



Investigation on Switching Structure Material Selection for RF-MEMS Shunt Capacitive Switches Using Ashby, TOPSIS and VIKOR

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Abstract

This paper utilizes three material selection methodologies to select the most promising material for switching structure of RF-MEMS shunt capacitive switches. The material should be selected such that RF-MEMS capacitive switches should have low pull-in voltage, low RF loss, high thermal conductivity and maximum displacement of the beam. For this purpose, the concerned material indices are as follows: low value of Young's modulus, low electrical resistivity, high thermal conductivity and high fracture strength. Following Ashby, TOPSIS and VIKOR method were used to select the best material. The results obtained from these methods show good correlation. The end results suggest that gold and copper are the most suitable materials for RF-MEMS switches.

Keywords Ashby's method · RF-MEMS · Switches · TOPSIS · VIKOR

1 Introduction

Radio Frequency Micro Electro Mechanical Systems (RF-MEMS) is a promising technology for implementing passive devices for future wireless communication systems. Among the various devices, switches have gained much attention as they can be used at many places in a wireless communication system. RF-MEMS technology based switches have low insertion loss, high isolation, less power consumption and high linearity [1–3]. This paper focuses on the shunt capacitive switches. The shunt capacitive switches have two stable states i.e., up-state and down-state as shown in Fig. 1. In up-state of the switch, power can flow from the input port to the output port, whereas down-state corresponds to the off-state of the device [1, 2]. Electrostatic actuation is mostly used for changing the state of the switch as it is compatible with the IC technology.

Optimizing the performance of the switching structure involves optimizing number of parameters like pull-in voltage, RF response (insertion loss and isolation), maximum displacement, thermal conductivity etc. As there are a number of parameters involved, material selection becomes

important. In addition, due to availability of a large number of materials, material selection methods are used in order to reduce human effort.

Material selection has been greatly improved by the development of Multiple Criteria Decision Making (MCDM) techniques. MCDM can be divided into Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making (MADM). Among the many MODM techniques the most used is Ashby's methodology [4, 5]. Ashby's method is difficult to implement given that there are multiple selection criteria present, normally more than three. Hence, the MADM techniques like Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and *Vise Kriterijumska Optimizacija Kompromisno Resenje* (VIKOR) become important in such cases. These techniques look promising [6–8]. The MADM techniques have not been extensively studied and implemented in RF-MEMS. Hence, TOPSIS and VIKOR methods have also been used in this paper. Furthermore, results obtained from these methods are compared with the well-established Ashby's methodology for the case of the MEMS based capacitive shunt switch. The properties selected for this purpose are low pull-in voltage, low RF loss, high thermal conductivity and maximum displacement of the beam structure.

The above given material selection methods are explained with the involved computational steps under Sect. 2. Section 3 discusses in brief the material properties and the

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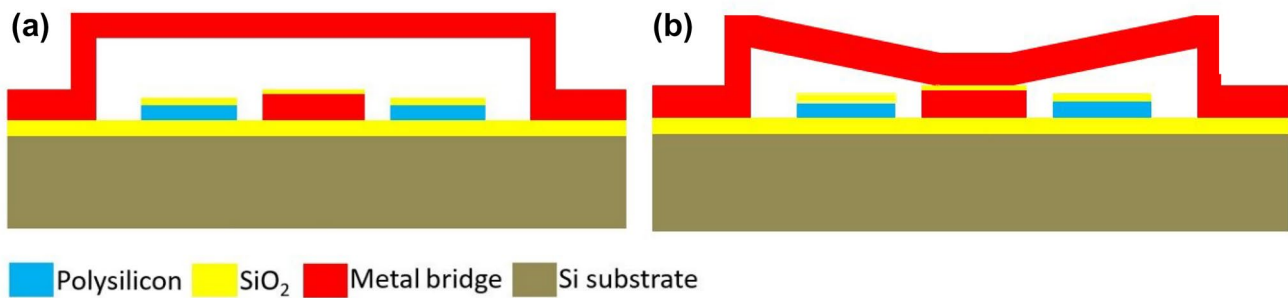


Fig. 1 Cross sectional view of a capacitive RF MEMS switch **a** up-state **b** down-state

material indices of the switching structure. Section 4 describes the material database and also presents the results obtained from Ashby's, TOPSIS and VIKOR methods. Section 5 gives the conclusion of the study.

2 Material Selection Methodologies

As discussed above, Ashby's methodology, TOPSIS method and VIKOR methods have been used for material selection in this study. Ashby's methodology uses material selection plots with material indices plotted on the axes while TOPSIS and VIKOR methods make use of decision matrix and computational formulae to get the ranking for the materials.

2.1 Ashby's Methodology

Ashby's approach is MODM approach which gives an insight into the material properties and helps in choosing the optimum material from the available pool of materials. Ashby's approach takes into account the following three points i.e., the role of constituent in the device working, objectives to be optimized and constraints which have to be fulfilled. After purpose is decided, the performance parameters (P) are chosen. The performance parameters are expressed as a function of functional necessities (F), geometrical parameters (G) and material indices (M) [4, 5]. Therefore,

$$P = f(F, G, M) \quad (1)$$

In most of the cases the Eq. (1) can be split as

$$P = f_1(F)f_2(G)f_3(M) \quad (2)$$

From the performance parameters, the material indices are chosen. The material selection charts with all the available materials are plotted and analysis is done. The material indices or material properties are plotted on the axes. Analysis mainly depends on whether optimization refers to high or low values of material indices or material properties. Ashby's method (from Eq. 2) simplifies the approach to select a material as for a given set of functional necessities (F) and

geometrical parameters (G) optimization is done only on the material indices (M). Trade-offs may arise in few of the plotted graphs. Addressing of the trade-offs is done after analysing most crucial requirement for the design. The flow chart of Ashby's procedure is shown in Fig. 2.

2.2 TOPSIS Methodology

TOPSIS methodology is one of the famous and widely preferred MADM tools. It was originally developed by Hwang and Yoon in 1981 and was later modified by Yoon in 1987. It can be implemented in many different fields [6].

In TOPSIS method first an evaluation or decision matrix is defined by the number of properties to be analysed and the number of materials. The matrix is then normalized and weights are multiplied to form the weighted normalized matrix. The weights can be given subjectively by the user or objectively derived from Analytic Hierarchy Process (AHP) entropy and other similar methods. The positive ideal solution (PIS) and negative ideal solutions (NIS) are decided for each criterion depending upon whether benefit or cost is associated with a certain criterion. The distance of each criterion from the positive ideal and negative ideal solution is calculated. Similarity matrix is then calculated upon which the materials are ranked. TOPSIS allows trade-offs between criteria and the hard elimination like in Ashby's method is eliminated. The mathematical steps in TOPSIS method are presented below:

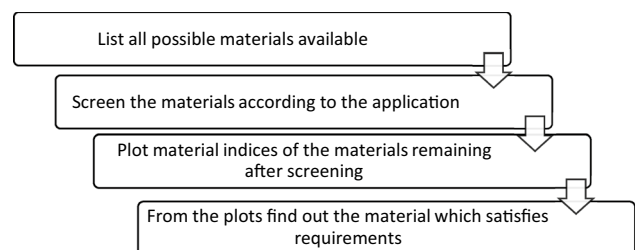


Fig. 2 Ashby's methodology

Step 1 The $m \times n$ decision matrix (X) is created consisting of m materials and n criteria.

Step 2 Construct the normalized decision matrix (R_n), where R_{nij} represents each element of the matrix.

$$R_{nij} = \frac{X_{ij}}{\sqrt{\sum_i X_{ij}^2}} \text{ for } j = 1, 2, \dots, n \tag{3}$$

Step 3 Construct the weighted normalized matrix (V) by multiplying weight w_j of a criterion to the column corresponding to the criterion, where each element of the matrix V is given by:

$$V_{ij} = W_j * R_{nij} \tag{4}$$

Step 4 From the weighted normalized matrix the positive ideal solution (A_b) and the negative ideal solution (A_w) is obtained as:

$$A_b = \{V_{1b}, V_{2b}, \dots, \dots, V_{nb}\}$$

where,

$$V_{ab} = \{ \min_i(V_{ij}) \text{ if } j \in J^-; \max_i(V_{ij}) \text{ if } j \in J^+ \} \text{ for } a = 1, 2, \dots, n \tag{5}$$

$$A_w = \{V_{1w}, V_{2w}, \dots, \dots, V_{nw}\}$$

where,

$$V_{aw} = \{ \min_i(V_{ij}) \text{ if } j \in J^+; \max_i(V_{ij}) \text{ if } j \in J^- \} \text{ for } a = 1, 2, \dots, n \tag{6}$$

where $J^+ = \{j = 1, 2, 3, \dots, n\}$ where j is benefit criterion $J^- = \{j = 1, 2, 3, \dots, n\}$ where j is cost criterion.

Step 5 Calculate the distance of each criterion from positive ideal solution (S_{ib}) and negative ideal solution (S_{iw}).

$$S_{ib} = \sqrt{\left(\sum_j (V_{jb} - V_{ij})^2\right)} \text{ } i = 1, 2, \dots, m \tag{7}$$

$$S_{iw} = \sqrt{\left(\sum_j (V_{jw} - V_{ij})^2\right)} \text{ } i = 1, 2, \dots, m \tag{8}$$

Step 6 Calculate the closeness to the ideal solution (C) and rank the materials in descending order of C

$$C_i = \frac{S_{iw}}{S_{iw} + S_{ib}} \tag{9}$$

C_i varies from 0 to 1.

2.3 VIKOR Methodology

VIKOR methodology is one of the widely used tools for ranking which is based on MADM approach. VIKOR stands for ‘*Vise Kriterijumska Optimizacija Kompromisno Resenje*’ in Serbian which translates to Multi Criteria Optimization and Compromise Solution. VIKOR method uses aggregate functions hence ranking is based upon the closeness to the ideal solution. VIKOR has applications in many fields [8]. In VIKOR method, first a decision or an evaluation matrix is defined by the number of materials and the criteria to be analysed. The decision matrix is then normalized. Then the best and the worst criterion value for each criterion is determined. The utility and regret measures are calculated for each material. In the last step value of Q_i (ranking index) is calculated and the ranking is done based on the Q_i values in increasing order to find out the compromise solution. The ranking in VIKOR may be affected by inclusion or exclusion of any material. The computational steps for VIKOR method are as follows:

Step 1 The $m \times n$ decision matrix (X) is created consisting of m materials and n criteria.

Step 2 Construct the normalized decision matrix (f) with its elements given as per following:

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \tag{10}$$

Step 3 Determine the best case (f_j^*) and the worst case (f_j^-) values for individual criterion taking into consideration the benefit and cost criterion.

$$f_j^* = \left\{ \begin{array}{l} \max f_{ij} \text{ for benefit criterion, } i = 1, 2, \dots, m \\ \min f_{ij} \text{ for loss criterion, } i = 1, 2, \dots, m \end{array} \right\} j = 1, 2, \dots, n$$

$$f_j^- = \left\{ \begin{array}{l} \min f_{ij} \text{ for benefit criterion, } i = 1, 2, \dots, m \\ \max f_{ij} \text{ for loss criterion, } i = 1, 2, \dots, m \end{array} \right\} j = 1, 2, \dots, n \tag{11}$$

Step 4 Calculate the utility (S) and the regret matrix (R) where w_j corresponds to the weight of the j th criterion.

$$S_i = \sum_{j=1}^n \left[\frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right] \tag{12}$$

$$R_i = \max \left[\frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \right] \text{ } j = 1, 2, \dots, n \tag{13}$$

Step 5 Calculate the Q matrix where Q_i is each element of the matrix and v is the weight of the strategy of the major-

ity criterion. Furthermore, rank the materials in increasing order of Q_i .

$$Q_i = \frac{\nu(S_i - S^*)}{(S^- - S^*)} + \frac{(1 - \nu)(R_i - R^*)}{(R^- - R^*)}$$

$$S^* = \min S_i \quad i = 1, 2, \dots, m \quad R^* = \min R_i \quad i = 1, 2, \dots, m$$

$$S^- = \max S_i \quad i = 1, 2, \dots, m \quad R^- = \max R_i \quad i = 1, 2, \dots, m$$
(14)

Generally, the value of ν is taken as 0.5.

3 Material Indices

3.1 Pull-In Voltage

Pull-in voltage (V_p) is one of the important performance parameters of the MEMS capacitive shunt switch. V_p is given by [3]:

$$V_p = \sqrt{\frac{8kd_o^3}{27\epsilon_o A}}$$
(15)

where ϵ_o is the permittivity of free space is, A is area of the plates, k is the spring constant and d_o is the initial height of the plates.

$$\text{also } k \propto E$$
(16)

where E is the Young's modulus.

As spring constant is directly proportional to the Young's modulus the first material index is-

$$MI_1 = E.$$
(17)

3.2 RF Loss

The second important property considered is RF power dissipation. For low RF losses, conductivity of the material should be high. The RF power dissipation (P) is given by:

$$P = I^2 R, \quad \text{where } R = \frac{\rho_e L}{A}$$
(18)

I = Current through the switching structure, R = Resistance of the switching structure, ρ_e = electrical resistivity, L and A are the length and cross-sectional area of the structure respectively.

As P is directly proportional to ρ_e the second material index is

$$MI_2 = \rho_e.$$
(19)

3.3 Thermal Conductivity

The heat conducting capacity of the structure should be good to increase the transfer of heat away from the structure i.e. its thermal conductivity should be more. Also, higher thermal

conductivity ensures higher lifespan of device as damage due to heat generated is reduced as heat is taken away at a higher rate. Hence the third material index is

$$MI_3 = \lambda$$
(20)

where λ is the thermal conductivity of the material.

3.4 Maximum Displacement

The maximum displacement that a beam can withstand is constrained by the fracture strength of the material.

$$\text{Young's Modulus} = \frac{\text{Stress}}{\text{Strain}} = \frac{\sigma L}{\delta}$$
(21)

where σ is the stress, L is the length of the beam and δ is the displacement of the beam. Therefore,

$$\delta = \frac{\sigma L}{E}$$
(22)

Hence,

$$\delta_{max} = \frac{\sigma_f L}{E}$$
(23)

where δ_{max} is the maximum displacement of the beam and σ_f is the fracture strength of the material.

Hence the fourth material index can be defined as

$$MI_4 = \frac{\sigma_f}{E}$$
(24)

The values of material properties and the above discussed material indices for various materials are given in Tables 1 and 2 respectively.

4 Results and Discussion

The values of the material properties have been mentioned in Table 1. The values of the material indices have been calculated using the values mentioned in Table 1 and are presented in Table 2. Using the values of material indices as mentioned in Table 2 the analysis using Ashby's methodology, TOPSIS approach and VIKOR approach has been carried out.

4.1 Ashby's Methodology

The material selection graphs help us to find out the best material for the bridge material and also to find out trade-offs present if any. The required properties are: low Young's modulus for lower pull-in voltage, low electrical resistivity for lower RF loss, higher thermal conductivity to increase the lifetime of the device and higher ratio of maximum

Table 1 Material properties

Material	Young’s modulus (E) (GPa) [7]	Electrical resistivity (ρ_e) (Ω m) [7]	Thermal conductivity (λ) (W/m–K) [9]	Fracture strength (σ_f) (MPa) [10–12]
Ni	193	6.99E–08	90	345
Au	70	2.44 E–08	315	220
Al	70	2.82E–08	204	47
Ag	83	1.59 E–08	407	110
Pt	168	1.05 E–07	73	125
Cu	117	1.68 E–08	386	314
Cr	279	12.9 E–08	90	370
W	411	5.28 E–08	163	1725
Co	209	6.24 E–08	69	675
Fe	211	9.61 E–08	73	540

Table 2 Material indices

Material	$MI_1 = E$ (GPa)	$MI_2 = \rho_e$ (Ω m)	$MI_3 = \lambda$ (W/m–K)	$MI_4 = \frac{\sigma_f}{E}$ (10^{-3} Pa)
Ni	193	6.99E–08	90	1.78
Au	70	2.44 E–08	315	3.14
Al	70	2.82E–08	204	0.67
Ag	83	1.59 E–08	407	1.32
Pt	168	1.05 E–07	73	0.74
Cu	117	1.68 E–08	386	2.68
Cr	279	12.9 E–08	90	1.32
W	411	5.28 E–08	163	4.19
Co	209	6.24 E–08	69	3.22
Fe	211	9.61 E–08	73	2.55

stress to Young’s modulus in order to increase the maximum displacement.

Figure 3 shows the plot between MI_1 i.e. Young’s modulus (E) and MI_2 electrical resistivity (ρ_e). We require low values of MI_1 and MI_2 . Hence, the best materials that satisfy our needs are Al, Au, Ag and Cu. Figure 4 depicts the plot for MI_3 i.e. thermal conductivity (λ) vs MI_1 i.e. Young’s modulus (E). Higher value of MI_3 and lower value of MI_1 will satisfy our purpose. Hence the optimum materials for our purpose are Ag, Au and Cu. As we require higher values of MI_4 and lower values of MI_1 , from Fig. 5 i.e. the graph between MI_4 i.e. $\frac{\sigma_f}{E}$ versus MI_1 i.e. Young’s modulus (E), it can be seen that the materials which satisfy our needs are Au and Cu. Figure 6 depicts the Ashby’s plot for MI_3 i.e. thermal conductivity (λ) versus MI_2 i.e. electrical resistivity (ρ_e). We require higher value of MI_3 and lower value of MI_2 for the fulfilment of our purpose. Hence the prime candidates from the plot are Ag, Cu, and Au.

Figure 7 depicts the Ashby’s plot for MI_4 i.e. $\frac{\sigma_f}{E}$ versus MI_2 i.e. electrical resistivity (ρ_e). Higher value of MI_4 and lower value of MI_2 is needed to fulfil our purpose. Hence the optimum materials are Au, Cu and W. From the plot between

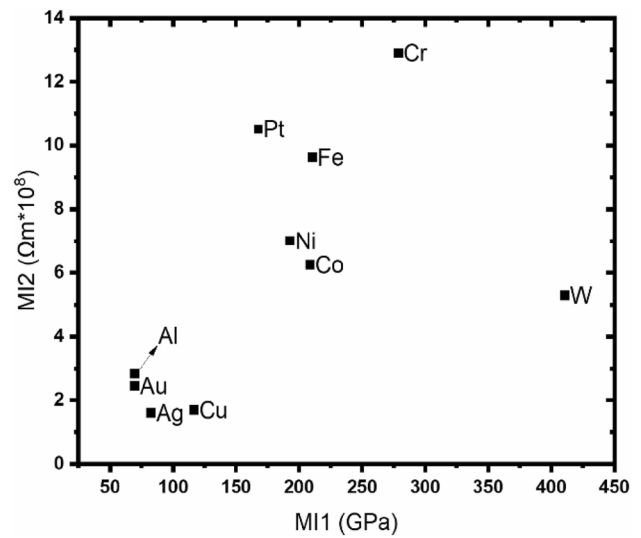


Fig. 3 Ashby’s plot for MI_2 versus MI_1

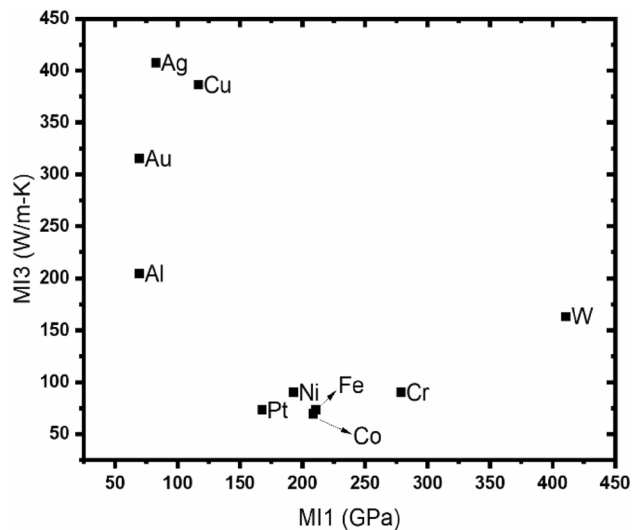


Fig. 4 Ashby’s plot for MI_3 versus MI_1

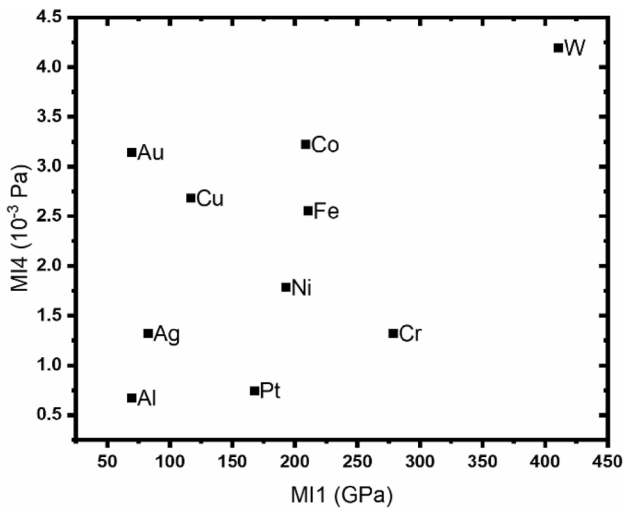


Fig. 5 Ashby's plot for MI_4 versus MI_1

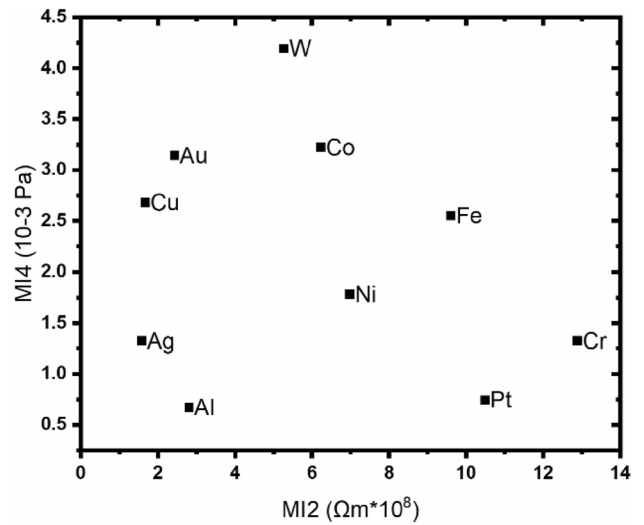


Fig. 7 Ashby's plot for MI_4 versus MI_2

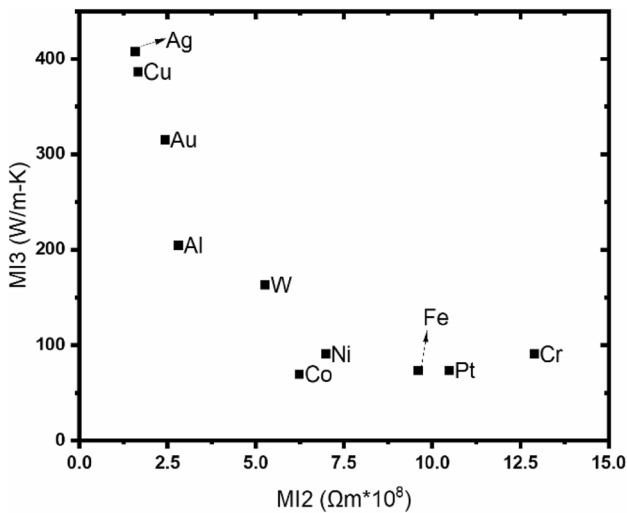


Fig. 6 Ashby's plot for MI_3 versus MI_2

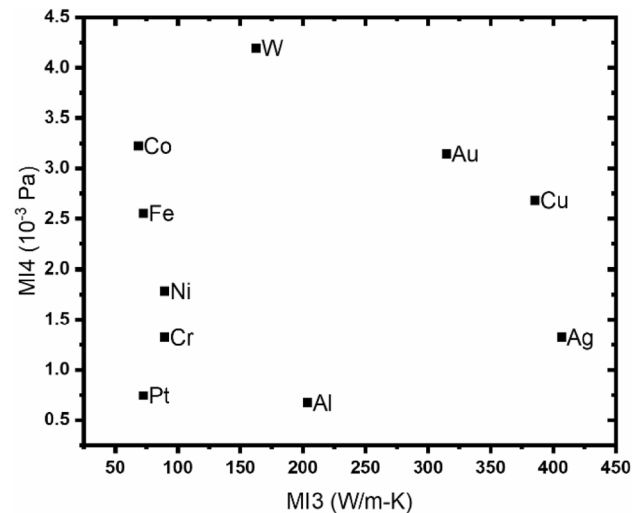


Fig. 8 Ashby's plot for MI_4 versus MI_3

MI_4 i.e. $\frac{\sigma_f}{E}$ versus MI_3 i.e. thermal conductivity (λ) shown in Fig. 8, it can be observed that for our requirement of higher values of both MI_3 and MI_4 , Au and Cu satisfy the conditions. Hence the best materials that fulfil the criteria are Au and Cu according to Ashby's methodology as they fulfil the criteria in every graph i.e. from Figs. 3 to 8.

4.2 TOPSIS Methodology

Under TOPSIS method, a decision matrix is created using the material indices values as given in Table 2. The materials are placed along rows and values for material indices for each

material along the columns. Here the matrix would be (10×4) as ten materials and four material indices are considered. From Eq. (3) the normalized decision matrix R_n is found out to be:

$$R_n = \begin{bmatrix} 0.2940 & 0.3114 & 0.1256 & 0.2315 \\ 0.1066 & 0.1087 & 0.4395 & 0.4084 \\ 0.1066 & 0.1256 & 0.2846 & 0.0871 \\ 0.1265 & 0.0708 & 0.5679 & 0.1717 \\ 0.2560 & 0.4677 & 0.1019 & 0.0962 \\ 0.1783 & 0.0748 & 0.5386 & 0.3486 \\ 0.4251 & 0.5746 & 0.1256 & 0.1717 \\ 0.6262 & 0.2352 & 0.2274 & 0.5449 \\ 0.3184 & 0.2780 & 0.0963 & 0.4188 \\ 0.3215 & 0.4281 & 0.1019 & 0.3361 \end{bmatrix}$$

From Eq. (4) the weighted normalized decision matrix V using the weights $W = [0.3 \ 0.3 \ 0.2 \ 0.2]$ matrix is found out to be

$$V = \begin{bmatrix} 0.0882 & 0.0934 & 0.0251 & 0.0463 \\ 0.0320 & 0.0326 & 0.0879 & 0.0817 \\ 0.0320 & 0.0377 & 0.0569 & 0.0174 \\ 0.0379 & 0.0212 & 0.1136 & 0.0343 \\ 0.0768 & 0.1403 & 0.0204 & 0.0192 \\ 0.0535 & 0.0225 & 0.1077 & 0.0697 \\ 0.1275 & 0.1724 & 0.0251 & 0.0343 \\ 0.1879 & 0.0706 & 0.0455 & 0.1090 \\ 0.0955 & 0.0834 & 0.0193 & 0.0838 \\ 0.0964 & 0.1284 & 0.0204 & 0.0663 \end{bmatrix}$$

In the weight matrix, more weight has been assigned to Young’s modulus and electrical conductivity as compared to thermal conductivity and fracture strength. This has been done as pull-in voltage and RF response of the device are more important parameters compared to thermal conductivity and fracture strength. From Eqs. (5) and (6) the positive ideal solution A_b and negative ideal solution A_w are obtained respectively as follows:

$$A_b = 0.0320 \quad 0.0212 \quad 0.1136 \quad 0.1090,$$

$$A_w = 0.1879 \quad 0.1724 \quad 0.0193 \quad 0.0174$$

The distance from the positive ideal solution S_{ib} , distance from the negative ideal solution S_{iw} and the C value is calculated from Eqs. (7), (8) and (9) respectively as seen from Table 3 for TOPSIS approach the best three materials are Au, Cu and Ag.

4.3 VIKOR Methodology

Under VIKOR method, the decision matrix created is similar to TOPSIS method, hence its size would be 10×4 . The

Table 3 TOPSIS approach results

Material	S_{ib}	S_{iw}	C	Rank
Ni	0.1419	0.1305	0.4792	6
Au	0.0392	0.2295	0.8542	1
Al	0.1089	0.2094	0.6579	4
Ag	0.0749	0.2335	0.7571	3
Pt	0.1815	0.1156	0.3892	9
Cu	0.0452	0.2260	0.8335	2
Cr	0.2130	0.0629	0.2281	10
W	0.1771	0.1394	0.4405	7
Co	0.1320	0.1444	0.5223	5
Fe	0.1617	0.1126	0.4105	8

Table 4 VIKOR approach results

Material	S	R	Q	Rank
Ni	0.5760	0.1876	0.5809	6
Au	0.1366	0.0597	0	1
Al	0.3527	0.2000	0.4468	4
Ag	0.1745	0.1631	0.2423	3
Pt	0.7162	0.2363	0.7828	8
Cu	0.1420	0.0858	0.0582	2
Cr	0.8345	0.3000	1.0000	10
W	0.5423	0.3000	0.7906	9
Co	0.5007	0.2000	0.5528	5
Fe	0.6276	0.2127	0.6702	7

normalized decision matrix f is calculated from Eq. (10) as:

$$f = \begin{bmatrix} 0.2940 & 0.3114 & 0.1256 & 0.2315 \\ 0.1066 & 0.1087 & 0.4395 & 0.4084 \\ 0.1066 & 0.1256 & 0.2846 & 0.0871 \\ 0.1265 & 0.0708 & 0.5679 & 0.1717 \\ 0.2560 & 0.4677 & 0.1019 & 0.0962 \\ 0.1783 & 0.0748 & 0.5386 & 0.3486 \\ 0.4251 & 0.5746 & 0.1256 & 0.1717 \\ 0.6262 & 0.2352 & 0.2274 & 0.5449 \\ 0.3184 & 0.2780 & 0.0963 & 0.4188 \\ 0.3215 & 0.4281 & 0.1019 & 0.3361 \end{bmatrix}$$

From Eq. (11) the best case value f^* and worst case values f^- for individual material indices are given below:

$$f^* = 0.1066 \quad 0.0708 \quad 0.5679 \quad 0.5449,$$

$$f^- = 0.6262 \quad 0.5746 \quad 0.0963 \quad 0.0871$$

The utility S , regret R and Q values for each material calculated from Eqs. (12), (13) and (14) respectively are represented in Table 4.

From Eq. (14) the values of S^- , S^* , R^- and R^* are obtained as:

$$S^- = 0.8345, \quad S^* = 0.1366, \quad R^- = 0.3000, \quad R^* = 0.0597$$

As seen from Table 4, for VIKOR approach the best three materials are Au, Cu and Ag.

5 Conclusion

Ashby’s approach, TOPSIS method and VIKOR method were successfully used for material selection for bridge of RF MEMS shunt capacitive switches. The results obtained from the three methods showed good agreement with each other. For VIKOR and TOPSIS methods, pull-in voltage and

electrical conductivity have been considered more important properties and thus more weight has been assigned to them and rest weight is equally shared among thermal conductivity and fracture strength. The performed analysis shows that gold and copper are the best materials. Gold being a costly metal should be used in space and defence sectors where quality is of utmost concern. For consumer applications, copper is the best material as cost precedes quality in these markets.

References

1. M. Angira, K. Rangra, Performance improvement of RF-MEMS capacitive switch via asymmetric structure design. *Microsyst. Technol.* **21**(7), 1447–1452 (2015)
2. M. Angira, K. Rangra, Design and investigation of a low insertion loss, broadband, enhanced self and hold down power RF-MEMS switch. *Microsyst. Technol.* **21**(6), 1173–1178 (2015)
3. G.M. Rebeiz, *RF MEMS: Theory, Design, and Technology*, 3rd edn. (Wiley, New Jersey, 2003)
4. M.F. Ashby, Multi-Objective optimization in material design and selection. *Acta Mater.* **48**, 359–369 (2000)
5. M.F. Ashby, Y.J.M. Bréchet, D. Cebon, L. Salvo, Selection strategies for materials and processes. *Mater. Des.* **25**(1), 51–67 (2004)
6. M. Behzadian, S.K. Otaghara, M. Yazdani, J. Ignatius, Expert systems with applications a state-of-the-art survey of TOPSIS applications. *Expert Syst. Appl.* **39**(17), 13051–13069 (2012)
7. M. Yazdani, A. Farokh, A comparative study on material selection of microelectromechanical systems electrostatic actuators using Ashby, VIKOR and TOPSIS. *J. Mater.* **65**, 328–334 (2015)
8. M. Yazdani, F.R. Graeml, VIKOR and its applications: a state-of-the-art survey. *Int. J. Strateg. Decis. Sci.* **5**, 56–83 (2014)
9. https://www.engineeringtoolbox.com/thermal-conductivity-metal-s-d_858.html. (2005)
10. “Material Science | News | Materials Engineering | News.” <https://www.azom.com/>
11. <http://www.mit.edu/~6.777/matprops/aluminum.htm>
12. <https://www.azom.com/article.aspx?ArticleID=7641>