MATERIAL SELECTION AND PARAMETER CHARACTERIZATION FOR RF MEMS SWITCHES

1AURITRO PALDAS, 2NAVNEET GUPTA

Dept. of Electrical & Electronics Engineering, BITS – Pilani
Email: auritrop@gmail.com, ngupta@pilani.bits-pilani.ac.in

Abstract—RF MEMS Switches are rapidly replacing the FET & PIN based switches as they offer a large spectrum of advantages over the traditional switches, most notable of which are their high isolation, low insertion loss, ultra low power consumption and high bandwidth. The spectrum of materials available to designers for the manufacturing of various components of these switches is continuously expanding. This calls for a systematic approach in material selection, looking into the parameters of the switch which need to be optimized for better performance, and how a particular material choice affects these parameters. This paper looks into the types of RF MEMS switches, characterizes a few parameters which affect their performances, and suggests using the Ashby approach that for low pull-down voltages, high switching speeds and lower losses. Barium Strontium Titanate (BST) is the best material choice for the dielectric layer, and Aluminum and Silicon Dioxide are the best choices for the membrane.

Keywords—Ashby approach, material selection, RF MEMS switches

I. INTRODUCTION

A. Overview
Micro electromechanical Systems, or MEMS, or simply, Microsystems, is an integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro fabrication technology. The size of MEMS components typically range from 1 micrometer to 1 millimeter [1]. The growing popularity and investments in this area can be attributed to the fact that MEMS technologies, particularly the fabrication techniques, are similar and compatible to the well developed IC fabrication techniques. This makes possible the realization of complete “systems-on-a-chip”, where signal sensing, processing and the resulting actuation can all be performed at the same place. As these devices have extremely small geometries, and as they are manufactured in bulk, a highly complex fully functional device can be obtained at a relatively low cost.

Owing to their various advantages, MEMS devices are extensively used today in the automotive, healthcare, aerospace and telecommunication industries, apart from their applications in various consumer products, and as sensors for industrial systems [1].

A. RF MEMS Switches
With the advent of wireless communication in the Radio Frequency domain in the past two decades, and with similar advancements in MEMS technology, switching devices having superior characteristics than traditional switches were thought of. The RF MEMS switch is a device which allows or blocks an RF signal along a transmission line. The switching operation is based on the mechanical movement of a membrane actuated by a control signal [2], [3]. The characteristics that make the RF MEMS switch a preferred device over the traditional PIN and FET based devices are its near zero power consumption, high isolation, low insertion loss, compatibility with IC fabrication, high quality factor, high linearity, low volume and mass, and good RF performance [2], [4]. Particularly significant among these is their high isolation, which represents a minimal coupling between the input and output paths when the switch is in the OFF state; and also their low insertion loss, which is the loss in signal power when the switch is in the ON state. It is interesting to note that a few of these advantages (low insertion loss, high isolation, linearity) come from the electro mechanical nature of the switches and a few others (low power consumption, low mass and volume) come from the solid state nature of these devices [5].

RF MEMS switches find extensive applications in commercial wireless communication systems, military communications and satellite communications. For instance, in satellite communications, these switches form the basis of the switching networks, and a periodic arrangement of the switches can be used as phase shifters in multi-beam satellite communication systems [2], [5], [6]. This paper discusses about the parameters which characterize the performance of these devices and suggests suitable material choices for the membrane and the dielectric layer for an improvement in certain characteristics, viz. the pull-down voltage, the switching speeds and insertion losses of the switches.

II. PHYSICAL DESCRIPTION

Based on the type of contact, the physical design of RF MEMS switches can be of four types: capacitive switches, metal-contact switches, switched capacitors and analog varactors [2], [7]. Capacitive switches have the advantage of handling larger values of RF
power given their larger contact area [5]. In this paper, we shall be discussing capacitive switches only.

Fig 1 An RF MEMS Series Switch

The capacitive switches primarily work by forming a low resistance path between two points on the system, either allowing or attenuating the signal. Based on this, these switches can be categorized into two classes:

i. RF MEMS Series Switch
ii. RF MEMS Shunt Switch

RF MEMS Series Switch: In this model, the switch is in the ON state when it is electro-statically actuated (i.e. when the membrane is in the down state). This is due to the fact that a low resistance path is formed between the two open ends of the transmission line when the membrane is lowered. The transmission line is assumed to be perpendicular to the plane of the page in Fig. 1.

RF MEMS Shunt Switch: In this model, the switch is in the OFF state when it is electro-statically actuated. This is because a low resistance path forms between the transmission line and the ground line when the membrane is lowered. This is shown in Fig. 2.

On lowering the membrane, the capacitance of the structure increases, which leads to a decrease in RF resistivity, and thus, the signal is routed on to the ground line rendering the switch to be OFF. The capacitance ratio of the switch (in the down and up states) is clearly one of the indicators of the isolation and the insertion loss values of the switch. The dielectric layer in the shunt RF MEMS switch guarantees D.C. isolation when the switch is in the down state [5].

It can also be shown that a series switch suffers from self actuation in the up state and a shunt switch suffers from latching in the down state. Thus, it can be concluded that a shunt switch is advantageous in the up state, whereas a series switch is advantageous in the down state [5].

Another difference in the structure of RF MEMS switches can be seen in the choice of the membrane, which is, in most cases, either of the fixed-fixed beam type, or of the cantilever type. The primary difference between these two structures is that the fixed-fixed beam has a higher spring constant than a cantilever of similar dimensions [3], [5]. As will be seen later, this results in a lower switching time in the fixed-fixed beam, but increases the pull down voltage. Due to other factors such as greater stability and lower sensitivity to stress, the fixed-fixed beam is usually the preferred choice for the membrane [5].

The actuation mechanisms of these switches can be of four types: electrostatic, magneto-static, thermal or piezo-electric. Among these, the electrostatic actuation mechanism is the most widely used due to its integrability, simplicity and low power consumption [5], [8].

Fig 2 An RF MEMS Shunt Switch

III. MODELING

The Spring Constant: For a fixed-fixed beam membrane, the spring constant can be modeled with the expression [3], [5]

\[ k = \frac{32Ew}{l^2} \left( \frac{l^2}{64} \right) + 8\sigma(1 - \nu)w \left( \frac{l}{h} \right) \]  (1)

Where \( E \) is the Young’s modulus of the material of the beam, \( w \) is its width, \( t \) is its thickness, \( l \) is its length, \( \sigma \) is the biaxial residual stress and \( \nu \) is the Poisson’s Ratio. The first term in the expression is a result of the material properties of the beam and the second term is a result of the residual stress, which can be attributed to the fabrication process [3].

The important result to note from this expression is that the spring constant is a direct function of the Young’s modulus of the material of the beam.

Electromechanical Modeling: This section derives the expression for the pull down voltage required to bring the membrane to the down state.

We start off by modeling the switch as a parallel plate capacitor. The capacitance is given by

\[ C = \varepsilon_0 \frac{A}{d} \]

Where \( A \) is the area of the plates and \( d \) is the separation between them, \( \varepsilon_0 \) being the permittivity of free space.

Now, if the width of the beam is \( w \) and the width of the transmission line is \( S \), then the area \( A \) of the capacitor is \( w \times S \) (Refer Fig 2). If the separation between the membrane and the transmission line at some particular instant is \( g \), then the capacitance at that instant is given by

Material Selection and Parameter Characterization For RF MEMS Switches
Having seen how the various parameters affect the performance of the RF MEMS switches, we can now discuss about its limitations and see in what ways improvements in certain aspects of their performance can be brought about. Most of the material in this section is referenced from [2] unless otherwise mentioned.

Reduction in the spring constant results in a reduction in the pull down voltage (5), but this leads to a decrease in the switching speed (8). The use of low bridge height membranes have been reported to decrease the pull down voltage, but this leads to a decrease in the capacitance ratio, affecting the isolation value of the switch. New materials such as AlSi0.04 and Pt as membranes have also been reported to decrease the pull down voltage by exploiting buckling and bending effects, but they have their own limitations.

Improvement in the switching speed is an area where not much work has been done. Most approaches involve increasing the spring constant, which in turn increases the actuation voltage. However, it has been demonstrated that miniaturization of the switches might lead to a reduction in switching times [9].

A few aspects of the dielectric layer also affect the performance of the switches. One is the surface roughness, which might adversely decrease the capacitance ratio of the device, affecting its isolation; the other is hysteresis, which might significantly change the values of the voltages at which actuation and release of the membrane take place.

Another aspects to be taken care of while designing an RF MEMS switch are those of RF self-actuation and RF latching. These parameters describe the ways in which a switch may fail to operate in the presence of an RF signal. A switch is said to be RF self-actuated when the incident RF signal pulls the membrane to the down state without application of the bias voltage, whereas a switch is said to be RF latched when the membrane remains in the down state even after removing the DC bias, due to the power of the RF signal. A few design rules can be followed to avoid these situations [5].

V. THE ASHBY APPROACH AND MATERIAL SELECTION FOR AN RF MEMS SWITCH

The previous section lists out the various parameters that can be looked upon while improving the performance of an RF MEMS switch. The mere

\[ C = \varepsilon_0 \frac{w_s}{g} \]  

(2)

Now, the energy stored in a capacitor is given by

\[ U = \frac{1}{2} CV^2 \]

where \( V \) is the potential difference between the plates.

Thus, the force between the plates of the capacitor at a separation of \( d \) is given by

\[ F = \frac{1}{2} \frac{V^2}{d} \frac{\partial C}{\partial d} \]

Applying this to (2) gives

\[ F = \frac{1}{2} V^2 \frac{\partial C}{\partial g} = -\frac{1}{2} V^2 \frac{\varepsilon_0 w_s}{g^2} \]  

(3)

The mechanical restoring force of the beam is

\[ F = -kx = -k(g_0 - g) \]

(4)

where \( g_0 \) is the initial height of the membrane.

Equating the forces given by (3) and (4), we have, after simplification

\[ V = \sqrt{\frac{2k g_0^2 (g_0 - g)}{\varepsilon_0 w_s}} \]

The beam becomes unstable when it reaches

\[ g = \frac{g_0}{3} \]  

(5)

This shows us how the pull down voltage is related to the dimensions of the spring, the spring constant, and the permittivity of free space.

It can also be shown that the voltage required to keep the membrane in the down state is given by [5]

\[ V_{\text{hold}} = \sqrt{\frac{2kg_0 t^2 d^2}{\varepsilon_0 w_s \varepsilon_r}} \]  

(6)

where \( t_d \) is the dielectric thickness and \( \varepsilon_r \) is its relative permittivity.

Switching Time and frequency: The angular frequency of any system modeled as a spring is given by

\[ \omega = \sqrt{k/m} \]

(7)

and the expression for the switching time to be [2], [5]

\[ \tau_s = \frac{3.67}{V_{\text{source}}} \frac{V_p}{V_{\text{source}}/k/m} \]  

(8)

Where \( V_{\text{source}} \) is the applied voltage, and is 1.2 to 1.5 times the pull down voltage, resulting in a faster switching speed [5]. These expressions tell us that a faster device calls for the membrane to be having a higher spring constant.

IV. LIMITATIONS AND SCOPE FOR IMPROVEMENTS

Material Selection and Parameter Characterization For RF MEMS Switches

9
number of such parameters and their compromising effect on one another calls for an unbiased and focused approach to designing these switches. This is made possible by the Ashby approach. In this method, at first, the materials suitable for the component are noted down and are then screened to suit the application. Then, the properties of the screened materials are studied, and, based on the parameters to be optimized, material selection charts are plotted, which gives us an unbiased picture of how the performance of the device is affected by selecting a particular material, and how the compromising effect of the parameters is reflected on the choice of materials [10].

**Material selection for the dielectric layer**

A number of properties of the dielectric layer play an important role in determining the performance of an RF MEMS switch, some of which are the dielectric constant, dielectric strength, resistivity, leakage current, surface roughness, etc [2].

The properties studied in this paper are the dielectric constant and the resistivity, as these values are spread over a wide range and directly affect a few critical properties of the device.

The dielectric constant or the relative permittivity of the dielectric layer directly affects the pull down and hold voltages as can be seen from (5) and (6). The hold voltage is inversely proportional to the dielectric constant. On the other hand, the resistivity of the dielectric layer gives a measure of the A.C. losses taking place in the device during operation, the relationship being direct. Table I gives the values of these parameters for various materials used as dielectrics in RF MEMS switches. The values are taken from references that claim an improved performance of the materials by novel manufacturing techniques.

In this table, the values of \((1/\varepsilon_r)\) are appended as these values are proportional to the hold down voltages, and the values of \(\log (\rho)\) are also calculated as the resistivity (\(\rho\)) values vary over an extremely large range, and taking logarithms limits the spread of the plot. Thus, the plot (Fig 3) is obtained by taking the last two columns.

For the pull down and hold voltages to be low, \((1/\varepsilon_r)\) must be low, and for the A.C. losses to be minimum, \(\log (\rho)\) must be small. This implies that the points at the bottom left corner give the best material choices for achieving these criteria. Hence, from the plot, we can conclude that Barium Strontium Titanate (BST) is the best material choice for the dielectric layer of a MEMS switch for low pull down voltages and low losses. Authors like [11] have demonstrated an elevated performance in RF MEMS switches whose dielectric layers were fabricated using BST.

### Table I

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant ((\varepsilon_r))</th>
<th>Resistivity ((\rho)) ((\Omega\cdot\text{cm}))</th>
<th>((1/\varepsilon_r))</th>
<th>(\log (\rho))</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO(_2)</td>
<td>3.9 (10^4)</td>
<td>0.25641</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Si(_3)N(_4)</td>
<td>7.5 (10^4)</td>
<td>0.13333</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>9.8 (10^4)</td>
<td>0.10204</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>ZnO</td>
<td>8.5 (10^4)</td>
<td>0.11764</td>
<td>-4</td>
<td></td>
</tr>
<tr>
<td>PZT</td>
<td>3850 (7\times10^3)</td>
<td>0.008026</td>
<td>4.8450</td>
<td></td>
</tr>
<tr>
<td>HfO(_2)</td>
<td>25 (10^4)</td>
<td>0.04</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Amorphous</td>
<td>6 (80\times10^8)</td>
<td>0.16666</td>
<td>-</td>
<td>4.0969</td>
</tr>
<tr>
<td>Diamond</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BST</td>
<td>800 (10^3)</td>
<td>0.00125</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>TiO(_2)</td>
<td>100 (10^3)</td>
<td>0.01</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

### Table II

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus ((E)) (GPa)</th>
<th>Mass density ((\rho)) (g/cm(^3))</th>
<th>(\sqrt{E})</th>
<th>(\sqrt{E/\rho})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>79</td>
<td>19.3</td>
<td>8.888</td>
<td>2.023</td>
</tr>
<tr>
<td>Pt</td>
<td>168</td>
<td>21.45</td>
<td>12.96</td>
<td>2.799</td>
</tr>
<tr>
<td>Si(_3)N(_4)</td>
<td>385</td>
<td>3.10</td>
<td>19.62</td>
<td>11.144</td>
</tr>
<tr>
<td>Ni</td>
<td>200</td>
<td>8.902</td>
<td>14.14</td>
<td>4.739</td>
</tr>
<tr>
<td>Al</td>
<td>70</td>
<td>2.70</td>
<td>8.367</td>
<td>5.091</td>
</tr>
<tr>
<td>Si</td>
<td>190</td>
<td>2.30</td>
<td>13.78</td>
<td>9.088</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>73</td>
<td>2.27</td>
<td>8.544</td>
<td>5.671</td>
</tr>
</tbody>
</table>

**Material selection for the membrane**

For the choice of the membrane, we look at the values of the Young’s Modulus \((E)\) and the mass density \((\rho)\) of the materials. This is because the pull down voltage is directly proportional to the square root of the spring constant (5) which is in turn proportional to the Young’s Modulus (1); and also as the frequency of operation is proportional to \(\sqrt{k/m}\) (7), which again is proportional to \(\sqrt{E/\rho}\). Table II lists out the values of these parameters.

Again, the plot (Fig 4) is obtained by looking into the last two columns.

For a low pull down voltage, the value of \(\sqrt{E}\) must be small, and for a high switching speeds, the value of \(\sqrt{E/\rho}\) must be large. Thus, Al, SiO\(_2\) and Au are good material choices for the membrane for having low pull down voltages, whereas Si\(_3\)N\(_4\) is a good choice for having faster switching speeds. Overall, it can be concluded that Al and SiO\(_2\) are the best choices for the membrane of an RF MEMS switch.
CONCLUSION

This paper studies the various types of RF MEMS switches, looking into their advantages and disadvantages. It goes about describing the various parameters that affect the performance of the switches and characterizes them. It looks into the areas where improvements in the performance are possible, and, by using the Ashby approach, suggests that BST is the best choice for the dielectric layer, and Al and SiO$_2$ are the best choices for the membrane of an RF MEMS switch to result in low pull down voltages, high switching speeds and lower losses. It also shows how the Ashby Approach can be used to arrive at a rational choice for material selection of Microsystems when two or more parameters need to be simultaneously optimized.

![Graph 3](image3.png)

![Graph 4](image4.png)
Material Selection and Parameter Characterization For RF MEMS Switches

REFERENCES


★ ★ ★