The State of RF/microwave Switch Devices

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RF and microwave switches are used extensively in wireless systems for signal routing finding wide use in switching signals from antennas to the transmit and receive chains. They are one of the highest volume RF devices in use today as several devices are typically contained in a block diagram. RF and microwave switches fall into the two main categories of electromechanical and solid-state switches. While electromechanical switches have not found wide use in RF and microwave applications since the PIN diode was developed, they are making some new in-roads in certain applications in the form of micro-electromechanical systems (MEMS) devices. Solid-state switches are typically more reliable and exhibit longer lifetime than electromechanical switches plus offer faster switching times. However, solid-state switches typically have higher intrinsic ON resistance and more harmonic distortion than mechanical switches.

Today's CMOS silicon-on-insulator (SOI) and silicon-on-sapphire (SOS) switches are starting to challenge GaAs MMIC switches in many applications as their cutoff frequencies and breakdown voltages improve. Each technology has it advantages and disadvantages which can be leveraged for various applications for an optimal solution. Up until a few years ago, MEMS switches were considered an emerging technology that had reliability and reproducibility issues but recent generations have solved many of those problems making them very competitive in several applications.

Oldie but Goodie

Starting in the 1950s, PIN diodes were the first widely used solid-state switching technology and are still used in wide use today. They still excel in very high power and high frequency applications with low insertion loss and better power handling capabilities when compared to most IC FET switches. A PIN diode operates as a variable resistor at RF and microwave frequencies. Its ON resistance varies from less than 1 ohm (ON) to more than 10 kohms (OFF) depending on the bias. One limitation of a PIN diode switch is its lower frequency limit of a few kHz to about a MHz depending on the thickness of the intrinsic or I region. Therefore they do not operate all the way down close to DC like most IC switches such as GaAs MMICs. They also require more current to operate compared to IC switches so typically are not a good fit for mobile applications. However, for higher power levels used in military, Satcom or basestation applications, they can be more desirable in many applications.

As explained in an Agilent application note, PIN diode switches can consist of a mixture of series and/or shunt diodes depending on the circuit requirements (ref). Series PIN diodes can function within a wide bandwidth limited by the biasing inductors and DC blocking capacitors while shunt diodes feature high isolation relatively independent of frequency (Agilent Figure). Circuit designers often use transmission lines to create series lumped inductance to achieve a low pass filter effect which enables the switch to work up to the desired frequency. Shunt diode switches have limited bandwidth arising from the use of quarter wavelength transmission lines between the common junction and each shunt diode. Circuit designers also often use a combination of both shunt and series diodes to achieve optimal insertion loss and isolation performance in a diode switch but there is a trade off between them. As seen in these various configurations, PIN diodes can require larger circuit areas to realize because of the passive components and multiple diodes are needed for the switch design compared to IC switches so the larger footprint is an issue in compact and mobile designs.

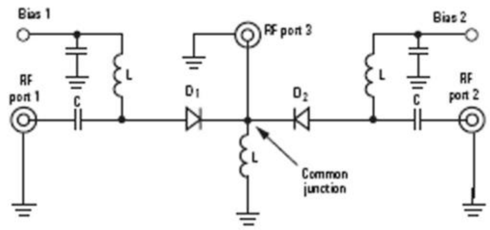


Figure 3a. Series pin SPDT switch[1]

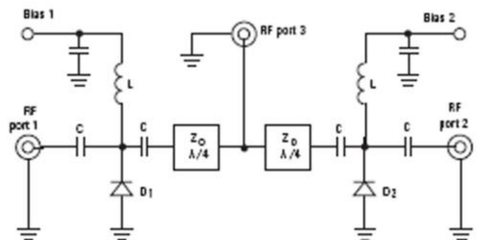


Figure 3b. Shunt pin SPDT switch

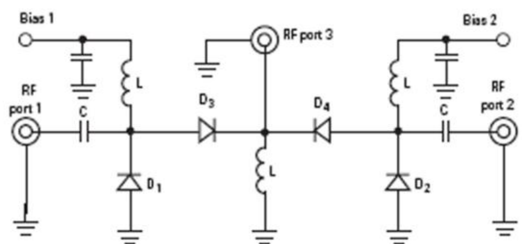


Figure 3c. Series-shunt pin SPDT switch

Some examples of high power PIN diode products are Aeroflex/Metelics who offers surface mount PIN diodes with 100 W CW power handling and 650 W pulsed power handling with insertion loss less than 0.2 dB and isolation of 53 dB. Skyworks offers a series of QFN packaged PIN diodes for high power applications of 50 W CW power handling and 500 W pulsed that operate to 6 GHz with better than 0.45 dB insertion loss and isolation of better than 37 dB. M/A-COM has a special KILOVOLT™ series of PIN diodes (ceramic packaged) that can handle multi-kilo watts of pulsed power for very high power applications in addition to many other offerings. These three companies, along with a several others, have been manufacturing PIN diodes for many years, so they are well characterized and have proven reliability in many demanding applications. They are available in many form factors such as chip, beamlead, ceramic packaged and surface mount packaged in addition to chip scale form factors.

PIN diodes are not just offered as discrete devices and many manufacturers offer integrated diode MMICs. M/A-COM Tech pioneered the diode MMIC in the late 1980s with the Glass Microwave Integrated Circuit (GMIC) which used a glass process to isolate the devices by fusing the GaAs with a glass wafer (ref Nov 2008 MWJ article). This was the predecessor to the

Heterolithic Microwave Integrated Circuit (HMIC) process which is glass and Si fused together. M/A-COM Tech has recently developed multi-octave, high power switches with their AlGaAs PIN diode HMIC devices including multi-throw switches with power handling of 50 W CW (over 100 W pulsed) with less than 2 dB insertion loss and over 30 dB isolation at 40 GHz. Figure X shows a SP8T broadband an AlGaAs HMIC PIN diode and it performance.

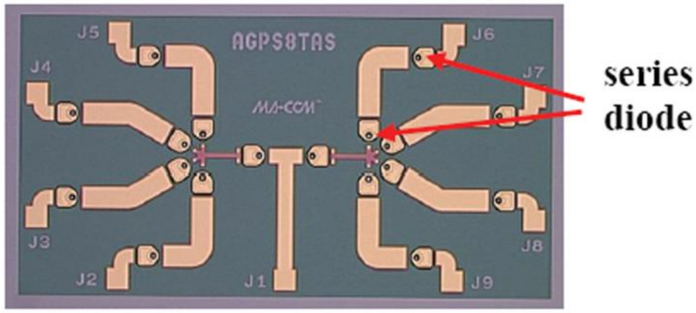


Fig. 7. An SP8T switch utilizing only series diodes

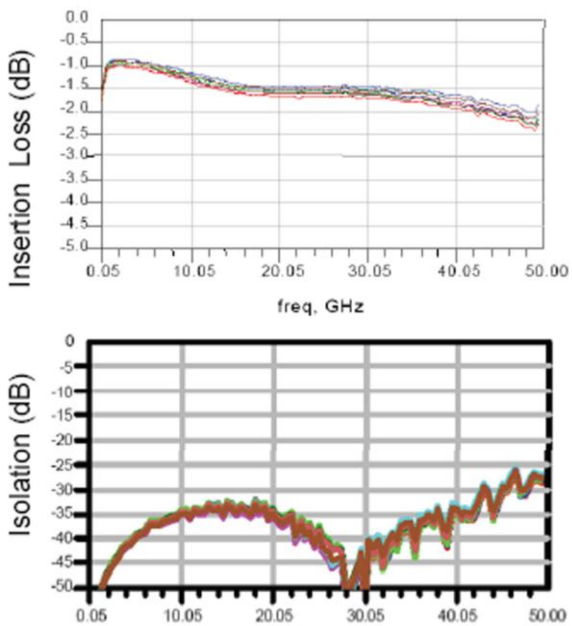


Fig. 8. Broadband performance of the SP8T switch

Another example is TriQuint who offers a vertical PIN process as a foundry service. An example device is a GaAs monolithic PIN diode SP4T switch that operates from DC to 20 GHz. At a bias current of 10 mA per output arm, typical mid-band performance is 0.6 dB insertion loss with 40 dBm isolation in the off-arms. Isolation and insertion loss can be adjusted by varying the output arm bias current of the switch.

The Current Workhorse

GaAs field-effect transistor (FET) based switches have been the mainstay of RF/microwave switches since the 1980s when MMIC circuits became widely available at relatively low prices.

Driven by DARPA funding for defense applications (MIMIC program) and a high demand for commercial wireless devices, GaAs MMIC reproducibility improved dramatically during this period and device costs were greatly reduced (ref June 10 MWJ article). FET switches are very stable and repeatable due to good control of the drain-to-source resistance. FET switches are voltage controlled resistors so they provide low power operation, small size and relative design simplicity compared to PIN diodes. They are broadband (DC to 20 GHz devices are widely available) and have relatively high linearity.

Initially, GaAs MMIC MESFETs were widely used in the 1980s and 90s but have given way to the PHEMT MMIC devices which have better noise characteristics and now more widely used for GaAs MMIC devices today. While MESFET devices were able to reach switching speeds down to tens of pico seconds, PHEMT devices suffer from gate lag as electrons can be trapped on the surface. PHEMTs typically have switching times in the hundreds of micro seconds as they can switch in tens of nano seconds (10 to 90%) but have gate lag times of several hundred microseconds (90 to 98%).

However, new developments such as M/A-COM’s nano second designs achieve about ten nano second switching times including gate lag. M/A-COM made a number of changes to the PHEMT process and device structure (ref AR 9279) to overcome this problem. The number of surface states and interface traps were reduced at the ungated GaAs surface using cleaning techniques and the deposition of a special passivating dielectric. The formation of the Schottky diode gate was modified to both reduce gate resistance with no additional gate capacitance in order to minimize the RC charging time associated with device turn-on and turn-off. And a proprietary III-V layer was added to the PHEMT structure to further reduce the channel resistance and enable enhanced movement of charge through the device especially from the ungated recess region. This process optimization for low gate lag not only resulted in an improvement in the 90 to 98 % switch settling time, but also exhibited reduction in the 10 to 90 % switching speed. While CMOS Si based switches do not suffer from gate lag, they only typically switch in the range of micro seconds. One of the drawbacks of MEMS switches is switching speed as they typically exhibit speeds of tens to hundreds of micro seconds for electrostatically operated devices.

Low channel resistance allows GaAs MMIC switches to operate at low frequencies (very near DC) and reverse biasing completely depletes the channel in the OFF state providing excellent isolation at low frequencies (ref 1 in Agilent WP). However, the isolation degrades at higher frequencies due the effect of the drain-to-source capacitance. Figure X (Agilent Fig 7) shows a simplified schematic diagram of a SPDT FET switch. The biasing path is not connected to the RF path simplifying the DC biasing path and eliminating the expensive RF choke. The chokes are used to reduce the insertion loss that results from the biasing path being connected to the RF port in PIN diode switches. The ON resistance of a FET is still typically higher than a PIN diode so the insertion loss performance of FET switches is not as good as PIN switches. FET switches are voltage controlled so they consume far less current than current controlled PIN switches.

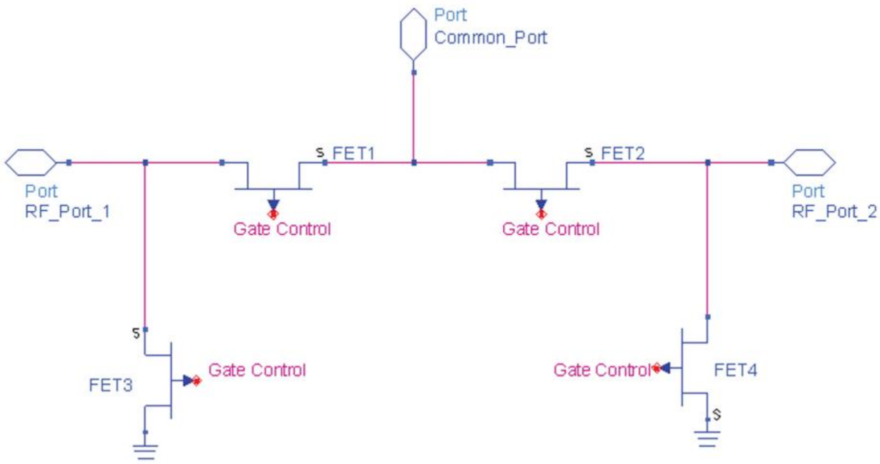


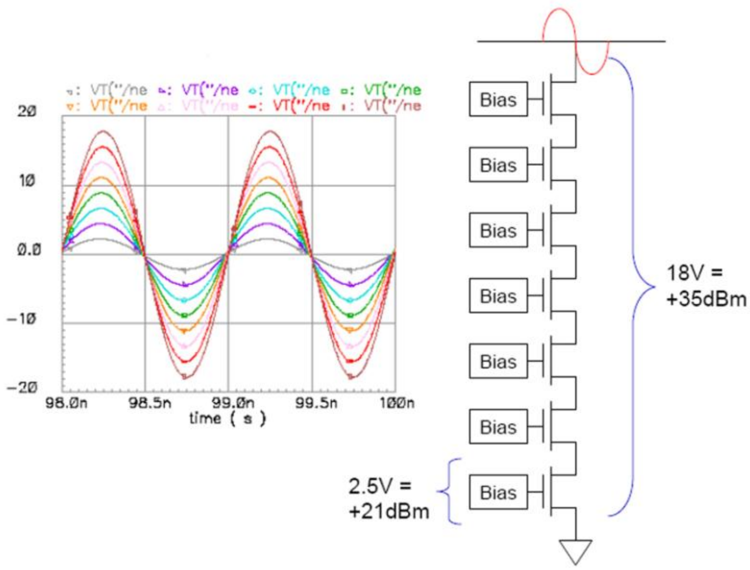
Figure 7. Simplified SPDT switch using FETs as switching devices

While GaAs MMIC switches were originally only available as depletion mode devices, they required a negative control voltage for operation which was not desirable compared to CMOS switches. An alternative to using a negative control voltage is to elevate or float the DC voltage at the source of the FET to +5 V and use a 0 V to +5 V control voltage. Floating the DC voltage requires blocking capacitors which complicates the design and requires more circuitry. But there are now a number of suppliers offering enhancement mode PHEMT (E-PHEMT) devices which do not require a negative gate voltage to operate. They are normally OFF and use a positive voltage to turn the FETs on. This also allows integration of logic on the same chip which has always been an advantage with Si based FET switches. Many companies and foundries also offer E/D-PHEMT processes that can incorporate both FET modes on an IC so that each device type within the circuit can use the process that best fits its needs for performance. Companies such as TriQuint, RFMD, Skyworks, Hittite and M/A-COM Tech, along with others, use this technology in their switches for appropriate applications where the increased complication in processing is worth the added benefits. Therefore the disadvantages for negative voltage operation and logic integration for GaAs MMICs has been diminished over the past few years with this change in technology.

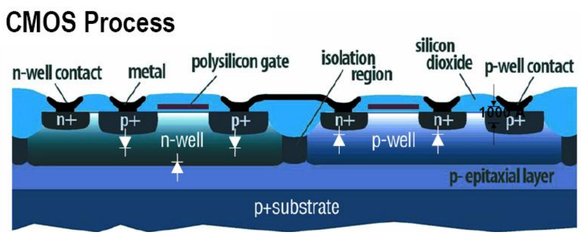
The GaAs MMIC switch market is still very large and they are used in many applications from commercial to military. Many circuit designs and switch types are available and optimized for almost any application. The design demands for compact, low current multi-throw handset devices are far different from high power basestation or military radar applications. Most of the widely known component manufacturers such as Skyworks, RFMD, TriQuint, Hittite, CEL/NEC, Mini-Circuits and M/A-COM Tech offer a wide variety of devices depending on the application. GaAs MMIC devices are still progressing as they shrink die sizes, develop chip scale packaging and optimize the FET design, but the technology is relatively mature so the improvements are not revolutionary at this point. Currently, GaAs PHEMT switches still offer the best performance for most high frequency (over a few GHz) and broadband applications that require low to medium power levels.

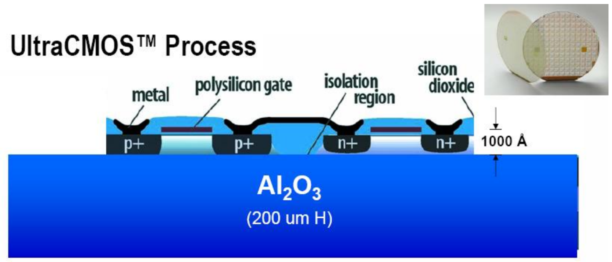
Gaining Ground

Standard Si CMOS based FET switches have previously not proven to be good RF switches as they suffered from significant leakage current through the insulating substrate and low breakdown voltages. One way to overcome the low breakdown voltage is to stack the FETs but it is difficult to accomplish spreading the voltage evenly across the FETs so this has not worked very well in standard CMOS. However, Si-on-insulator (SOI) and Si-on-sapphire (SOS) FET switches have recently been gaining market share in various applications as their cutoff frequencies and breakdown voltages have been improved over time, and they are competing well with GaAs switches in some of the high volume applications such as handset switches and even some military applications. These technologies accomplish FET stacking with even voltage distribution across the FETs, have low leakage current and much better linearity than standard CMOS. An example of higher voltage operation is Peregrine Semiconductor SOS switches that have recently achieved 50 W CW power handling on several switch designs which are much higher than most GaAs MMIC switches and similar to PIN diode MMICs (See Peregrine figure).



Peregrine Semiconductor and IBM recently teamed up to develop and manufacture future generations of Peregrine's patented UltraCMOS™ silicon-on-sapphire SOS process technology which is unique for it thin insulating layer. It provides the needed isolation but is thin enough to so that it minimizes the negative effects of a thicker Si layer that does not provide ideal high resistivity (see Fig). When fully qualified, the next-generation UltraCMOS RF ICs will be manufactured by IBM for Peregrine in the jointly-developed 180-nanometer RF CMOS process at IBM's 200 mm semiconductor manufacturing facility in Burlington, VT. This development marks the first commercial use of 200 mm (8-inch) wafer processing for silicon-on-sapphire process, a patented variation of SOI technology that incorporates an ultra-thin layer of silicon on a highly insulating sapphire substrate. An example high performance switch recently released by Peregrine is an absorptive switch that delivers operating from 450 MHz to 4 GHz with IIP3 of +58 dBm, IIP2 of +95 dBm and insertion loss of 1.6 dB (450 MHz). The switch handles maximum +33 dBm input power (across the range) with high ESD tolerance of 3.5 kV HBM.





While GaAs MMIC switches offer good linearity and isolation with low ON resistance and low OFF capacitance, they do have some disadvantages. In addition, GaAs technology is a mature technology that has nearly reached its limits. As a representative from Peregrine said, “There are not many more dials to turn to improve GaAs device performance.” SOS and SOI CMOS based devices are now closing in on a lower Ron*Coff product, a good figure of merit for switches, allowing the design of switches with lower insertion loss and higher isolation. Peregrine has projected that SOS will be able to achieve a product of less than 200 fs as they progress to 0.18 micron technology and even lower with 0.13 micron technology. But today some GaAs devices are already at this level.

Up until recently, SOI resistivity was not as ideal as GaAs or SOS so devices made with SOI technology exhibited higher levels of harmonic and intermodulation distortion. However, recent advancements in SOI CMOS technology have been able to reduce these effects to make them competitive with SOS (RFMD paper ref). RFMD has demonstrated a SP9T SOI switch with similar performance to current PHEMT switches with a Ron*Coff product of 250 fs which is close to a high quality PHEMT value of 224 fs. This compares favorably to current SOS products of 400 fs with 0.25 micron technology but with 0.18 micron technology, SOS is expected to be below 200 fs. RFMD has three new SOI switches that are being released and this lineup has been designed into two major handsets so it seems to be gaining momentum. Earlier this year, Skyworks introduced a symmetrical, SP4T SOI switch. The device is designed for 3GPP bands from 0.70 to 2.7 GHz with typical insertion loss as low as 0.6 dB and isolation as high as 30 dB and harmonic performance less than 75 dBc at 0.9 GHz. At the same time they also introduced a WCDMA DP4T SOI switch with a decoder. So today’s best GaAs PHEMT switches, 0.18 micron SOS and 0.18 SOI appear to be nearly equal in this figure of merit measurement. Table X compares the Ron*Coff figure of merit for various technologies.

Switch Technology Figure of Merit

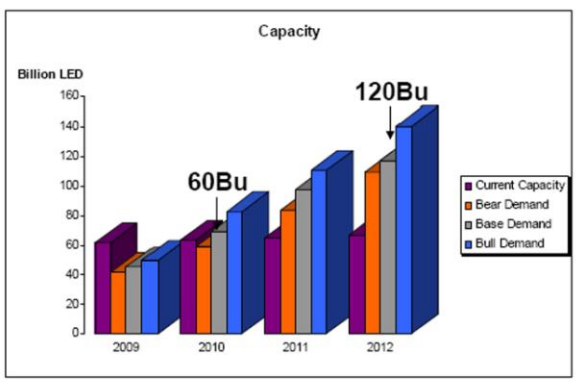
Process	Device	Ron [Ω-mm]	Coff [fF/mm]	Ron*Coff [fs]
0.18um thick-film SOI	5V NFET Lg=0.6um 13.0nm gate ox	1.9	255	485
0.18um thin-film SOI	2.5V NFET Lg=0.32um 5.2nm gate ox	0.8	310	250
0.5um SOS	NFET 10.0nm gate ox	2.8	270	756
0.25um SOS	NFET 5.0nm gate ox	1.6	280	448
pHEMT		1.4	160	224

Add .18 micron SOS data?

GaAs MMIC devices can have more contact resistance than these Si technologies increasing losses and cannot integrate logic circuits as well as Si based technologies. Driving GaAs switches also frequently requires extra interface components and GaAs has limited capability to integrate other functions such as logic control and memory. While CMOS switches have about 2000 V (HBM) ESD sensitivity which is relatively robust, most GaAs MMIC switches are only around 200 V making them susceptible to ESD damage and typically require special handling procedures. The same is true with most RF MEMS switches.

Cost is a major advantage of any type of Si wafer processing for large volume applications compared to GaAs because Si has lower material costs and larger wafers to reduce the cost per unit area. While in the past SOS substrates were very expensive and only available in small diameters, this is changing as the LED market is fueling demand for lower cost substrates and driving high volumes. According to Peregrine Semiconductor, Government funding for the LED market along with the demand for low energy lighting could make sapphire substrates the highest volume electronic devices in the near future (See Fig). Peregrine also recently announced availability of 150 mm wafers putting them on the same substrates sizes as high volume GaAs.

Sapphire has potential to be highest volume semi substrate



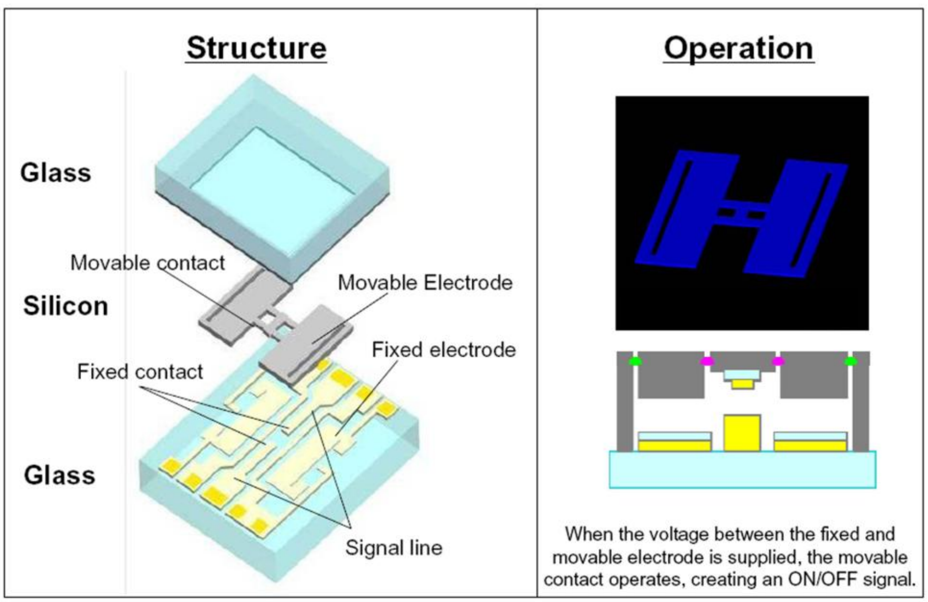
Source: Canaccord Adams estimates

However, neither SOS nor GaAs wafer processing is even close to the low cost of SOI switches which use standard Si processing and larger wafer sizes. As their performance improves to match GaAs and SOS switches, they will have a significant cost advantage for high volume applications. One way that GaAs devices compete on cost is their setup costs (lower cost mask sets) are typically much less for wafer runs than Si so for lower volumes they can sometimes gain a cost advantage especially for IDMs that produce their own devices (ref MWJ June 10 article).

While SOI technology has not been competitive in the past, it seems poised to compete in the lower frequency, high volume market such as handset and perhaps even WLAN markets. As one representative from RFMD put it, “While SOI was thought to have poor linearity, we are finding that through careful switch branch layout, charge pump optimization and an excellent collaboration with our foundry partners, we are now meeting or exceeding the best of SOS reported performance, and SOI substrate costs are a fraction of what sapphire at 200 mm, not counting the fact that SOI uses standard technologies and libraries.”

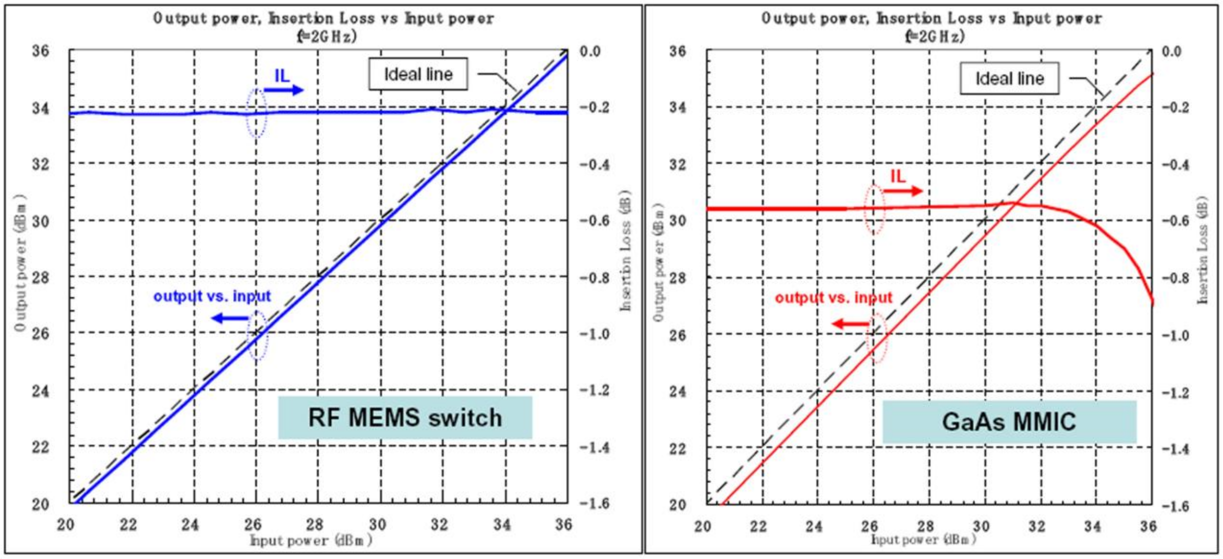
Starting to Compete

RF MEMS capacitive switches were first developed and used in the early 1990s and typically use an electrostatic means to actuate the switch. They offer very low loss and high linearity compared to FET switches but their switching speed is typically much lower. There are basically two types, the ohmic contact and capacitive contact. With ohmic switches, two metal electrodes are brought together to create a low resistance contact while in capacitive switches, a metal membrane is pulled down onto a dielectric layer to form a capacitive contact (Fig Omron construction). Figure X shows the construction used by Omron for their MEMS switches. The electrode is a special metal composition the flexes down when voltage is applied to turn the switch on and returns back to its original position without the applied voltage. The use of capacitive coupling has eliminated issues associated with older generation MEMS switches of dry contact, metal to metal ohmic switching. Issues with sticking contacts, wear, etc. have been mitigated using this newer technology as suppliers have optimized the metallic materials and design.



Omron has designed a SPDT switch that operates at 34 V with typical insertion loss of 1 dB, isolation of 30 dB and return loss of 10 dB at 10 GHz. RF MEMS switches have no compression point until +36 dBm as shown in the comparison to GaAs switches in Figure X. Radant manufactures some high isolation, low loss MEMS switches such as a SP6T DC – 20 GHz device with 22 dB isolation and less than 0.8 dB loss at 18 GHz and near zero harmonic distortion. They also have a very high isolation DC – 12 GHz MEMS switch with better than 70 dB isolation and less than 0.3 dB insertion loss at 2 GHz.

RF MEMS Switch has no compression point up to +36dBm(4W) RF power.



RF INPUT POWER : 20～36dBm@2GHz

Over the past decade, processing improvements, materials refinements and design changes have enabled designs with less than 0.1 dB loss through 40 GHz, low power consumption of tens of nanojoules per cycle and high linearity of greater than 66 dB according to Memtronics. Reliability is on the order of 100 million cycles, minimum. This has allowed them to compete in several applications such as test & measurement and switching arrays for antennas. The advantage of the mechanical switch is that when it is off, it is physically isolated so there is little leakage. Leakage current is about 100 fA at 100 VDC. MEMS offer lower off state capacitance and better off-state RF isolation than either FETs or PIN diodes. Like GaAs FETs, they have low ESD sensitivity of around 100 V HBM so they require special handling.

iSuppli recently reported that they anticipate RF MEMS revenue to rise to $8.1 M this year, $27.9M in 2011 and then $223.2M in 2014. Much of this is projected to be from cell phone front end adoption of tuning using RF MEMS switches and varactors to help boost the performance of smart phones. iSuppli states that WiSpry and TDK-Epcos are offering RF MEMS for high volume cell phone applications while Analog Devices, Radant Technologies and XCOM Wireless (in cooperation with Teledyne Technologies) as well as Omron are targeting high end applications for testing and instrumentation such as ATC and RF test.

An example of the new MEMS tuning technology is the TDK-EPC high performance antenna tuner module that employs a closed-loop algorithm that optimizes the matching to the conditions of use. Unlike open-loop systems the antenna tuner only requires a synchronization signal, making it easy to design into advanced multiband/multimode mobile devices. Startups Radant and MEMtronics are focusing on defense applications also. Outside of cell phone and instrumentation, wireless infrastructure switches could be replaced by cheaper, higher performance RF MEMS devices and another opportunity is in defense applications for radio systems and phased array antennas.

Future Technologies

While most of the recent advances in switch technology have concentrated on the lower power applications driven mostly by handsets, the higher power applications are still dominated by PIN diode technology. GaN has been developed mostly for high power amplifier applications but it also shows great promise as a future switch technology. A couple of GaN suppliers have started to release switch products. TriQuint has developed three broadband GaN on SiC MMIC switches to cover frequency ranges of DC-6, DC-12 and DC-18 GHz (see photo). These devices have maximum insertion loss of 0.7, 1.0 and 1.5 dB and demonstrate 40, 15 and 1 W RF power handling, respectively for 6, 12 and 18 GHz designs. Cree has advanced datasheet information available on a 25 W, 0.1 to 3 GHz SPDT GaN MMIC switch. It features less than 0.7 dB insertion loss, 15 ns switching speed, over 30 dB isolation and over 60 dB TOI. With the need for high power switches with lower current consumption, GaN switches should eventually find their way into several applications especially in satellite and military applications.

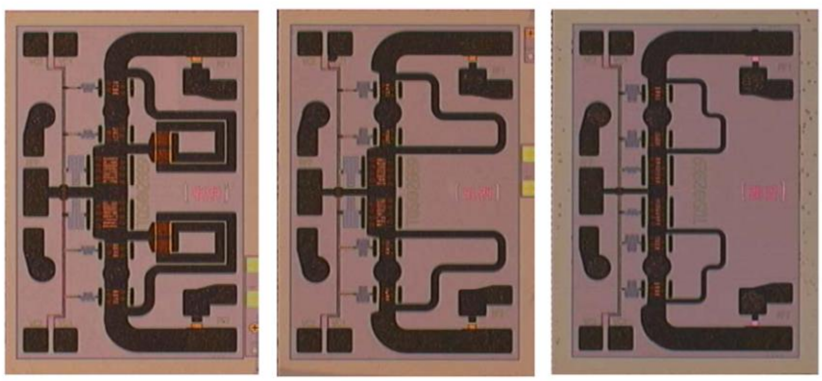
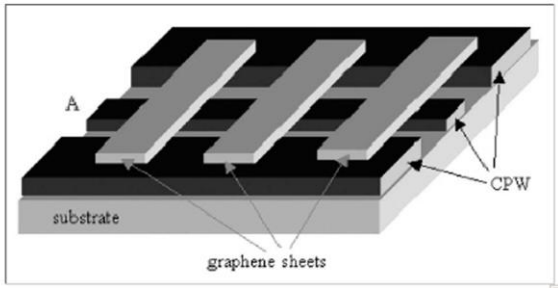


Fig. Die photographs of **TriQuint's** 6 GHz, 12 GHz and 18 GHz SPDT switch MMICs.

There also has been some work done with microwave nano electromechanical systems (NEMS) switches that potentially could overcome the drawbacks of the current MEMS devices. Work has been done that shows graphene flakes that can operate as a switch up to 60 GHz with switching times of less than a nano second (ref nanotech paper). This could enable all the benefits of MEMS switches while obtaining fast switching times comparable to the fastest solid-state switches. The simplified construction is shown in Figure X (nanotech paper). The device is a coplanar waveguide and an array of metallic graphene sheets suspended over it. The waveguide is made from gold strips deposited on a 500 micron thick semi-insulating Si substrate. The graphene flakes are suspended over the waveguide due to van der Waals forces but could be attached via metallic contacts.



Top view of the graphene NEMS switch configuration. Credit: *J. Appl. Phys.*

The State of Switches

Table X shows a summary of the key performance metrics for the various switch technologies covered. The "state" of RF and microwave switch technology today shows that the PIN diode is still very viable in high power, high frequency applications, but the most widely used technology is the GaAs MMIC which still offers the best performance for most high frequency (over a few GHz) and broadband applications that require low to medium power levels. The market is changing as SOS and SOI CMOS switches are making significant in-roads in some high volume applications as their performance is approaching that of GaAs MMICs at frequencies up to a few GHz and they offer cost and integration advantages. SOI and SOS switches are also proving they can be viable in medium to high power applications as breakdown voltages have improved with FET stacking. In the future, GaN MMIC switches show great promise to take a foothold in higher power applications, probably replacing PIN diodes in some of these areas. MEMS switches are showing promise in the test/measurement, phased array and tunable module market which promises to be significant in the large handset market.

Switch Technology/Parameter	**Monolithic PIN diode**	**GaAs MMIC**	**CMOS SOI/SOS**	**RF MEMS**	**GaN MMIC**
Insertion Loss (dB)	0.3-1.5	0.3-2.5	0.3-2.5	0.1-5	0.1-1.5
Isolation (dB)	>=30	>=25	>=30	>=30	>=30
Power Handling (W)	<=50	<=10	<=50	<=10	<=100
Power Consumption	High	Low	Low	Low	Low
Switching Speed	ns to µsec	ns to µsec	µsec	µsec	ns
Ron*Coff (fs)	100-200	224	250 (.18 µ)	?	400
Cost	High	Low	SOS-Low SOI-very Low	Medium	High
ESD sensitivity	Medium	High	Low	High	Low