Dielectric Material Selection for High Capacitance Ratio and Low Loss in MEMS Capacitive Switch using Ashby’s Methodology

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Abstract. The performance of the RF MEMS capacitive switch is majorly decided on capacitance ratio and loss in the dielectric layer as they decide the isolation (in dBs) in off condition. The capacitances in a MEMS capacitive switch in pull-up and pull-down states are used for deciding the capacitance ratio. In this article, we have presented a method to find out the best dielectric material using Ashby’s methodology for high capacitance ratio and low loss thus high isolation in switch off condition. Firstly, a database of 10 mostly employed dielectric materials have been created, and then, material indices are derived using material properties such as dielectric constant, resistivity, conductivity, and loss tangent which have been used in the selection of dielectric material. Through the study it is observed that to have a high capacitance ratio and low loss in dielectrics, the down capacitance should always be much greater than pull-up capacitance and tangent loss must be kept at possible minimum. This method will be highly useful in the selection of the best dielectric material by switch designers.

1. Introduction
Integrated circuit (IC) industries have seen revolutionary developments in the RF components in the last few decades due to growth in MEMS [1]. The switches are one of these components which have witnessed lots of new technological development in recent years. The MEMS technology has tremendously acquired an important position in development of these switches [2]. In general, if a switch has been fabricated using micromachining process it possess various advantages such as very small size, low voltage requirement, low weight and most importantly a greater RF characteristics even at higher frequencies [3-5]. Taye et al. (2013) [6] presented a capacitive switch using MEMS where silicon nitride was used as dielectric material to have better isolation and high capacitance ratio. Use of silicon nitride as dielectric material had resulted in better down state capacitance and thus provided an improved capacitance ratio in the range of 83.20-177 for air gap variation of 2-3 µm. Reddy et al.[7] have proposed a novel capacitive RF MEMS switch by using a beam of butterfly shape in which aluminium nitride was used as dielectric material. The results were obtained for capacitance ratio and it is found that the capacitance ratio is 44-125 for air gap variation of 1-3 µm. Fouladi et al. [8] have presented a RF MEMS switch structure in which a standard 0.35 µm CMOS technology was used to create a wrapped metal- dielectric membrane. In their result it was found that the capacitance ratio was enhanced to 91 using standard CMOS process. Yu Liu et al. [9] introduced a new MEMS switch based on (BaSrTiO) thin film technology, through their results it is found that the capacitance ratio was improved to 175. A.B. Yu et al. [10] demonstrated a membrane polarisation method for enhancing isolation of MEMS switch. The capacitance ratio was calculated as 38 for a range of air gap
of 2.5-3 µm. Jae Y. Park et al. [11] experimentally tested the Strontium titanate oxide (STO) material for fabricating a MEMS switch. The thin films of STOs were fabricated and tested for dielectric constant at different temperatures and it was found that STO can work even at higher temperature and provide a good dielectric constant for having a capacitance ratio of 600 or more. V. Thakur et al. [12] designed a three metal switch structure using MEMS for energy harvesting where the capacitance ratio was observed as 72 for an aluminium oxide thin membrane of dielectric material and X Rottenberg et al. [13] had used three structures for their study as standard, top metal and boosted. All three structure uses tantalum pent-oxide (Ta$_2$O$_5$) as dielectric material where it was found that the boosted structure provides the capacitance ratio value as 459 which was way better that the top metal structure. This increase in the capacitance ratio was achieved because the pull up capacitance was lowered to approximately 5 times compare to top metal.

Therefore from above introduction, it can be said that the selection of a dielectric material should be done carefully to obtain good performance in RF MEMS switches. The Dielectric material used and capacitance ratio achieved by using them is listed in Table. 1.

| Sr. no. | Dielectric material used in the switch structure | Capacitance ratio obtained | References |
|---------|-------------------------------------------------|-----------------------------|------------|
| 1       | Silicon nitride (Si$_3$N$_4$)                   | 83.20-177 for varying air gap of 2-3 µm | Taye et al. [6] |
| 2       | Aluminium nitride (AlN) (er-9.5)               | 44-125 for varying air gap of 1-3 µm | Reddy et al. [7] |
| 3       | Dielectric developed under standard 0.35 µm CMOS process | 91 for a wrapped metal dielectric membrane | Fouladi et al. [8] |
| 4       | BST-MEMS Switch                                | 175                         | Yu Liu et al. [9] |
| 5       | Silicon nitride (Si$_3$N$_4$)                   | 38                          | A.B. Yu et al. [10] |
| 6       | Strontium titanate oxide (STO) with high dielectric constant 110-120 at 300 degree celcius | 600                         | Jae Y. Park et al. [11] |
| 7       | Al$_2$O$_3$                                   | 72.7                        | V. Thakur et al. [12] |
| 8       | Ta$_2$O$_5$                                   | 459                         | X Rottenberg et al. [13] |

2. Methodology for Selection of Materials

This section presents methodology used for selection of dielectric material for an RF MEMS capacitive switch. To select a material for dielectric layers from available materials, Ashby’s Methodology [14] is used which is considered as one of most employed methods for selection of material for microsystem and MEMS devices previously. As per Ashby’s Methodology, any systems performance can be characterised by three requirements namely functional requirements F, geometric requirements G and materials requirements M.

\[ P = f(F,G,M) \]

The three parameters F, G and M are independent. If functional and geometric requirements are met, the material requirement can be obtained easily. The material selection process requires material indices to select best available material from all materials. The material indices are found using
material properties of a material. Then, these material indices are plotted to select best available material from all materials. This can be understood from flowchart provided below.

![Figure 1 Ashby’s material selection methodology](image)

To select a dielectric material from all available dielectric materials, the material indices are deduced from available information in the literatures. This study aims to suggest a material to improve capacitance ratio of a capacitive MEMS switches. Thus, equations for capacitance will be utilized in up and down capacitance. Later, equations for ratio of down-state capacitance to upstate capacitance will be used to see which material will provide good capacitance ratio.

The up-state capacitance in a MEMS capacitive switch is given by [15],

\[ C_u = \frac{\varepsilon_0(A_o - A_h)}{\varepsilon_0 + \frac{t_d}{\varepsilon_r}} + C_f \]  

(1)

Where, \( C_u \) is upstate capacitance, \( \varepsilon_0 \) is permittivity of free space, \( A_o \) is overlapping contact area, \( A_h \) is area of one perforation made on beam bridge, \( t_d \) is thickness of dielectric materials and \( C_f \) is fringe capacitance.

The down state capacitance in an RF MEMS switch is expressed as [15]

\[ C_d = \frac{\varepsilon_0 \varepsilon_r (A_o - A_h)}{t_d} \]  

(2)

where, \( C_d \) is downstate capacitance.

**Dielectric constant**

Here, \( t_d \) is the only one parameter which affects material properties and will be considered as first material index.

\[ C_u, C_d \propto \frac{1}{t_d} \]  

(3)

The \( t_d \) is related to dielectric constant ‘k’ as [16]

\[ k' = \frac{C_d t_d}{\varepsilon_0 \varepsilon_r} \]  

(4)

Where, \( k \) is the dielectric constant of dielectric material. It can be seen that \( k \) is proportional to dielectric thickness ‘\( t_d \)’. So first material index is
Resistivity

The resistivity of a dielectric material should be high to offer good isolation property. The capacitance in down state should be high to offer high capacitance ratio. Thus, capacitance and resistivity are proportional to each other. Thus, next material index would be

\[ MI_2 = \rho \]  

(6)

Loss tangent

The losses in the MEMS capacitive switch are not only dependent of metal electrodes but it is also dependent on dielectric loss tangent (\( \tan \delta \)). The loss tangent (\( \tan \delta \)) is a quantitative parameter which is used to see the losses in dielectrics due to their material properties such as electrical conductivity and polarisation of dielectrics (\( \varepsilon_r \)). The dielectric loss can be expressed as [22]

\[ Dielectric \ loss = \frac{\sigma}{2} \sqrt{\frac{\mu_0}{\varepsilon_r}} \]  

(7)

Where, ‘\( \sigma \)’ is electrical conductivity of the dielectric material, and \( \varepsilon_r \) is polarisation of the dielectric material. From equation (8), it can be observed that the loss in dielectric layer of the switch is related to two material properties electrical resistivity (\( \sigma \)) and is polarisation of the dielectric material (\( \varepsilon_r \)). So, next two material indices are

\[ MI_3 = \sigma \] and \[ MI_4 = \frac{1}{\sqrt{\varepsilon_r}} \]  

(8)

The above four material indices will be used in the selection of dielectric material for a MEMS capacitive switch using Ashby’s methodology.

3. Result and Discussions

The material properties as per material indices requirement have been listed in Table-2. As per methodology discussed in previous section, the plots have been presented below.

| Dielectric Material               | Dielectric constant \( k' \) | Resistivity(\( \Omega \)-m) | Electrical Conductivity [S/m] |
|----------------------------------|-------------------------------|-----------------------------|--------------------------------|
| Silicon nitride (Si\(_3\)N\(_4\)) | 9.5                           | \( 10^{12} \)               | \( 10^{-12} \)                   |
| Aluminium nitride (AlN)          | 9.3                           | \( 10^{11} \)               | \( 10^{-11} \)                   |
| SiO\(_2\)                        | 3.9                           | \( 10^{15} \)               | \( 10^{-15} \)                   |
| HFO\(_2\)                        | 23.4                          | \( 10^{7} \)                | \( 10^{-7} \)                    |
| Strantium titanate oxide (STO)   | 120                           | \( 10^{6} \)                | \( 10^{-6} \)                    |
| Al\(_2\)O\(_3\)                  | 9.8                           | \( 10^{12} \)               | \( 10^{-12} \)                   |
Ashby's methodology of material selection uses material indices to find out best available material. In MEMS capacitive switches, the down capacitance is required to be as high as possible. Thus to obtain a high downstate capacitance in the switch, the dielectric material needs to have large dielectric constant value. The dielectric in MEMS switches must exhibit good resistance to electrical signals in off state and thus, to maintain good isolation in the switch. The isolation property in the switch is related to dielectric material resistivity ($\Omega \cdot m$), high resistivity results in good isolation in the switch and vice-versa is true. It is desired that a good dielectric material must have good resistivity in off state and high dielectric constant.

| Material | Dielectric Constant | Resistivity |
|----------|---------------------|-------------|
| Ta$_2$O$_5$ | 25 | $10^{11}$ | $10^{-11}$ |
| TiO$_2$ | 86 | $10^{10}$ | $10^{-10}$ |
| ZnO | 8.5 | $10^{13}$ | $10^{-13}$ |
| ZrO$_2$ | 23 | $10^{10}$ | $10^{-10}$ |

The plot for dielectric constant and resistivity of dielectric material has been presented in Figure.2 where the resistivity is taken in logarithmic due to simplifying a larger range of resistivity of dielectric materials. Thus, from Figure.2 it is found that the dielectric material TiO$_2$ and STO have high dielectric constant and also moderate resistivity compared to other available materials. So, these two materials can be a good choice for obtaining good capacitance in downstate conditions. However, a material with a very high dielectric constant may cause stiction issues in the switch and reduces the reliability of the switch [21]. HFO$_2$ is also used in the MEMS capacitive switches but its resistivity is comparatively low from other dielectric material which is not desired for good isolation in the switch. The dielectrics such as Si$_3$N$_4$, Al$_2$O$_3$, ZnO, and AlN would be preferred choice for MEMS switches since they have good resistivity and moderate dielectric constant which will also improve the reliability of the switch. SiO$_2$ shows excellent resistivity among all available materials in this study but it is not preferable since it has the lowest dielectric constant.
The loss of signals in dielectric also reduces switch performance and therefore, while selecting a dielectric material a MEMS switch requires prominent attention. The electrical signal conductivity and reciprocal of dielectric polarization are considered to be two very important material indices for the selection of a dielectric material which results in the low loss while switching operation. The plot for logarithmic of electrical conductivity and reciprocal of dielectric polarization is depicted in Figure. 3. The modulus and logarithmic functions in electrical conductivity are used for positive value and to cover a larger range respectively. As discussed above, the material which exhibits good resistance to electrical signals that is bad electrical signal conduction and extremely low value of $\frac{1}{\sqrt{\varepsilon_r}}$ will be best choice of material for low loss in the dielectrics. The dielectric materials HFO$_2$ and STO are the best choices of materials for the low loss but the reliability issues due to these two make them less utilized in MEMS switches. SiO$_2$ is not recommended at all since it will allow more loss in the dielectric layer. The TiO$_2$ is the most suitable candidate for low loss and however, the stiction and dielectric charging is more compared to other dielectrics such as AlN, Si$_3$N$_4$, Al$_2$O$_3$, ZnO, and Ta$_2$O$_5$ will result in a moderate loss but the advantage is that the switch will be free from stiction and improved reliability is achieved.

4. Conclusion

The selection of material in any device demands utmost care since it improves the performance of that device. The method for selection of dielectric material has been proposed on the basis of Ashby’s methodology. The dielectric constant, electrical resistivity, electrical conductivity, and tangent loss of the dielectric material are used as material indices to get a material that improves performance in the switch. The capacitance ratio and dielectric loss are considered a key parameter for the selection of dielectric material in this study since good capacitance ratio and minimum loss results in high isolation. The good choices of materials for the dielectric layer are Si$_3$N$_4$, Al$_2$O$_3$, ZnO, and AlN since they offer good isolation in the switch. These materials are preferred since they improve reliability in the switch, unlike TiO$_2$ and STO. Further, Ashby’s methodology of material selection proved to be most accurate among all available material selection methods. This study also concludes that a trade-
off is needed between performance and reliability in MEMS switches while selecting a material for these switches.

References

[1]. Nagod, S., & Halse, S. V. (2017). Evolution of MEMS Technology. *Evolution, 4*(12).
[2]. Cao, T., Hu, T., & Zhao, Y. (2020). Research Status and Development Trend of MEMS Switches: A Review. *Micromachines, 11*(7), 694.
[3]. Iannacci, J. (2018). RF-MEMS technology as an enabler of 5G: Low-loss ohmic switch tested up to 110 GHz. *Sensors and Actuators A: Physical, 279*, 624-629.
[4]. Shekhar, S., Vinoy, K. J., & Ananthasuresh, G. K. (2017). Surface-micromachined capacitive RF switches with low actuation voltage and steady contact. *Journal of Micromechanical Systems, 26*(3), 643-654.
[5]. Kageyama, T., Shinozaki, K., Zhang, L., Lu, J., Takaki, H., & Lee, S. S. (2018). Fabrication of an Au–Au/carbon nanotube-composite contacts RF-MEMS switch. *Micromachines, 11*(7), 694.
[6]. Reddy, B. L., & Shanmuganantham, T. (2014). Design and analysis of RF MEMS shunt capacitive switch for low actuation voltage and high capacitance ratio. In *Physics of Semiconductor Devices* (pp. 445-448). Springer, Cham.
[7]. Shekhar, S., Vinoy, K. J., & Ananthasuresh, G. K. (2017). Surface-micromachined capacitive RF switches with low actuation voltage and steady contact. *Journal of Micromechanical Systems, 26*(3), 643-652.
[8]. Fouladi, S., & Mansour, R. R. (2010). Capacitive RF MEMS Switches Fabricated in Standard 0.35-μm CMOS Technology. *IEEE transactions on microwave theory and techniques, 58*(2), 478-486.
[9]. Liu, Y., Taylor, T. R., Speck, J. S., & York, R. A. (2002, June). High-isolation BST-MEMS switches. In *2002 IEEE MTT-S International Microwave Symposium Digest (Cat. No. 02CH37278)* (Vol. 1, pp. 227-230). IEEE.
[10]. Yu, A. B., Liu, A. Q., Zhang, Q. X., Alphones, A., Zhu, L., & Shacklock, A. P. (2005). Improvement of isolation for MEMS capacitive switch via membrane planarization. *Sensors and actuators A: Physical, 119*(1), 206-213.
[11]. Park, J. Y., Kim, G. H., Chung, K. W., & Bu, J. U. (2000, January). Electroplated RF MEMS capacitive switches. In *Proceedings IEEE Thirteenth Annual International Conference on Micro Electro Mechanical Systems* (Cat. No. 00CH36308) (pp. 639-644). IEEE.
[12]. Thakar, V., Wu, Z., & Rais-Zadeh, M. (2012). A high ON/OFF ratio MEMS capacitive switch with applications in solar energy harvesting. In *Solid-State Sensors, Actuators and Microsystems Workshop* (pp. 385-388).
[13]. Rottenberg, X., Jansen, H., Nauwelaers, B., Fiorini, P., De Raedt, W., & Tilmans, H. A. C. (2002, November). Boosted RF-MEMS capacitive shunt switches. In *Proceedings of Workshop on Semiconductor Sensor and Actuator (SeSens, Veldhoven, The Netherlands, 2003)* (pp. 667-671).
[14]. Ashby, M. F., & Cebon, D. (1993). Materials selection in mechanical design. *Le Journal de Physique IV, 3*(C7), C7-1.
[15]. Mehmood, Z., Haneef, I., & Udrea, F. (2018). Material selection for Micro-Electro-Mechanical-Systems (MEMS) using Ashby's approach. *Materials & Design, 157*, 412-430.[15]
[16]. Yakut, S., Ulan, K., & Deger, D. (2019). Effect of thickness on the dielectric properties and glass transition of plasma poly (ethylene oxide) thin films. *Materials Science and Engineering: C, 104*, 109962.
[17]. Muhamad, N. F., Osman, R. A. M., Idris, M. S., & Yasin, M. N. M. (2017). Physical and electrical properties of SrTiO3 and SrZrO3. In *EPJ Web of Conferences* (Vol. 162, p. 01052). EDP Sciences.
[18]. Patra, P., & Angira, M. (2019). Investigation on Dielectric Material Selection for RF-MEMS Shunt Capacitive Switches Using Ashby, TOPSIS and VIKOR. *Transactions on Electrical and Electronic Materials, 1*-8.
[19]. Todorova, Z., Donkov, N., Ristić, Z., Bundaleski, N., Petrović, S., & Petkov, M. (2006). Electrical and Optical Characteristics of Ta2O5 Thin Films Deposited by Electron-Beam Vapor Deposition. *Plasma processes and polymers, 3*(2), 174-178.

[20]. Raimondi, D. L., & Kay, E. (1970). High resistivity transparent ZnO thin films. *Journal of Vacuum Science and Technology, 7*(1), 96-99.

[21]. Bansal, D., Kumar, A., Sharma, A., & Rangra, K. J. (2015). Design of compact and wide bandwidth SPDT with anti-stiction torsional RF MEMS series capacitive switch. *Microsystem Technologies, 21*(5), 1047-1052.

[22]. https://rb.gy/ec78op