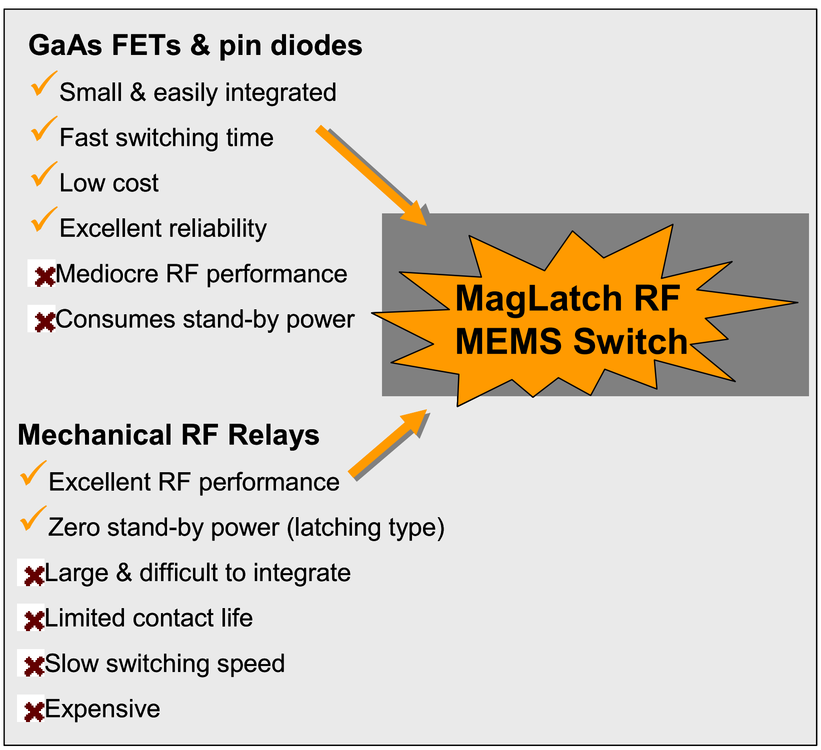
MagLatch™: The Superior RF Switch Technology
Part I – The Advantages of MEMS

C. Wheeler
Microlab, Inc.
cwheeler@microlab.net

The problem with current RF switches

It is tempting to think of an RF switch as a simple gating device that is either ON or OFF. In reality, the picture is not so simple – especially at high frequencies. Any ON-state series resistance or impedance mismatch will cause insertion loss and return loss, respectively. Similarly, any OFF-state capacitance will degrade the isolation. Further, any nonlinearity or dispersion in the power transfer characteristics can lead to the generation of unwanted frequency components that degrade system performance. While all real switches, solid state or electromechanical, exhibit some degree of these non-ideal behaviors, electromechanical relays come closest to matching ideal behavior. Even though electromechanical relays (EMRs) have been in use since the 1930's, they still provide the best high frequency performance of any available technology. For example, DC-40GHz coaxial switches are commercially available that have an insertion loss of less than 1dB, isolation of better than 50dB and can switch several watts of signal power. The main problem with conventional RF relays is that they are very large, have a limited mechanical lifetime, slow switching speed, are only available as discrete units and can be expensive. While mechanical switches and relays do have very good RF performance, these components are best suited for rack-mounted systems where size and cost are secondary considerations. On the other hand, semiconductor RF switches based on PIN diodes or GaAs FETs, are very small, easy to integrate at the chip level, have very fast switching time, infinite cycles to failure and can be very inexpensive. The disadvantage of solid state switches is that their high frequency (actually, wide bandwidth) performance is limited. While it is possible to design a FET or diode-based switch to have decent characteristics over a narrow frequency range, when used in broadband applications the insertion loss, isolation, linearity and low frequency series resistance are generally poor. Even when designed for narrow-band operation, the insertion loss, isolation and linearity characteristics of a solid-state switch are inferior to mechanical switches. A clear trade-off is evident: high frequency performance must be sacrificed for size, cost and switching speed. Normally, the end use application will dictate which type of switch technology is appropriate, locking the designer into a particular set of advantages and disadvantages. MEMS switches provide a solution that combines the performance of electromechanical relays with a dimension scale and cost structure of microelectronic devices.



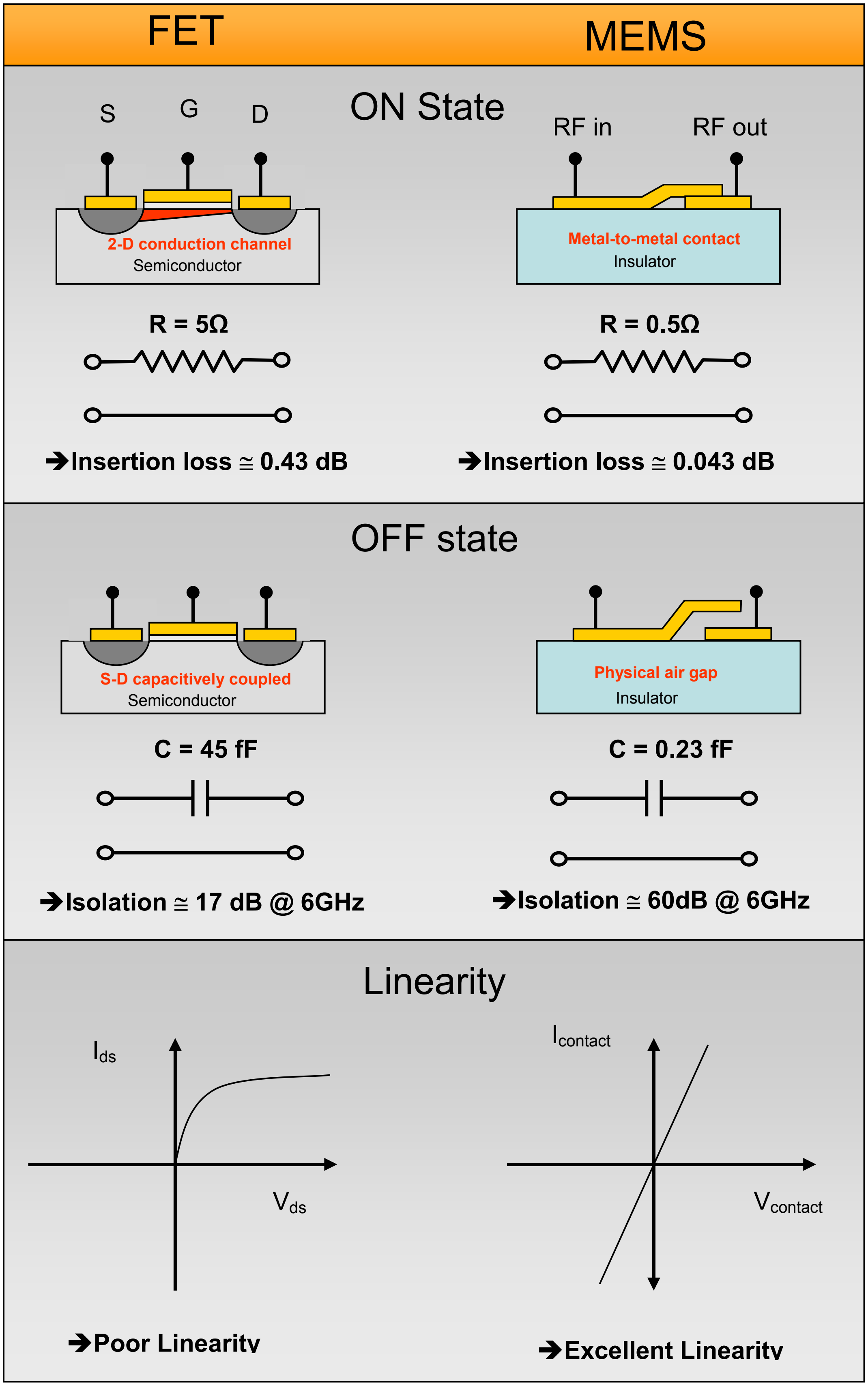
Because of this, it is safe to say that MEMS RF micro-relays will replace some - although not all - types of RF switches used today. More importantly, MEMS RF solutions will enable new applications that require the high performance switching performance of mechanical relays at the size and cost of solid state current solid state switching techniques.

Why MEMS are better

To understand why mechanical switches (MEMS and relays) provide better insertion loss, isolation and linearity than solid state devices, consider the figure below that compares these three properties of a FET transistor switch to those of a MEMS switch. The FET is assumed to be a typical 600µm gate length GaAs MESFET [1] and the MEMS switch is a Microlab MagLatch™ device [2]. Simple analysis is sufficient to highlight the main mechanisms that bring about the drastic differences between the two types of devices. First, consider insertion loss of the devices in the ON-state. Assuming reflective and reactive losses can be neglected – not bad assumptions - insertion loss can then be viewed as a measure of resistive loss through a device. In that case, the larger the resistance, the larger the insertion loss will be. As shown schematically in the figure, the 2-dimensional sheet charge of electrons in the FET channel creates an impedance of about 5Ω, whereas the metallic conduction path of the closed MEMS switch has an impedance of only 0.5Ω. When modeled as simple 2-port (series) resistive networks as shown in the figure, S_{21} is easily calculated from ABCD parameters [3] and insertion loss then given by

$$\text{I.L.} = -20 \log (S_{21}) \tag{1}$$

The simple calculations result in an I.L. of 0.43dB for the FET and 0.043dB for the MEMS switch – the FET transmits 95% of incident power, whereas the MEMS switch transmits 99.5%. These results are in good agreement with measured values at 2GHz. Next, consider RF isolation for the two OFF-state devices as shown in the center of the figure. The analysis is similar to that just described for insertion loss, but now the devices are in the OFF-state and can be modeled as parallel plate capacitors. The fundamental difference between the devices is that the FET relies on a depleted channel to isolate the source and drain – which are still physically connected through the semiconductor substrate – whereas the MEMS switch utilizes a physical air gap to separate the RF input and RF output electrodes. The drain-source capacitance of the FET is taken to be 45 fF and the capacitance of the open air gap is 0.23 fF. Again using ABCD parameters to calculate S_{21} for the OFF-state case (assuming 6GHz), and eq.(1) to now calculate isolation, results in 17dB for the FET and 60dB for the MEMS switch. This means that the OFF-state FET will transmit 14% of the incident power, whereas the MEMS switch will only transmit 0.1%. Finally, consider linearity of the two devices as compared by output I-V characteristics in the bottom section of the figure. Qualitatively, one can see that a FET is inherently nonlinear – actually a voltage dependent resistor - whereas the MEMS switch resembles an ideal resistor. The physical mechanism responsible for the FET's nonlinearity is a result of being a semiconductor device in that for a fixed gate voltage, the carrier (drift) current density saturates above a certain drain voltage. The MEMS switch, conversely, is an all-metal structure that behaves like a low resistance transmission line and is consequently not governed by these same carrier statistics. The third order intermodulation product (IP3) is a two-tone measurement that describes the extent of nonlinearity by quantifying the power level of the third order mixing products relative to the carrier signal peaks, as shown in the figure. Typically a FET will have a IP3 of about -45 dBc, whereas a MEMS switch is typically in the -65 dBc range – this parameter is normally so small for MEMS switches that particularly sensitive instruments must be used in order to detect any nonlinearity whatsoever.


FET
MEMS
ON State
S
G
D
2-D conduction channel
Semiconductor
RF in
RF out
Metal-to-metal contact
Insulator
R = 5Ω
R = 0.5Ω
➔Insertion loss ≅ 0.43 dB
➔Insertion loss ≅ 0.043 dB
OFF state
S-D capacitively coupled
Semiconductor
Physical air gap
Insulator
C = 45 fF
C = 0.23 fF
➔Isolation ≅ 17 dB @ 6GHz
➔Isolation ≅ 60dB @ 6GHz
Linearity
I_{ds}
V_{ds}
$I_{contact}$
$V_{contact}$
➔Poor Linearity
➔Excellent Linearity

MagLatch™: The Best Alternative

MEMS (micro-electromechanical systems) switches provide a new alternative that offers the advantages of both mechanical and solid state switches. A fabrication technology, very similar to silicon integrated circuit manufacturing, called surface micromachining is used to produce mechanical switches that are about the same size as solid state devices but retain similar RF performance characteristics of conventional mechanical relays. Table 1 compares several properties of solid state, electro-mechanical relays (EMR) and MEMS switches, where it is assumed that the operating frequency is to be DC-6GHz. While no one switch technology is ideal for all applications, the recent availability of the MagLatch™ RF MEMS switch adds a degree of design flexibility which until now was not available.

RF Switch Technology comparison (at 5 GHz)

Characteristic	MagLatch MEMS	GaAs FET	Pin Diode	EMR (PCB)	Coaxial RF Switch
Size	**Very small**	Very Small	Very Small	Medium	Large
DC Resistance	**<0.5 Ω**	1-5 Ω	1-5 Ω	0.1 Ω	0.5 Ω
Carrying Power	**3 WCW**	0.5 WCW	5 WCW	10 WCW	35 WCW
Breakdown Voltage	**Medium**	Low	Varies	High	High
Speed	**<0.5 msec.**	5 nsec.	10-100nsec.	6 msec.	1-40 msec.
Life Cycle	**>10^7 (cold) >10^6 (hot)**	infinite	infinite	$5x10^6$ (cold) $3x10^5$ (hot)	$10^5 – 10^6$
Frequency Performance	**DC - 6 GHz**	< 8 GHz (narrow-band)	< 20GHz (narrow-band)	DC < 6 GHz	< 40 GHz
Insertion Loss (dBmax)	**<0.5**	2	0.5	0.5	0.1
Isolation (dB min)	**>40**	28	30	40	80
3rd Order Harmonics	**Very Good**	Poor	Poor	Very Good	Very Good
Power Consumption (OFF state)	**Zero**	Low (1-20 mW)	Medium (10mW)	High (0-900 mW)	High (0-700)
Drive Voltage	**5V or less**	5-8 V	3V, 5 V	3-24 V	12 V, 28 V
Integration Capability	**Very Good**	Very Good	Very Good	Poor	Very Poor
Est. Retail Cost – SPDT Type	**Low**	Low (Few $)	Low ($1-$8)	High ($30-$100+)	Very High ($100-$200+)

References:

[1] Alan Noll, " GaAs MMIC Switch is Designed Around Low-Capacitance MESFETs, Microwaves & RF, March 2000.

[2] www.microlab,net

[3] David M. Pozar, Microwave and RF Design of Wireless Systems, p. 55, 2000. ISBN 0-471-32282-2