabricated electrostatic actuators," *Sens Actuators A*, Vol. 102, 279–285, 2003.
7. Rao, R. V., "A material selection model using graph theory and matrix approach," *Materials Science and Engineering*, Vol. 431, 248–255, 2006.
8. Roth, R., F. Field, and J. Clark, "Multi-attribute utility analysis," *Journal of Computer-Aided Materials Design*, Vol. 1, No. 3, 325–342, 1994.

9. Guisbiers, G., E. Herth, B. Legrand, N. Rolland, T. Lasri, and L. Buchaillot, "Materials selection procedure for RF-MEMS," *Microelectronic Engineering*, Vol. 87, 1792–1795, 2010.
10. Ashby, M. F., *Materials Selection in Mechanical Design*, 2nd Edition, Butterworth-Heinemann, Oxford, UK, 1999.
11. Puyal, V., D. Dragomirescu, C. Villeneuve, J. Ruan, P. Pons, and R. Plana, "Frequency scalable model for MEMS capacitive shunt switches at millimeter-wave frequencies," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 11, 2824–2833, 2009.
12. Ekkels, P., X. Rottenberg, R. Puers, and H. A. C. Tilmans, "Evaluation of platinum as a structural thin film material for RF-MEMS devices," *J. Micromech. Microeng.*, Vol. 19, 065010–065018, 2009.
13. Palego, C., J. Deng, Z. Peng, S. Halder, J. C. M. Hwang, D. I. Forehand, D. Scarbrough, C. L. Goldsmith, I. Johnston, S. K. Sampath, and A. Datta, "Robustness of RF MEMS capacitive switches with molybdenum membranes," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 12, 3262–3269, 2009.
14. Alam, A. H. M. Z., M. R. Islam, S. Khan, N. B. Mohd Sahar, and N. B. Zamani, "Effects of MEMS material on designing a multiband reconfigurable antenna," *Iranian Journal Of Electrical and Computer Engineering*, Vol. 8, No. 2, 112–118, 2009.
15. Reddy, G. P. and N. Gupta, "Material selection for microelectronic heat sinks: An application of the Ashby approach," *Materials and Design*, Vol. 31, 113–117, 2010.
16. Rebeiz, G. M., *RF MEMS: Theory, Design, and Technology*, 3rd Edition, John Wiley & Sons Inc., New Jersey, 2003.
17. Callister, W. D., *Material Science and Engineering: An Introduction*, 7th edition, John Wiley & Sons Inc., New York, 2007.
18. Kingsley, N., D. E. Anagnostou, M. Tentzeris, and J. Papapolymerou, "RF MEMS sequentially reconfigurable sierpinski antenna on a flexible organic substrate with novel DC-biasing technique," *J. Microelectromech. Syst.*, Vol. 16, No. 5, 1185–1192, 2007.
19. Reines, I., B. Pillans, and G. M. Rebeiz, "Thin-film aluminum RF MEMS switched capacitors with stress tolerance and temperature stability," *J. Microelectromech. Syst.*, Vol. 20, No. 1, 193–202, 2011.
20. Dai, C.-L. and J.-H. Chen, "Low voltage actuated RF micromechanical switches fabricated using CMOS-MEMS technique," *Microsyst. Technol.*, Vol. 12, 1143–1151, 2006.