

An investigation of dielectric material selection of RF-MEMS switches using Ashby's methodology for RF applications

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Received: 17 July 2017 / Accepted: 18 August 2017 / Published online: 2 September 2017
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Abstract This paper presents a dielectric material selection methodology for RF-MEMS switch used for radio frequency applications. Here Ashby's material selection approach is used to optimize the performance indices of RF-MEMS switch such as dielectric charging, stability, hold down voltage and RF performance. In this work, dielectric constant (ϵ_r), electrical resistivity (ρ), thermal conductivity (λ), thermal expansion coefficient (α), Young's Modulus (E) are chosen as material indices of dielectric layer in RF-MEMS switch to evaluate the various performance indices. The Ashby's material selection charts shows that Al_2O_3 and SiN are the best suitable material for dielectric layer in RF-MEMS switches to exhibit improved performance for radio frequency applications.

1 Introduction

With immense growth in the field of modern satellite communication and radar communication, the demand for reconfigurable communication devices is always essential. Therefore, the reconfigurable antennas (RA) have received significant attention in satellite communication because a single RA is capable of altering its radiation pattern characteristics as per different geographical coverage. Recent advancements in MEMS based RF switches offer less mass, reduced size, improved RF performance (insertion loss and isolation) at GHz frequencies and low RF power

handling capabilities (Yao et al. 1999; Jung and Lee 2006; Jung et al. 2008; Vinoy and Vardan 2001). These MEMS based RF switches are widely used in satellite RA to change their radiation pattern coverage area by changing its geometrical structure for various frequency bands. Satellite-based RA are generally developed with RF-MEMS capacitive switch based fed-networks due to their low insertion loss and low power requirements as compared to semiconductor switches (PIN diode & FET) (Muldivin and Rebeiz 2000).

RF-MEMS capacitive contact switches are most critical component in micro-electromechanical systems (MEMS) devices for wireless applications. A RF-MEMS switch utilizes mechanical movement of switch beam (MEMS bridge) to attain an open or short circuit with transmission line (Cetiner et al. 2010). When the switch beam is in up-state, the CPW central conductor and switch beam creates small capacitance, thereafter an applied RF signal transmitted from one end to the other side of CPW. However, the actuation voltage is applied on pull-down electrode, the MEMS bridge touches the dielectric layer and RF signal in GHz range blocked for further transmission (Jung and Lee 2006; Jung et al. 2008). Therefore the MEMS-bridge is touched with dielectric layer having high dielectric constant (ϵ_r) and enables high capacitance to the ground (Sharma and Gupta 2012). The RF-MEMS switch performance significantly degraded due to less down-state capacitance, when MEMS bridge and dielectric layer are not perfectly smooth. Several researchers have proposed the use of high dielectric-constant materials to gain a high capacitance ratio with lower insertion loss and return loss in down state position (Rebeiz 2003). Vinoy and Vardan (2001) described a RF MEMS switch based pattern reconfigurable fractal antenna design, and concluded that thin dielectric layer of BST has impetus importance on

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isolation in on state and insertion loss in off state. A detailed survey of different types of RF MEMS switches based reconfigurable antenna have been made in various articles, which indicates that these RF-MEMS switches have slower response, limited RF performance and reliability due to their dielectric charging mechanism. Papaioannou (2010) described that dielectric material of capacitive RF-MEMS switches increases the pull-out voltage, which leads to stiction and device failure. Sharma and Gupta (2012) described the various RF MEMS switch design parameters, which improves the switch performance, and these design parameters ultimately improves the RA performance for beam scanning and pattern reconfigurable antenna.

However, the major challenging part of RF-MEMS switch design is choosing an appropriate dielectric material for pattern reconfigurable antenna application (Sharma and Gupta 2012; Rebeiz 2003; Papaioannou 2010). Several material selection approaches have been implemented in the past, the methodology for choosing the dielectric material for RF-MEMS switches especially for reconfigurable antenna has not implemented. Ashby provides a comprehensive material selection strategy with less computation. So the Ashby approach is utilized in this work to prefer appropriate dielectric layer material utilized for RF-MEMS switch (Ashby 1999).

In this research work the possible dielectric materials utilized as dielectric layer in fixed–fixed beam RF-MEMS capacitive shunt switch are SiO₂, SiN, Al₂O₃, AlN, ZrO₂, HfO₂, TiO₂, BST, Ta₂O₅ (Muldavine and Rebeiz 2000; Cetiner et al. 2010; Rebeiz 2003; Papandreou et al. 2008). Here, the basic dielectric material indices such as dielectric constant, Young's modulus, electrical resistivity, thermal conductivity, thermal expansion coefficient are considered for Ashby's approach.

The main objective of this paper is to show the outcomes of our research on dielectric layer material selection process. This paper is discussed as follows: The Ashby material selection approach is described in Sect. 2. The RF-MEMS switch design and performance are explained in Sect. 3. Section 4 describes the performance indices required for Ashby's approach. Results and discussion are explained in Sect. 5, and at last Sect. 6 concludes the study of dielectric layer material selection.

2 Ashby material selection approach

The Ashby material selection strategy suggests how to characterize the appropriate material for desired performance depending upon their attributes (mechanical, electrical and thermal properties of the material). A design demands a certain profile of these attributes. The

identification and short listing of these attribute profile will be done by screening and ranking (Ashby 1999).

Ashby material selection approach involves five steps, as illustrated in Fig. 1. In the first step of the design requirement for a structural component will be derived based on function, objectives and constraints. The next step of Ashby methodology shows that the immense wide choice is narrowed, first by applying property limits which screen out the material which cannot meet the design requirements. Further narrowing is achieved by ranking the candidate based on their ability to provide best performance. Then the detailed supporting information for each shortlisted candidate provides the final choice of material (Parate and Gupta 2011). Material indices a combination of material properties which maximize the performance of a component for a given requirement. These material indices are derived from the design requirement for a device through an analysis of function, objectives and constraints. A performance index is group of material properties which governs some aspect of the performance of a component. A material selection using performance indices is best achieved by plotting one material property on each axis of material selection chart (Reddy and Gupta 2010). The design properties of a device can be considered in mathematical model to define

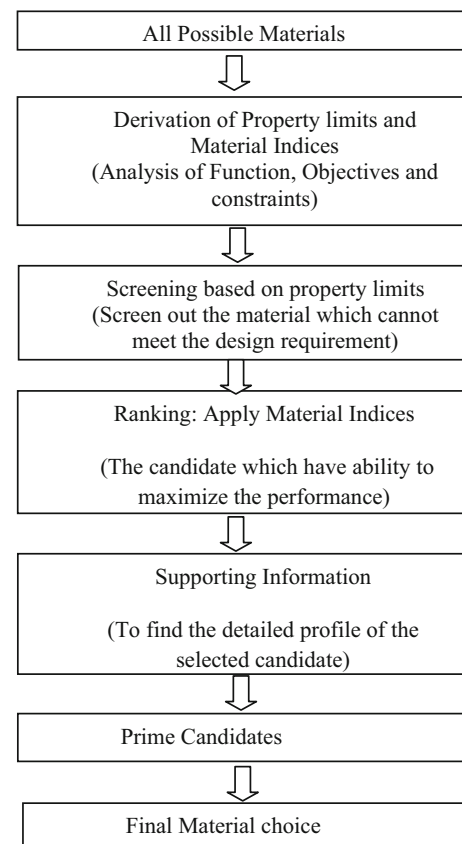


Fig. 1 Material selection chart

the performance of considered material. Here the performance of device is expressed through functional requirements, geometric properties and material indices. The performance of device is described by

$$P = f[(FGM)] \tag{1}$$

Here P expresses the optimized performance of a device and f shows the function of the functional requirement (F), geometrical properties (G) and material indices (M) respectively. The device performance may be defined in separate function of F , G , and M as follows.

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

Therefore the device performance may be enhanced for all functional requirements (F) and geometrical properties (G) through optimizing the appropriate material indices by using various plots with axis corresponds to different material indices (Reddy and Gupta 2010). Here it is required to identify important key attributes of dielectric layer material, used in RF-MEMS switch. In this investigation only functional requirements are considered for various dielectric material properties (indices). Here the device performance is described by

$$P = f_1(F)f_2(M) \tag{3}$$

In this study following attributes have been considered for dielectric layer material.

- Functional requirements $f_1(F)$: Hold down voltage (V_h), dielectric charging, dielectric stability, RF performance.
- Material Indices $f_2(M)$: dielectric constant (ϵ_r), electrical resistivity (ρ), thermal conductivity (λ), thermal expansion coefficient (α), Young’s Modulus (E)

3 RF-MEMS switch design and performance

RF-MEMS capacitive switch consists a thin metal membrane “bridge” suspended over the center conductor of a coplanar waveguide (CPW) and fixed at two ends to the ground conductors of the CPW line as shown in Fig. 2a, b.

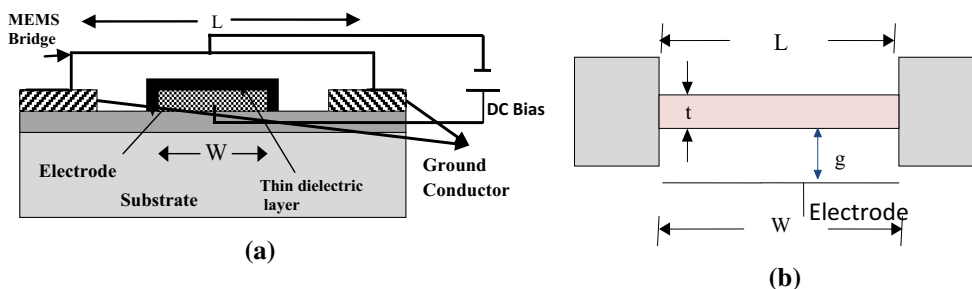


Fig. 2 a Sketch of a typical RF-MEMS design with DC bias. b Sketch of a fixed–fixed capacitive beam model

A dielectric layer is used to separate dc actuation voltage of the switch to that of CPW center conductor. When the switch membrane is in up-state, the switch presents small capacitance, and when it is in down-state due to the applied actuation voltage, the switch experiences a high capacitance (Yao et al. 1999; Rebeiz 2003).

Here, the major limitations of MEMS switch is charging of dielectric layer during the on-state, thereafter the MEMS bridge get sticks on the pull down electrode. This dielectric charging arises due to the presence of dielectric layer, which ultimately increases the pull out voltages thus leads to stiction, device failure (reliability) and switch lifetime. However, by choosing an appropriate dielectric layer material the above mentioned limitations can be overcome in the RF-MEMS switch. So that performance of RF-MEMS switch can be optimized and improved with better RF characteristics.

4 Ashby approach to the dielectric material selection

The various dielectric layer material properties of RF MEMS switches, such as dielectric constant (ϵ_r), electrical resistivity (ρ), thermal conductivity (λ), thermal expansion coefficient (α), Young’s Modulus (E) have been chosen for Ashby’s approach. The dielectric material properties related to the considered dielectric materials are shown in Table 1.

4.1 Performance indices

4.1.1 Hold-down voltage

The capacitive RF-MEMS switch consists of pull-down electrode and MEMS bridge, which acts as parallel plate capacitor with a dielectric material. A low hold down voltage is required to maintain the MEMS bridge in down state position, when the mechanical restoration force is smaller than electrostatic force. This hold-down voltage is given as (Muldavin and Rebeiz 2000)

Table 1 Dielectric material properties of the considered materials (Yao et al. 1999; Rebeiz 2003; Papaioannou 2010; Papandreou et al. 2008; Gallot-Lavallee 2013; Smith 2011; Nirmal et al. 2013; Luo et al. 2006; Kar 2013)

Material code	Dielectric material	Dielectric constant (ϵ_r)	Electrical resistivity (ρ) ($\Omega - m$)	Thermal conductivity λ (W/m-K)	Thermal expansion coefficient (α) (10^{-6} ($^{\circ}\text{C} - 1$))	Young's modulus E (GPa)
A	SiO ₂	3.9	1×10^{14}	1.4	5.6	71
B	SiN	7	2×10^{14}	29	3	304
C	Al ₂ O ₃	10	1.4×10^{14}	39	7.4	380
D	AlN	9.14	1.1×10^{14}	16	7.7	330
E	HfO ₂	25	9×10^{13}	1.1	6	57
F	Ta ₂ O ₅	22	1×10^7	8	6.3	140
G	TiO ₂	80	1×10^{12}	11.7	9	230
H	BST	800	10	12	9.4	1000
I	ZrO ₂	25	1×10^{11}	3.9	9.2	200

$$V_h = \sqrt{\frac{2K_c}{\epsilon\epsilon_0 A} (g_0 - g) \left(g + \left(\frac{t_d}{\epsilon_r} \right) \right)^2} \quad (4)$$

Here K_c is equivalent spring constant of the MEMS bridge; g_0 is the gap between MEMS bridge and dielectric layer; g is the height of the beam above electrode, ϵ accounts for the reduction in the parallel-plate capacitance due to the roughness of the metal-to-dielectric interface; ϵ_0 , t_d , ϵ_r , W and w are the permittivity of free space, thickness of the dielectric layer, relative dielectric constant of the dielectric layer, length of pull down electrode and width of MEMS bridge respectively.

From Eq. (4), it is clear that the hold-down voltage depends on dielectric material properties. Therefore, the hold-down voltage can be reduced by a dielectric material with higher dielectric constant.

Here it is observed that hold-down voltage is inversely proportional to dielectric constant of the dielectric material. So, the first material index (MI) related to the hold-down voltage can be given as

$$MI_1 = \frac{1}{\sqrt{\epsilon_r}} \quad (5)$$

Therefore, the first performance index related to the hold-down voltage can be given as

$$PI_1 = f\left(\frac{1}{\epsilon_r}\right) \quad (6)$$

4.1.2 Dielectric charging

Second performance index is related to the charging of the dielectric material. This dielectric charging mechanism can be minimized significantly by choosing suitable dielectric layer material having good electrical resistivity. After

removing the actuation voltage, the decay of polarization can be given as (Papandreou et al. 2008)

$$P(t) = P_p \cdot \exp\left(\frac{-t}{\tau}\right) \quad (7)$$

where P_p is steady state polarization, t is the time duration of electrical discharging and τ is relaxation time constant for electrical discharge which is given by (Gallot-Lavallee 2013).

$$\tau = \epsilon_r \rho \quad (8)$$

where ρ and ϵ_r are the electrical resistivity and dielectric constant of the dielectric material respectively. From the Eqs. (7) and (8), we can conclude that dielectric charging can be limited through a higher rate of decay of polarization after removing the DC bias. Here it is clear that a dielectric material with high electrical resistivity and dielectric constant results in less dielectric charging. So, the second material index is given by

$$MI_2 = \rho \times \epsilon_r \quad (9)$$

Therefore, the second performance index related to the dielectric charging can be given as

$$PI_2 = f(\rho, \epsilon_r) \quad (10)$$

4.1.3 Stability

Third performance index is related to the stability of dielectric layer material, ultimately it improves the reliability of the RF-MEMS switch with longer switch operation. The dielectric layer stability can be characterized through dielectric rigidity and dielectric breakdown. The dielectric rigidity can be given as follows (Rebeiz 2003)

$$G = \frac{E}{2(1 + \nu)} \quad (11)$$

where E is young’s modulus and ν is Poisson’s ratio of dielectric material. From the Eq. (11), it is observed that dielectric rigidity is directly proportional to young’s modulus of dielectric material. From Eq. (11), we can infer that a dielectric layer material with higher value of young’s modulus provides a higher dielectric rigidity. So third material index can be given as

$$MI_3 = (E) \tag{12}$$

The stability of dielectric layer is also significantly affected due to the thermal stress of the layer. The thermal stress is that stress, which occurs in a dielectric layer due to its temperature change through self-heating when DC bias is applied for longer duration. Thermal stress in dielectric layer can be given as (Sharma and Gupta 2012)

$$\Delta\sigma = E \alpha \Delta T \tag{13}$$

where α is the thermal expansion coefficient and ΔT is the temperature change of the dielectric material. However the expansion and contraction of dielectric layer can be prevented through the thermal expansion coefficient (α) of the dielectric layer material. From Eq. (13), we can infer that a lower thermal expansion coefficient provides the less thermal stress in dielectric layer. So fourth material index can be given as

$$MI_4 = (\alpha) \tag{14}$$

From Eqs. (11) and (13) it is clear that for lower value of α and higher value of young’s modulus (E) must be significant (neither to low nor to high) to provide better dielectric stability (rigidity) and less thermal stress.

In down state position of MEMS bridge, the Pull-down electrode and MEMS bridge exhibit the electrical coupling and stray capacitance. Therefore the dielectric layer should have good thermal conductivity (λ) to drain away the heat to improve the switch life time. So fifth material index can be given as

$$MI_5 = (\lambda) \tag{15}$$

Therefore, the third performance indices related to dielectric layer stability can be given as

$$PI_3 = f(E, \alpha, \lambda) \tag{16}$$

4.1.4 RF Performance

RF-MEMS switch radio frequency performance is characterized by electrical parameters (C–L–R) of RF-MEMS switch through S-parameters in up and down state of MEMS bridge. These S-parameters S_{11} and S_{21} represents the return loss and insertion loss in down state position with return loss and isolation in up-state position respectively. In RF-MEMS switch inductance is majorly depends

on the current distribution on the portion of the bridge over CPW gap not depends on the portion of the bridge over the central conductor of CPW. Hence the dielectric layer situated over the pull down electrode does not play any role in inductance of the RF-MEMS switch. Similarly the resistance of the RF-MEMS switch is majorly contributed through the bridge resistance (Rebeiz 2003; Sharma and Gupta 2015). Therefore out of these electrical parameters only capacitance in down state plays an important role for dielectric layer material in RF-MEMS switch. These S-parameters S_{11} and S_{21} in down state position can be improved sufficiently through down-state capacitance (C_d) by choosing suitable dielectric material. The MEMS switch down-state capacitance can be given as (Sharma and Gupta 2014)

$$C_d = \frac{\epsilon_0 \epsilon_r A}{t_d} \tag{17}$$

where ϵ_0 is the permittivity of free space, A is capacitive area between MEMS bridge and pull down electrode and ϵ_r , t_d are the dielectric constant and dielectric layer thickness of thin dielectric layer. The use of high dielectric constant material improves down-state capacitance which further improves capacitance ratio. Therefore, the high capacitance ratio allows the fabrication of very small RF-MEMS capacitive shunt switches with high isolation and less insertion loss (Sharma and Gupta 2015)

Therefore, sixth material index related to RF Performance of dielectric material can be given as

$$MI_6 = \epsilon_r \tag{18}$$

Therefore, the fourth performance index related to the RF performance in dielectric material can be given as

$$PI_4 = f(\epsilon_r) \tag{19}$$

5 Results and discussion

The optimal performance of dielectric layer varies with different material indices. The various material indices are plotted with respect to each other to optimize different performance indices. These material selection plots are used to identify the best candidate for dielectric layer material in RF-MEMS switches and also used to find the trade-offs between the contrary material indices.

Figure 3 shows the plot between electrical resistivity (ρ) and thermal expansion coefficient (α) for all possible dielectric materials. It is considered that a dielectric material with high value of electrical resistivity and low value of thermal expansion coefficient is suitable to minimize the dielectric charging and stability. From the plot it is observed that material B followed by A shows the high

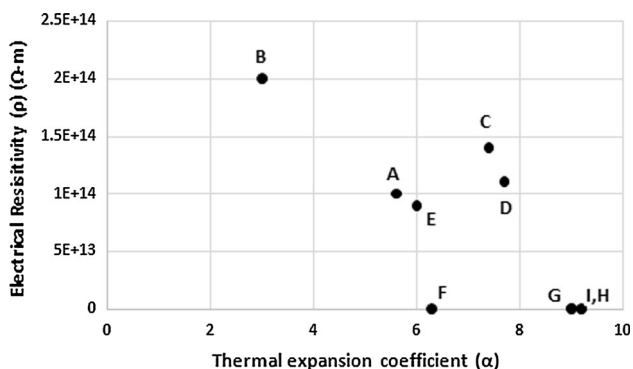


Fig. 3 Electrical resistivity (ρ) versus thermal expansion coefficient (α) for considered materials

value for electrical resistivity ($\gg 10^{14}$) with least value of thermal expansion coefficient as compared to other considered materials. Hence material B followed by A can be better choice to improve dielectric layer charging and stability of RF-MEMs switch.

Figure 4 shows the variation of Young’s Modulus (E) with respect to thermal conductivity (λ). From Sect. 4.1.3 it is concluded that a dielectric material with high value of Young’s Modulus (E) and thermal conductivity (λ) improves the dielectric stability and switch life time with improved switching speed. From the plot it is observed that there is trade-off between the material H and C followed by B. Because material H shows a higher value of Young’s Modulus (E) with lower value of thermal conductivity (λ), but material C followed by B shows a higher value of λ and lower value of E . Here material H is discarded due to low passion ratio (ν), which ultimately reduces the dielectric stability given in Eq. 10 with extremely low value of λ as compared to material C and B. Therefore it can be concluded that material C followed by B are best suitable material to improve the switch stability for longer lifetime.

Figure 5 describes the plot of Young’s modulus (E) versus thermal expansion coefficient (α) to improve the

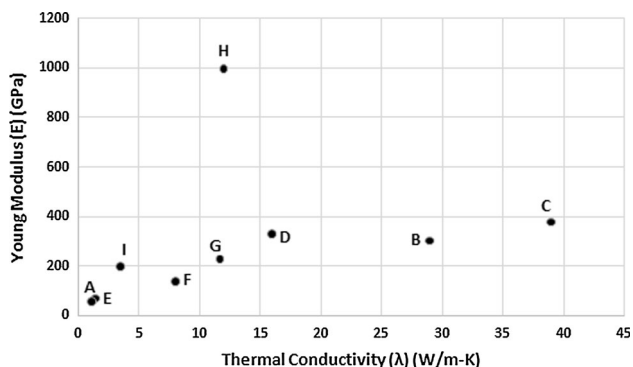


Fig. 4 Young’s modulus (E) versus thermal conductivity (λ) for considered materials

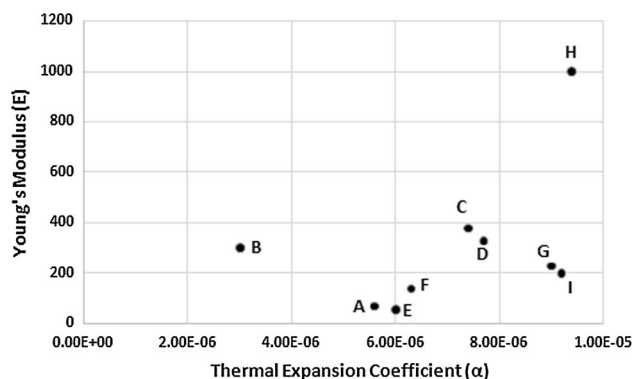


Fig. 5 Young’s modulus (E) versus thermal expansion coefficient (α) for considered materials

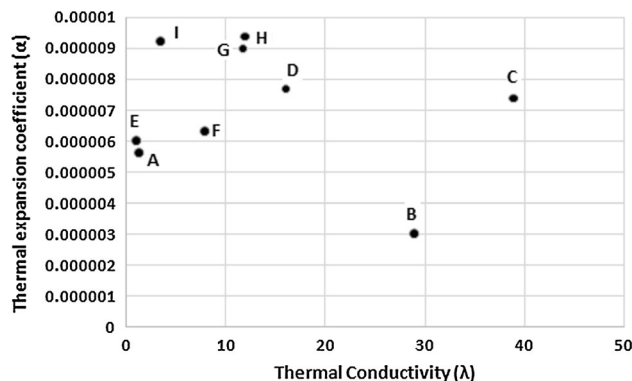


Fig. 6 Thermal expansion coefficient (α) versus thermal conductivity (λ) for considered materials

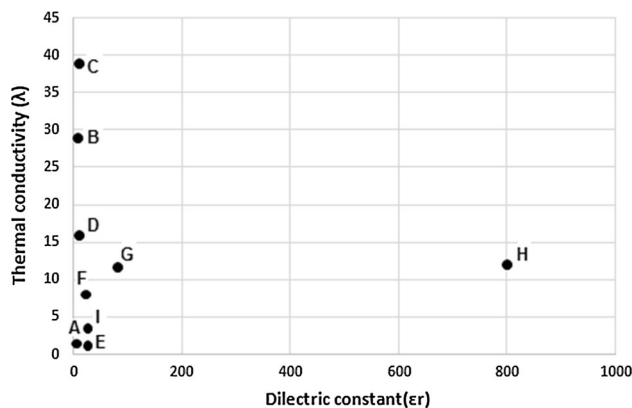


Fig. 7 Thermal conductivity (λ) versus dielectric constant (ϵ_r) for considered materials

dielectric stability. Here it is observed that material B followed by C shows low value of thermal expansion coefficient and optimum value of young’s modulus. Here other material are not considered due to their high thermal expansion coefficient or their extremely low ($\ll 100$) Young’s Modulus (E).

Figure 6 shows the plot between thermal expansion coefficient (α) and thermal conductivity (λ). This plot shows that material B followed by C are the best possible material to reduce the thermal stress and heating effect in order to improve the switch life time. Here materials B and C are considered due to better λ as compared to other considered materials.

Figure 7 shows the plot between dielectric constant (ϵ_r) and thermal conductivity (λ).

From the plot it is observed that there is a trade-off between material H and C. Because material H shows a higher value of dielectric constant with a lower value of thermal conductivity, however C shows higher value of thermal conductivity with lower value of dielectric constant. Here material H will not be suitable choice to improve RF performance due to high dielectric constant, which increases surface wave losses at higher microwave radio frequencies (Muldavin and Rebeiz 2000; Sharma and Gupta 2015).

So in order to fulfill the desirable criteria of dielectric material for RF-MEMS switches, the results shows that C (Al_2O_3) is the best possible material followed by B (SiN) of all possible material taken into consideration for four performance indices. SiN is the most suitable dielectric layer material used in RF-MEMS switches due to their low temperature deposition, which significantly improves switch life time with reduced dielectric charging for RF application. In order to validate the outcome of this study, the results are compared with experimental results of various researchers and found the confirmation of this study (Papandreou et al. 2008; Pacheco et al. 2000).

6 Conclusion

Dielectric material selection Ashby's methodology for RF-MEMS capacitive switches has been discussed in this paper. Here four performance indices based on various dielectric material indices are considered to improve the RF-MEMS switch stability and lifetime. Based on material indices selection chart, it is observed that Al_2O_3 and SiN are the best possible dielectric material for RF-MEMS switches to obtain better life time and stability with improved dielectric charging in reconfigurable antenna application.

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