RF MEMS in mobile phones

The need for multiband, multimode band switching at low insertion loss while maintaining excellent linearity in mobile phones is driving the need for RF MEMS-based switches. Since this switching problem gets even more acute as new complex waveforms, such as WiMAX are added to this mix, this article looks at the current state of development in RF MEMS switches and discusses its impact on 3G cellular phones.

By Refugio Jones and Mark Chapman

Carriers are launching third generation or 3G wireless networks globally. These newer 3G standards provide a variety of services, including data and on-demand video. But as wireless networks advance, so too are challenges for mobile phone designers. In addition, recent developments in wireless communications have resulted in hand-held cellular phones that can use up to seven different wireless standards or bands including DCS, PCS, GSM, EGSM, CDMA, WCDMA, GPS and Wi-Fi. Each standard has its own unique characteristics and constraints and brings with it its own specific challenges. RF micro electromechanical systems (MEMS) may help engineers design phones that meet the challenges of integrating multiple bands while maintaining long battery life and progressively reducing the overall size of the handset, adding new capabilities, while keeping these devices small and affordable.

About 75% of the 100 or so components in a mobile phone are “passive” elements such as inductors or variable capacitors. MEMS versions of these components promise to make phones more reliable and power efficient.

Cellular phones of today

Most cellular phones on the market today use a transmit/receive (T/R) switch or a band switch, and/or duplexers at the point where the phone’s antenna interfaces with the cellular phone’s chipset as shown in Figure 1. The use of one or any combination of these depends on the number of different bands employed by each of the major cellular systems operators. Each type of these devices supports the

<table>
<thead>
<tr>
<th>Standard</th>
<th>Transmission Frequency Band (MHz)</th>
<th>Reception Frequency Band (MHz)</th>
<th>Full-Duplex</th>
<th>Half-Duplex</th>
<th>Max. Output Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM 900</td>
<td>890 – 915</td>
<td>935 – 960</td>
<td>√</td>
<td>√</td>
<td>2 W</td>
</tr>
<tr>
<td>EGSM 900</td>
<td>880 – 915</td>
<td>925 – 960</td>
<td>√</td>
<td>√</td>
<td>2 W</td>
</tr>
<tr>
<td>DCS 1800</td>
<td>1710 – 1785</td>
<td>1805 – 1880</td>
<td>√</td>
<td>√</td>
<td>2 W</td>
</tr>
<tr>
<td>PCS 1900</td>
<td>1850 – 1910</td>
<td>1930 – 1990</td>
<td>√</td>
<td>√</td>
<td>2 W</td>
</tr>
<tr>
<td>CDMA</td>
<td>824 – 849</td>
<td>869 – 894</td>
<td>√</td>
<td>√</td>
<td>1.5 W</td>
</tr>
<tr>
<td>GPS</td>
<td>1227.6 &amp; 1575.42</td>
<td></td>
<td>√</td>
<td>√</td>
<td>2 W</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>2.4 GHz &amp; 5 GHz</td>
<td></td>
<td>√</td>
<td>√</td>
<td>1 W</td>
</tr>
<tr>
<td>Wi-MAX</td>
<td>Varies: 2.4 – 5.9 GHz</td>
<td></td>
<td>√</td>
<td>√</td>
<td>2 W</td>
</tr>
</tbody>
</table>

Table 1. Worldwide wireless standards.

\[\text{Figure 1. Basic mobile phone block diagram.}\]
In the electronics and high-technology industries, the MEMS switch was seen as a hopeful entry into the optical switching market, which significantly slowed in the year 2000.

of RF MEMS switches and the cost-competitive nature of T/R switching has caused the market to move beyond the price range of RF MEMS. But a new switching application has emerged in the form of band switching. Today, the demand for worldwide compatibility of mobile phones has forced phone developers to implement triple and quad-band and multimode solutions. Switching between up to eight different wireless bands complicates the possibility of developing a single all-encompassing world phone. Figure 2 illustrates the potential need for a switch that functions as a superset to the T/R switch.

RF MEMS can potentially provide a solid replacement for existing solid-state switches, but the devices have been on the verge of breaking into the high-tech electronics industry for more than 20 years. The main barriers for development fall into the similar categories that were faced when the integrated circuit was on the verge of competing with discrete transistor electronics (cost, manufacturability, reliability and performance).

A brief background
MEMS technology dates back to the 1970s when micromachines first began to see use in the automotive industry as pressure sensors. Further developments in the automotive industry led to the creation and implementation of MEMS accelerometers for collision airbags. Today, MEMS-based gyroscopes are being implemented to help fine tune location finding in automotive GPS systems.

In detail, RF MEMS switch devices resemble a mechanical relay, but the geometries are typically in the submillimeter or hundreds of micrometers in size. The scales of size make these devices attractive because they make it possible to have switching solutions that can ideally take up 1 mm² or less of space. In addition, the switches can be altered to create a variety of micro applications such as delay lines and switched capacitor networks.

In theory, RF MEMS technology is capable of surpassing the performance of high-speed semiconductors with devices that can route and control well up to 50 GHz signals. The reality is that there are many factors that have limited the viability of RF MEMS in mobile phone applications. Such factors include fabrication processes, packaging (hermetic isolation and parasitics), control voltages, long-term switching life cycles (contact point stiction), switching speed, RoHS compliance (reflow temperatures), and manufacturing costs.

An RF MEMS switch is not much different than an optical MEMS switch, but because of the power-handling requirements of RF, slightly different design techniques have to be employed to limit and reduce the impact of current and the resultant heat on the contact points of the switch. A typical switch is built up with a cantilever (a suspended beam anchored at one point) and is actuated either electrostatically or electromagnetically. A contact head rests at the “floating” end of each cantilever and is comprised of conducting metals not typically used in semiconductor fabrication.

Problems and solutions
- Fabrication: RF MEMS devices are fabricated as layered structures on top of a variety of substrates. The manufacturing options include semiconductor processing, which tends to be the most popular method, and ceramic or silicon substrate wafers. The ceramic substrates method can be more expensive, but allows for easy packaging by hermetically bonding the lids on to the RF MEMS wafer and sawing/singulating the finished components. MEMS switches can be built from almost any semiconductor technology including polysilicon and GaAs. This makes for a truly agnostic technology, which when given time and resources can be adapted to almost any fabrication process.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Insertion Loss (dB)</th>
<th>Isolation (dB)</th>
<th>Linearity (dBm)</th>
<th>Return Loss (dB)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>SOI</td>
<td>1.50</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>GaAs</td>
<td>0.90</td>
<td>35</td>
<td>48</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>RF-MEMS</td>
<td>0.45</td>
<td>40</td>
<td>70</td>
<td>40</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

Table 2. Typical specifications for a single-pole, double-throw RF switch at 6 GHz.
The main concern in manufacturing is the flatness of the substrate so that the photolithography steps used in the process result in consistently flat layers to build up each structure. Standard silicon tends to be an excellent choice for this because the wafer-polishing step is part of the process. Ceramic wafers are not normally polished or smoothed and so adding this step to the process adds to the overall cost of the manufacturing, which in turn makes RF MEMS on ceramics somewhat cost prohibitive for mobile phone applications.

Solid-state circuits and RF MEMS are similar in that they have various layers of conducting and insulating materials. Aluminum (Al) and now copper (Cu) have become the primary conducting materials found in silicon processing. RF MEMS developers use these conducting materials to create the metal layers needed to create the electrostatic or electromagnetic fields to actuate or move the cantilever beams. But the switch contact points have to be made with a highly conductive material in order to complete the circuit path needed in a micromechanical switch. So far, the material of choice for conduction is pure gold (Au). The majority of standard silicon fabs do not have Au processes and this limits development. Pure-play MEMS and specialty fabs use Au in their processes and thus open up the possibilities for device development. Other fabrication vendors use GaAs, which normally include gold implantation in their process, but a limiting factor of this technology is the inability to integrate the high-voltage control circuitry needed to actuate the RF MEMS switches. However, new developments in GaAs fabrication are showing promising possibilities for full integration of control and switching functions.

Packaging concerns: Package cost and size are the leading considerations in T/R switch development. The high demand for T/R switches has driven the cost to the tens of cents, which makes it difficult to provide RF MEMS for this type of application. At the same time, the choice of packaging is constrained by the fact that RF MEMS switches are moving devices that have to operate in a clean environment. A clean environment is needed because the mechanical construction and minute dimensions of the switches makes them vulnerable to contamination from various environmental sources such as dust, moisture and gas vapors.

Hermetically sealed ceramic packaging is typically used because it can protect the actuators, but the packaging costs are far greater than the typical plastic molding used to house GaAs switches and standard semiconductor components. Ceramic packaging differs in price from plastic packaging by as much as five times due to materials and assembly costs. On the other hand, standard plastic costs less, but it does not offer sufficient environmental isolation to be contamination free. Typical ceramic packages resemble those used in SAW oscillators and filters. They are comprised of a ceramic base with vias and a ceramic lid. The lid alone typically comprises the majority of the cost of this choice of packaging.

However, lower cost and newer packaging alternatives exist, which can enable RF–MEMS to solve problems in mobile phones. These methods include die level sealing or overmolding and near hermetic chip scale packaging. There are various methods used to seal a die. Methods include growing a layer of semiconductor insulator or depositing a thin film over the device as shown in Figure 3. The overmold can be grown using semiconductor processes or deposited as a thin film. In either case, the process results in a hermetic seal, which protects the RF MEMS and eliminates the need for the more expensive ceramic packaging. This method is perhaps the most promising because it could enable manufacturers to house RF MEMS in readily available plastic packages in a variety of standard surface-mount configurations.

Control and operating power concerns: Typical RF MEMS devices are mechanically actuated (displaced) in one of two ways, either electromagnetically or electrostatically. Electrostatic actuation is probably the simplest method of mechanical switching, but it requires higher voltages to create the forces that move the cantilever. This method involves creating a charged field much like a capacitor that deflects the cantilever in Figure 4. The problem is that the when compared to a capacitor, a MEMS switch needs much larger voltages to create the needed electric field.

Over the years, the actuation voltages have dropped from 100 volts to about 50 volts and lower. In addition, the structures cannot handle high currents above 500 mA because

![Figure 3. Cut-away view of RF MEMS level die sealing.](image)

![Figure 4. Illustration of the electrostatic actuation of RF MEMS switches.](image)

![Figure 5. Conversion of a high-voltage RF MEMS switch into a low-voltage device.](image)
of the heat created by the resultant power. Thus, the actuation voltage has to be current-limited (dc) in order to avoid damage to the actuator.

Mobile phones do not have these types of voltages available and so it becomes necessary for the MEMS developer to provide an intermediary step that enables an RF MEMS switch to operate at much lower voltages. Dc-dc voltage conversion can be used to do this task. With more integration, a voltage converter and logic controller can be integrated with a high-voltage RF MEMS device to create a low-voltage solution as shown in Figure 5.

There are various dc-dc voltage conversion methods available including transformers and multistage amplifiers. CMOS fabrication along with MEMS is achievable, but MEMS require a good contact material for the actuators such as gold (Au) or gold alloys. Gold is normally deposited on the surface of die as die-attach material, but implanting gold in between semiconductor layers is complicated and forces changes into the typical fab process flow. The Au process hurdle and the availability of high-voltage transistors for the voltage conversion portion of the circuit complicate integration into an RF MEMS switch. These factors have limited the integration that has been achieved to date.

Current implementations of voltage conversion next to RF MEMS switches leverages the packaging techniques of monolithic microwave ICs (MMICs) and multichip modules (MCMs) where multiple die are integrated into one package. Ultimately, the goal is to reach a monolithic or fully integrated switch solution. The illustration in Figure 5 shows the eventual path toward full integration. With fab availability there will be no problem in providing low-voltage RF MEMS switches. Currently, several semiconductor technology vendors in CMOS, SOI and GaAs are investigating this path toward integration.

Long-term switching life-cycles and switching speed: A standard T/R switch sees in the order of hundreds of millions of switching cycles in its lifetime of use, which can typically run from two to four years. The conditions can vary from low current to high current hot switching in low voltages. An RF MEMS switch can typically actuate up to tens of billions of times under no load and current conditions before the switch begins to near the useful end of its lifetime. But when hot switched, the lifetimes can drop to the hundreds of millions. Yet as the heat increases, the actuation voltage has to be lower in order to make for a seamless transition between transmit and receive. The mobile phone user should not notice any difference in the quality of the call when talking or listening. RF MEMS devices switch in the tens of microseconds, which makes them far too slow for the T/R switch application.

On the other hand, as a band switch, an RF MEMS device has both the qualities of switching speed and hot switching lifespan to make it an appropriate fit for the application. Band switches need not switch as fast or as many times as a T/R switch. Once a band is selected, the switch stays connected to the corresponding throw until another band is detected or required. In a typical multiband application a band switch is used along with duplexer and T/R switches.

The band switch serves as a routing device that enables other components to do the needed functions of filtering and bandpassing. Since a band switch is an additional component in the signal path, it must have as little impact on the overall performance of each band and this makes RF MEMS switches ideal candidates because of the low power consumption, small overall size, low insertion loss, and high isolation as previously shown in Table 2. In conclusion, the availability, cost and performance of RF MEMS switches for mobile phones will continue to improve. First, applications have evolved to such a point as to mandate an alternative to semiconductor solutions. Second, new fabrication and packaging techniques will enable the mass production of the devices and accelerate their market acceptance. The fabrication techniques that have evolved to support low-cost solutions complete a virtuous cycle of product definition where volume drives cost and cost drives applications. 

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