JETIR.ORG
ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

A Comparative Analysis Of RF MEMS Switches and Semiconductor Switches

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Abstract

This paper addresses the fundamentals of RF switches providing a comparison between semiconductor and RF MEMS switches. The basis of comparison is introduced by defining a figure of merit that is a function of the off-state capacitance and the on-state resistance. A simple trans mission line model is presented to illustrate the impact of the switch off-state capacitance on the switch isolation and frequency range of operation. The figure of merit analysis given in this paper demonstrates that RF MEMS switches have superior insertion loss and isolation performance in comparison to MESFET and p-i-n diode switches. The paper also addresses several other design considerations beside insertion loss and isolation for selecting the right RF switch. A discussion is given on the potential use of RF MEMS switches in satellite and wireless applications.

Keywords:

RF MEMS, Semiconductor, MESFET, p-i-n diode, Membrane switch, FOM

1. Introduction

The common microwave switches currently employed in the microwave industry are mechanical switches (coaxial and waveguide) and semiconductor switches (p-i-n diode and FET). Mechanical coaxial and waveguide switches offer the benefits of low insertion loss, large off-state isolation, high power handling capabilities, and are highly linear. However, they are bulky, heavy and slow. On the otherhand, semiconductor switches such as p-i-n diodes and FET provide much faster switching speed and are smaller in size and weight, but are inferior in insertion loss, DC power consumption, isolation, power handling, and intermodulation than their mechanical counterparts. MEMS switches promise to combine the advantageous properties of both mechanical and semiconductor switches. They offer the high RF performance and low DC power consumption of mechanical switches but with the small size, weight and lowcost features of semiconductor switches.

We have worked on improving the performance of microwave switches for several years [1, 2, 3]. Over that time MEMS devices have become a focus for research in microwave switches [7, 8, 6]. For a review of RF MEMS devices see [9]. While it is generally accepted that mechanical switches offer superior isolation, we have not seen an analysis of the fundamental limits of semiconductor switches. In this paper we will present an analysis of fundamental issues in microwave switching. First we will review the two basic function of a microwave series. We hope that this review will be of use to those who have been working in the MEMS field but are not familiar with microwave devices. The principle comparison criterion for devices is the figure of merit (FOM) which we will relate to fundamental material physics. We briefly discuss the electronic models of MESFET, p-i-n, and photo conductive semi conducting switches. The FOM of MEMS switches will be discussed and used for comparison with semiconductor devices. Based on this comparison we will show some fundamental reasons for the advantages that MEMS switches offer for microwave routing. There are many application areas possible for microwave switches. Given the existing state of the art in semiconductor switches and the benefits that MEMS offers we will describe possible application areas where MEMS devices will be used to advantage.

In order to make a comparison, we will consider an ideal switching element. While each semiconductor switch has a different circuit model when considered in detail, the fundamental element that each provides is a low resistance in one state which can be controllably changed to a small capacitance in the other state. We do not consider circuit combinations of multiple switching elements as these inevitably involve tradeoffs in bandwidth, isolation, insertion loss and become a switching system issue. In this paper we address fundamental physics of switching elements rather than circuits and system.

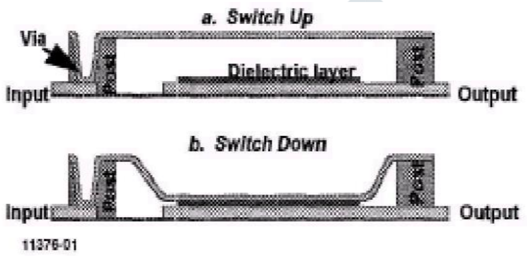

Fig 1.Cross sectional view of capacitive membrane switch

While electronic devices are widely used as switching elements for routing signals there is a surprisingly small body of literature devoted to microwave routing switches. In many microwave texts, the general problem of switching receives less than a chapter. In the area of devices, the requirements of a good switching element can be as demanding as those for a good amplifier. In the following section we offer a basic introduction to microwave switches as reflectors of quasi TEM waves propagating on transmission lines. All of the switch models discussed in this paper. A small part of the wave is transmitted through the switch to port 2. In the figures, we show the electrical signal as a short pulse, which emphasizes the sign of the reflection coefficient which for the series switch is +1 and for the shunt switch is –1. We also chose a pulse to emphasize the very broadband nature of switching that is possible using MEMS. In terms of microwave scattering parameters, in the frequency domain, the reflected signal is S_{11} and the transmitted signal is S_{21}, the forward transmission is given by the following equations:

2. Microwave switch

While electronic devices are widely used as switching elements for routing signals there is a surprisingly small body of literature devoted to microwave routing switches. In many microwave texts, the general problem of switching receives less than a chapter. In the area of devices, the requirements of a good switching element can be as demanding as those for a good amplifier. In the following section, we offer a basic introduction to microwave switches as reflectors of quasi TEM waves propagating on transmission lines. All of the switch models are discussed in this paper and they are based on the assumptions that the switch element itself is very small in comparison with the wavelength of the signal that is routed. This is true for semiconductor switches and for MEMS switches at frequencies up to the range of 100 Ghz, that is free space wavelength of 3 mm at that frequency, the guided wavelength is typically 1.5 mm while the dimensions of the switch is much smaller.

2.1. Series switch

The series reflecting microwave switch is introduced schematically in Fig. 1. The off-state at the top and the on-state on the bottom. To switch microwaves it must be possible to transmit microwave signals to and from the switch, hence it is connected at input and output by transmission lines or waveguides. When closed the switch is a transmitting device with some reflection. In the open state, the switch is fully reflecting with a small unwanted transmission.

In the off-state case, a signal arriving at port 1 of the open switch is reflected with a voltage reflection coefficient of +1 as is shown schematically in the upper part of Fig. 1. A small part of the wave is transmitted through the switch to port 2. In the figures, we show the electrical signal as a short pulse, which emphasizes the sign of the reflection coefficient which for the series switch is +1 and for the shunt switch is –1. We also chose a pulse to emphasize the very broadband nature of switching that is possible using MEMS. In terms of microwave scattering parameters, in the frequency domain, the reflected signal is S_{11} and the transmitted signal is S_{21}, the forward transmission is given by the following equations:

$$S11 = 1/1+jCoff.2Zo \quad (1)$$

$$S12 = jCoff.2Zo/1+ jCoff.2Zo \quad (2)$$

The ideal requirement is $C_{\text{off}} = 0$, but for practical conditions, if $jC_{\text{off}} = 1$ the denominators of both equations is approximately 1. This gives unity reflection, while in transmission the circuit is basically a differentiator. Usually, the forward transmission under off state conditions is termed the isolation of the switch.

In the on state, the bottom part of Fig. 1, a signal is mostly transmitted through the switch with some small reflection and some absorption. The insertion loss is the ratio of the transmitted power to the difference between the incident and reflected power. If the reflected power is low then S_{21} is the insertion loss. The reflected power under these conditions is the return loss and in the case sketched is equal to S_{11}. The on-state scattering parameters are given by

$$S11 = Ron/Ron+2Zo \quad (3)$$

$$S21 = 2Zo/Ron+2Zo \quad (4)$$

In the Off state case, a signal arriving at port 1 of the open switch is reflected with a voltage reflection coefficient. The ideal condition is $R_{\text{on}} = 0$, but it is clear that if $R_{\text{on}} = 2Z_0$ then $S_{11} \approx 0$ and $S_{21} \approx 1$.

In the above discussion of the series switch configuration we have presented an abstract model of a "switching device" that can be characterized by a small capacitance in one state and a small resistance in the other state. This may seem like an oversimplification, however in practice the simple parameter model provides quite accurate prediction of switching circuit performance. It is also straight forward to extract these simple parameters from the basic properties of each type switch. It can be shown that for a shunt configuration of a reflecting switch the same device properties are required [5]. That is, we want lower resistance and lower capacitance which leads to the concept of figure of merit.

3. Figure of Merit

With direct current one uses the off-on resistance ratio to characterize a switch. Since at microwave frequencies the off state is determined by capacitance, we use the ratio of impedance to compare switches. The impedance ratio for our simple two parameter device is just

$$Zratio = Zon/Zoff = jCR \qquad (5)$$

The ratio is frequency-dependent, a trait which we would expect since one state is determined by a capacitance. The Product of *CR* is a characteristic number called the figure of merit (FOM) of a switch. It has been used by several authors without very much discussion. A smaller FOM is better since it means a small on impedance relative to the off impedance. The reciprocal of the FOM is also used as a metric and is called the cut-off frequency. The FOM matches what is expected intuitively. We can make a better switch element by reducing either *R* or *C* or both.

While we have developed the FOM from an impedance ratio, we cannot assign it a great deal of physical meaning. In a MEMS switch FOM values are in atto seconds (as), which corresponds to cut-off frequencies of tens of terahertz (THz). These frequencies are extrapolations far beyond the range of validity of the assumptions that we made earlier in developing our simple switch model. That means that we cannot plot a graph of frequency response for a circuit and find a break in the THz region. For example, if we consider any series switch in a circuit, the impedance of the trans- mission line introduces a break frequency that is lower than the cut-off frequency by the ratio of line impedance to R_{on}. The FOM provides useful insight into the fundamental behaviour of switching elements and lets us compare switching element behaviour in isolation from circuits and from device geometry.

The first case for which we want to extract an FOM is not one of our switching elements at all but an ideal element of semiconductor material. We assume that some external control is exercised to switch the material from an insulating state to a conducting state. The capacitance of this small element of material is just $C = \varepsilon_r \varepsilon_0 dxdy/dz$. The resistance of the same volume of material is $R = dz/dxdy$. Then, the FOM is

$$FOM=CR=€€rdxdydz/dz = €€rdxdy \qquad (6)$$

Thus, the geometry cancels and the FOM is just dependent on the basic material properties of dielectric constant and resistivity. We cannot improve on the FOM by changing geometry. For example, if we want to decrease R_{on} we can make dz smaller. At the same time however, that would C_g. The C_g is determined by the width of the depletion zone and the gate length. We have measured commercial MESFETs and found an FOM of 500 fs. Published values by Blackwell [12] for a specially designed switching MESFET give an FOM of 270 fs. These values have been achieved after about 20 years of development of MES- FETs as commercial devices. The FOM is limited by the conductivity of the AlGaAs channel. The channel is heavily doped, near the solubility limit, but it must be made thin enough that the Schottky diode can pinch it off before breakdown. There is a further limitation on the FOM be- cause of the planar structure of the electrodes which add fringing fields making C_{off} relatively large. In fact Blackwell's improvement in the FOM was achieved by selectively thinning the substrate in order to reduce the fringing field.

4. Semiconductor switches

4.1. MESFET

The model of a MESFET switch was presented by Ayasli [11] to describe the relationship between the device physics and the RF switching behaviour of MESFETs. In the conducting state, the MESFET is operated with zero bias and the channel is approximately a linear conductor. In the insulating state, the gate to channel Schottky diode is reverse biased depleting the channel. The off state capacitance is determined by the C_{sd} in parallel with the series combination of the C_{sg} and C_{gd} or C_g. The C_g is determined by the width of the depletion zone and the gate length. We have measured commercial MESFETs and found an FOM of 500 fs. Published values by Blackwell [12] for a specially designed switching MESFET give an FOM of 270 fs. These values have been achieved after about 20 years of development of MES- FETs as commercial devices. The FOM is limited by the conductivity of the AlGaAs channel. The channel is heavily doped, near the solubility limit, but it must be made thin enough that the Schottky diode can pinch it off before breakdown. There is a further limitation on the FOM because of the planar structure of the electrodes which add fringing fields making C_{off} relatively large. In fact Blackwell's improvement in the FOM was achieved by selectively thinning the substrate in order to reduce the fringing field.

4.2. P-i-n

The model of a p-i-n diode is given in several sources [10, 13, 14, 15]. The off-state capacitance can be modeled as a simple parallel plate,

$$\mathrm{Coff} = A\text{€}_0\text{€}_{r\,/}\,W \tag{7}$$

The on-state resistance is given by [13] as:

$$R_{on} = W^2/Q(p_n+p_p) \tag{8}$$

where $Q = I_F$, is the charge in the intrinsic region which equals the injection current times the lifetime. The FOM is thus

$$\mathrm{FOM} = WA\text{€}0\text{€}r/(p_n+p_p)\mathrm{If.p} \tag{9}$$

The FOM can be reduced by decreasing W or A, i.e. by decreasing the volume of the conducting region. Since $WA/(I_F\,\text{þ})$ is the reciprocal of charge density, eqn. (9) reduces to eqn. (6). While increasing charge density does improve the FOM, what the model does not explicitly show is the dependance of carrier lifetime on carrier density. As carrier concentration in semiconductors increases, carrier. Carrier interaction causes an increased recombination rate. We extract from commercial literature R_{on} and C_{off} for p-i-n diodes. At 5 m Watts, an FOM of 220 fs can be achieved and at 25 m Watt that can be reduced to 110 fs. There are several reasons for the slow reduction in FOM with increasing power. The increased re-combination rate as noted above is one reason, but there is also the effect of contact resistance as values of R_{on} reach the 1 Ω level.

4.3. Photo Conductive

Photoconductive switches have been used for very high-speed optically controlled switching of microwave signals [16] and there has been an interest in making efficient optically controlled switches [1]. A photoconductive switch has the geometry of an interdigital capacitor. Under illumination photo carriers generated in the semiconductor regions between the fingers provide an R_{on} which closes the switch. The structure of this switch is very similar to that of a MESFET in that the electrodes are planar. However, the isolation is somewhat better because the gap is usually made longer than the short channel length of a MESFET. The R_{on} is dependent on the optical power, the carrier mobility and lifetime in a manner similar to a PIN diode when optical power is substituted for bias current. Starting with eqn. (6), we can write the FOM for the photoconductive region as following.

$$\mathrm{FOM} = \text{££}r\ .h^{-}\ \mu_{n\,\Gamma}\ /\ \mu_n\ \mu_{n\,f}\,q\,P \tag{10}$$

where μ_n is the electron mobility, q is the electronic charge, μ_n is the carrier lifetime, P is the optical power density, f is the optical frequency, $\bar{h}$ is Planck's constant, and Γ is the quantum efficiency .While we could use this theoretical value for FOM, for our comparison in Table 1 we take experimentally determined values of Ron and Coff.

5. MEMS switches

There are both resistive MEMS switches that make metal to metal contact and variable capacitor MEMS switches that make metal to insulator contact. The MEMS switch that we consider is the metal to metal contact type described in reference [3]. The microwave structure is based on a gap in a coplanar waveguide. A top contact suspended from an insulating beam can be lowered to make electrical contact across the gap thus closing the switch. Two large capacitors act as the actuator to bend the bridge and lower the contact. This structure provides a small area and large gap which results in a small capacitance in the off state. The simple material model shown in Fig. 2 is not an appropriate starting place to derive a MEMS FOM, because geometry changes in a MEMS switch are used to effect control. We will examine capacitance and resistance separately. The contact resistance in a MEMS switch is much greater than would be expected based on resisitivity of metals. It is believed that the higher resistance arises because contact actually takes place at only a small number of "high" spots leading to a reduced effective surface area. For example, gold-gold contacts with an area of 2020 μm, a conducting length of 0.4 μm and resistivity = $2.5x10^{-6}$ Ω cm would give a calculated resistance of $2.5x10^{-5}$ Ω. In practise, a resistance of 0.22 Ω was measured. This is 8800 times greater than expected which we interpret as an effective area factor of about 10^{-4}. We calculate the capacitance of a single MEMS gap as $C = \varepsilon_0 A/G$. For the on state resistance, we use an effective area factor a_e, a conducting length equal to the thickness of the contact films and a resistivity to give $R = \rho l/(A \cdot a_e)$. This leads to an FOM of

$$\text{FOM} = CR = \frac{\varepsilon_0 \, l\rho}{G \cdot a_e}. \qquad (11)$$

Comparing eqn. (11) with eqn. (6), we see that ε_r has been reduced to 1 giving an FOM reduction of 10^{-1}. The resistivity of the metal is 10^{-4} less than the semiconductor giving a reduction of FOM of 10^{-5}. The effective area factor is approximately 10^{-4} meaning that much of the benefit of the material change is largely lost due to the effective area factor. However, in contrast to eqn. (6), this FOM includes 2 geometry factors, the gap and the conducting length. The conducting length is the thickness of the films that make up the contact which we cannot reduce without introducing loss in the signal path to the contact. Thus, the principle degree of freedom that is introduced by MEMS is the gap G. It accounts for a factor of less than 10^{-1} in the MEMS switch if we consider a 2 μm gap to represent a MEMS switch and an 0.4 μm channel length to represent a MESFET. For our comparison in Table I, we take experimental values from the literature to determine FOM. R_{on} of 0.22 Ω has been re-ported for a contact area of 2020 μm. Off state capacitance values of 1 to 10 fF have been reported for those same structures. There are three important conclusions to draw from the FOM analysis of MEMS switches.

That is the ability to set the gap independently of the materials. The FOM can be reduced by as much as the gap, or mechanical travel distance, can be increased. Secondly, the change in dielectric from semi conductor to air gives an order of magnitude lower value for capacitance. The third conclusion is that the effective area factor is the dominant "material" property. It is not known if the factor of 10^{-4} is a fundamental limit or if improvements can be made. The study of the physics of metal to metal contact in small areas may be productive in future im-provements in FOM.

6. Comparison

A number of sources were used to compile the data that is summarized in the following Table 1. The capacitance and resistance data was extracted from commercial infor-mation, published papers or determined experimentally by the authors. The last entry was taken from **ARPA's website.** A further comparison of the switching elements is presented in Fig. 3. In this graph we plot the ratio of $S^{\text{off}}/S^{\text{on}}$

for a switching element connected in a series configuration. For the optical switch and the MEMS switches, this is a con-figuration that might be be used. The curves for individual p-i-n diodes and MESFETS were produced by simulation using Touchstone models. The data for the models was extracted from commercial data sheets or measured from sample transistors.

A point that this graph emphasizes is that semiconductor devices have similar off-on ratios even though they do not function by the same principles. The MEMS devices shown are about 30 dB better in switching ratio even though they are first generation devices. This is predicted by our the- oretical analysis presented above and represents a general advantage of MEMS devices over semiconductor devices

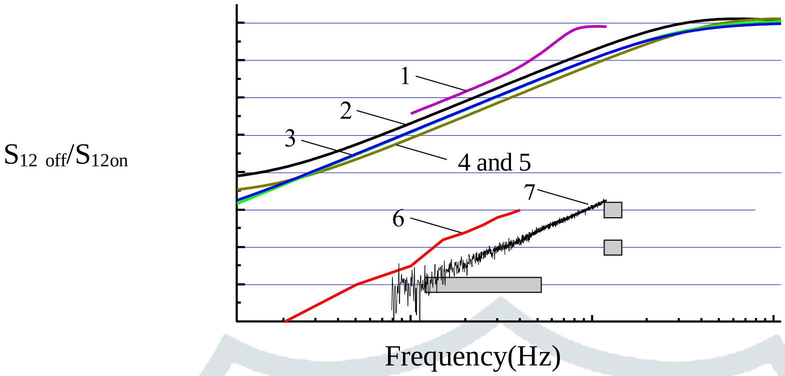

Figure 2. Graph showing the comparison of the *FOM* for a number of RF switches. The la-belled curves are for 1 - measured S_{21} NRC opto, 2 - Opto 40 Ω, 80 fF, 3 - PIN 1 Ω, 110 fF, 4 - Opto 100 Ω, 30 fF, 5 - FET 5 Ω, 100 fF, 6 -Rockwell MEMS switch, and 7 - 60 μm coplanar waveguide gap on quartz measured at NRC. Gray boxes are the switching ratio for mechanical coaxial switches.

Device	**Class**	**FOM (fs)**	**Power (mW)**	**Capacitance (fF)**	**Resistance (Ω)**
IMS-Small	Opto	4000	5	80	50
IMS-large	Opto	3000	5	30	100
NE3290	FET	500	0	100	5
Blackwell	AlGaAsFET	270	0	170	1.6
MA4GP022	GaAsPIN4.5	220	5	110	2
MA4GP022	GaAsPIN20	110	25	110	1
Raytheon	MEMSmemb	12	0	35	0.35
Rockwell	MEMScant	2.5	0	11	0.22
COMDEV	Coaxial	0.07	0	0.35	0.2
ARPA-proj	MEMS	0.01	0	0.05	0.2

Table 1. Summary of devices used in the comparison.

7.Application of Figure Of Merit

The FOM may be of most use when trying to develop a new switch device. Our use of the FOM was developed after attempting to invent a new type of semiconductor switch without initially considering the high frequency AC behavior. The assumption was that if a large change in DC resistance could be produced, then it would be possible to find a width to length ratio that would produce a useful switch. In work which we have reported earlier [1], we developed an optically controlled semiconductor switch. What we found was that the switching characteristics were similar to that available in other devices even though those devices functioned by apparently quite different physics. This can be seen in Fig. 3 and is in fact predicted by eqn. (6) which we subsequently developed. Which shows that the limit of microwave switching behavior is largely predicted by the di- electric constant of the material in the off state and by the conductivity in the on-state. What eqn. (6) makes quite explicit is that there is no geometry that will improve this result. What is further demonstrated by eqn. (11) is that if the switch physically moves when changing from the off-state to on-state, we can introduce an "engineerable" degree of freedom into the device. So far, we have not found a simi- lar degree of freedom available by using conventional semiconductor engineering.

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8. Applications of MEMS switches

Of the many possible applications of MEMS switches, we consider only 2 that reflect opposite extremes of the switch market. Spacecraft applications demand the highest switching performance and benefit by mass/volume reductions. At the other extreme, wireless handheld phones use low cost semiconductor switches.

8.1. Satellite Applications

Fig. 4 illustrates a simplified block diagram of a satellite payload. It consists of receive/transmit antenna, a beam forming network (BFN), input filter assembly (IFA), high gain receiver (RCV), input and output multiplexers, high power amplifiers (HPA) as well as several switch matrices. A satellite system of this type would typically have 100's of switches on-board integrated in the form of switch matrices to provide system redundancy. The receiver input/output and low power switch matrices are typically implemented using coaxial switches while the high power switch matrix is implemented using waveguide switches. The RF-MEMS technology could be potentially used to build miniaturized switch matrices to replace the bulky coaxial technology for the receiver input/output as well as the low power switch matrix. One would expect to achieve more than one order of magnitude reduction in mass and volume by replacing the coaxial technology with MEMS technology.

Such mass and volume reduction would have a dramatic impact on the economics of a satellite program, since launch costs are related to satellite weight. Alternativley, the mass saved in the switch matrix could be replaced in other areas to increase the capability to the satellite. That could be in the form of increased capacity by adding payload electronics or extended station keeping life by adding more fuel. MEMS switches could be also potentially used in beam forming networks (BFN), particularly, in the de- sign of reconfigurable Butler matrices and phase shifters for the multi-beam satellite communication systems.

8.2. Wireless Applications

MEMS switches can replace the SP2T and SP3T switches, which are currently used in dual-band, and triple band cell phones. These switches are currently implemented using semiconductor technology. The advantage of using MEMS technology in this case would be RF performance improvement, which would in turn reduce dc power consumption. This is a very low cost high volume application at present filled by GaAs MESFET switches. A commercial MESFET provides about 0.9 dB insertion loss which by itself consumes about 19% of generated RF power. In principle a MEMS switch could pro- vide 0.2 dB insertion loss which reduces the power loss to 4.5%. This improvement is a worthwhile engineering objective, but as a consumer product it would have to be available at about the same cost as a GaAs MES- FET. Presently GaAs MESFET switches cost less than $1 in quantities of 100,000. There are as yet no similar commercially available MEMS switches so that we cannot make a cost comparison.

A further requirement for this application is that the switches must be specified for the environment found in a hand held phone. The temperature range required is -40 °C to 85 °C. The state of development of MEMS switches seems to be still at a level of ensuring basic functioning. We have not found references to RF characterization over the required temperature range.It is expected that future wireless receivers would need to operate at several bands covering a wide range of frequencies from 900 MHz up to 5 GHz. These receivers will have also to operate in an environment of increasing interference. Such requirements could be met with the switched filter bank as shown in

Fig. 5. The entire band to be covered by the receiver is divided into several channels where the appropriate narrow-band is selected using a switched tunable filter bank. In view of current conventional technologies for RF filters, a receiver with such capability would be bulky, power consuming and very expensive. However, with the use of MEMS technology, MEMS switches could be integrated with MEMS tunable filters to build the whole re-configurable receiver on one single chip. The availability of high performance MEMS switches and filters is a keyto miniaturization of such type of wireless receivers.

9. Conclusion

In comparison with the dominant semiconductor devices, MEMS offers a fundamentally superior basis for developing microwave routing devices. This will become particularly advantageous as frequency is increased. There are numerous unresolved problems of developing suitable fabrication techniques and a need for more reliable switches. The choice between RF MEMS switched and semiconductor switches depends on the specific requirements of the RF application. RF MEMS switches excel in low insertion loss and high isolation applications where speed is critical, while semiconductor switches are more versatile and cost-effective for various RF applications. However, some applications of RF MEMS switches are expected in the next few years.

10. Acknowledgements

I would like to thank Dr.Raghavan who encouraged me to publish a paper and also I express my sincere thanks to my family members.I would like to extend my heart felt thanks to my friends.

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