RF-MEMS for Wireless Communications

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ABSTRACT

This article presents an introduction and overview of MEMS technology with a focus on RF applications of MEMS in the design of cellular handsets. A novel, integrated, high-Q tunable digital capacitor is discussed to demonstrate how RF-MEMS technology can be utilized to make high frequency components whose RF characteristics can be adjusted during operation, allowing for the first time reconfiguration of radio hardware under software control. It is concluded that as the consumer wireless market continues to grow and evolve, product designers will remain under ever increasing pressure to develop smaller, lighter, thinner products that are more functional, energy-efficient, and intuitive, and to do so faster and at lower cost. Although issues and challenges persist, opportunities abound, and RF-MEMS technology holds the promise of being a key enabler of future generations of more highly converged, cognitive, and flexible consumer wireless products.

INTRODUCTION

Continuous advances in silicon and wireless technology have fueled the availability of a growing diversity of wireless products. Today, the preeminent such device is the ubiquitous mobile handset or cell phone, which has rapidly evolved from a voice-only communications tool to a multimedia device providing connectivity to information and people on a global basis. In 2007 it was estimated that the number of new cell phones sold during the year passed the one billion unit mark for the first time [1]. In addition to such large annual and growing volumes, the cellular handset market is also characterized by very short product development cycles, short (and getting shorter) product lifetimes, and ongoing consumer demands for greater functionality, ease of use, and higher quality of service.

A broad overview of the cellular communications market reveals an infrastructure of hardware component and module suppliers coupled with software developers and contract assemblers who service a set of handset suppliers. The handset suppliers, along with content providers, sell their products to the network providers or carriers who in turn provide a growing diversity of services to the end consumer. Traditionally, carriers have heavily discounted handset prices to the consumer with the goal of selling services and access to content on a contract basis. As competition continues to intensify, carriers are putting increasing pressure on their suppliers to lower their already low costs faster while providing additional functionality and higher performance. In some cases carriers have begun to move toward selling their own branded phones as a way of protecting sales margins. All of the cellular market trends and characteristics, when combined with the multitude of different cellular standards and operating frequencies in use around the world and the carriers' very large investment in proprietary network infrastructure, result in ever increasing pressure on mobile handset product developers from all sides. Today this pressure is concentrated in a few key areas of the typical device architecture. Perhaps the primary such area is the radio frequency (RF) (or front-end) portion of the radio(s) or modem(s) in the cell phone. What is needed is a new hardware implementation technology that will support the rapid development of scalable, flexible, high-performance RF components.

RF micro-electro-mechanical systems (RF-MEMS) is a semiconductor technology that allows micro-scale moving mechanical devices to be integrated with electrical transistors on silicon wafers. RF-MEMS technology can be utilized to make high-frequency components whose RF characteristics can be adjusted during operation, allowing for the first time reconfiguration of radio hardware under software control. The ability to reconfigure operating characteristics in real time results in a substantial reduction in the required number of discrete components for a given set of functions, significantly relieving pressure on the handset product developer.

This article provides an overview and introduction to MEMS technology in general, reviews the potential applications of RF-MEMS in the design of mobile handsets, and provides as an example a novel integrated high-Q tunable digital RF-MEMS capacitor. A summary of the key lessons learned in the development and application of RF-MEMS technology is presented. The article concludes with a review of the issues, challenges, and opportunities associated with utilizing RF-MEMS technology in the design of high-performance cost-sensitive wireless consumer products.

MEMS TECHNOLOGY

There are many different definitions for what types of devices and functionality are included under the MEMS banner. In fact, "MEMS" are

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not always "MEMS." Depending on the application and geography, the terms *microsystems* and *micromachined devices* are often used to refer to the same set of objects. Independent of the actual term, MEMS can be thought of as involving both electronic and nonelectronic elements, and as performing functions that can include sensing, signal processing, actuation, display, and control [2]. MEMS devices are inherently passive elements that require some sort of external interface and control circuitry. Thus, as the name implies, they truly need to be "systems." As systems, the design of MEMS devices must comprehend important system considerations including system partitioning, packaging, calibration, signal-to-noise ratio, stability, and reliability [2]. MEMS are "micro" in size with dimensions in the range of micrometers up to millimeters. We can also think of MEMS as a class of microscale structures or microstructures, in particular those microstructures that exhibit some sort of mechanical motion. An excellent introduction and overview of MEMS technology is presented in [3].

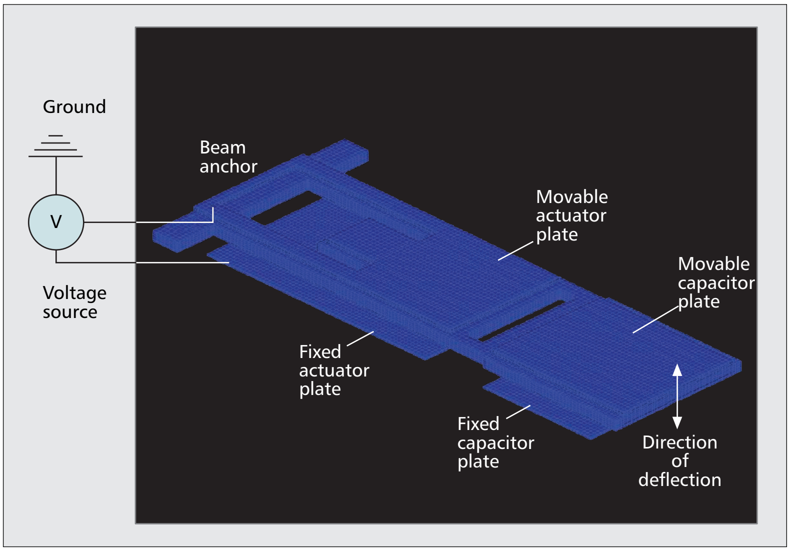


Figure 1. *Electrostatic actuation of a cantilever beam.*

A Brief History of MEMS

One possible origin for the field of MEMS is Richard P. Feynman's 1959 presentation entitled "There's Plenty of Room at the Bottom." Feynman concluded that the subject of the miniaturization of systems provided a vast new field of scientific inquiry which at the time was limited by our ability to make physically small things [4]. This limitation began to be removed with the availability of batch-oriented fabrication techniques for semiconductor devices beginning in the 1960s. The first batch-fabricated MEMS device, a resonant gate transistor, was produced in 1964 at Westinghouse. The 1970s and '80s saw a string of continuing advances in the fabrication of a variety of MEMS sensors, broader application of mainstream semiconductor materials and processing to MEMS devices, and low-frequency applications for MEMS switches [5]. MEMS development accelerated rapidly in the 1990s as government funding became available for defense and military applications, micro-fluidic and optical devices appeared, and RF-MEMS devices moved into the microwave range. By the second half of the 1990s venture-capital-backed MEMS companies had begun to appear, and by the turn of the century MEMS devices were in volume production in a variety of applications including automotive sensing, ink jet printing, displays, and medical instrumentation. Beginning in the mid to late 1990s, a MEMS industry infrastructure began to emerge and continues to evolve today. While the presence of MEMS devices has continued to expand across the board in the first decade of this century, one of the areas seeing the most growth and activity is the consumer electronics space. To meet the volume and cost requirements of the consumer market, MEMS practitioners continue to focus on improving their product development infrastructure with increasing emphasis on leveraging the advances in semiconductor manufacturing technology. Emerging MEMS consumer applications include microphones, resonators for quartz crystal replacement and clock generation, accelerometers and gyros for gaming controllers, disk drive sensors for head protection in PCs, micro-mirror arrays for digital television and low power portable projection devices, and capacitors, switches, and filters for cell phones.

How Do MEMS Work?

Depending on the application, performance requirements, and constraints, the MEMS designer can choose from a variety of actuation mechanisms to cause motion. Typical actuation methods include electrostatic, magnetic, thermal, piezoelectric, composite material, pressure, and mechanical spring forces. Each mechanism has its benefits and drawbacks. In some applications a combination of these approaches is used. As an example, in electrostatic actuation a voltage differential is applied across a pair of actuation electrodes or plates, one of which is fixed and the other movable. Figure 1 depicts a cantilever beam that is anchored to the surface of the silicon wafer at one end. Application of the voltage differential to the actuator plates as shown results in the tip of the beam being pulled down toward the silicon wafer surface. To give some sense of scale, the beam may be hundreds of microns long and tens to hundreds of microns wide, and the vertical distance may be measured in a single digital number of microns. As long as the voltage is maintained across the actuator plate, the beam will stay deflected. Once the voltage is removed, the beam will act like a spring and return to its original undeformed position.

There are numerous possible variants of the electrostatic actuation scheme shown in Fig. 1 including actuating in the up direction instead of down or actuating in both directions to provide for more symmetric operation. It is also possible to devise mechanical latching mechanisms to hold a deflected beam in place, although some type of force would also typically be required to unlatch the device. The amount of voltage required to deflect a mechanical beam is a complex function of the beam materials and geometry, the distance of travel, and the type of

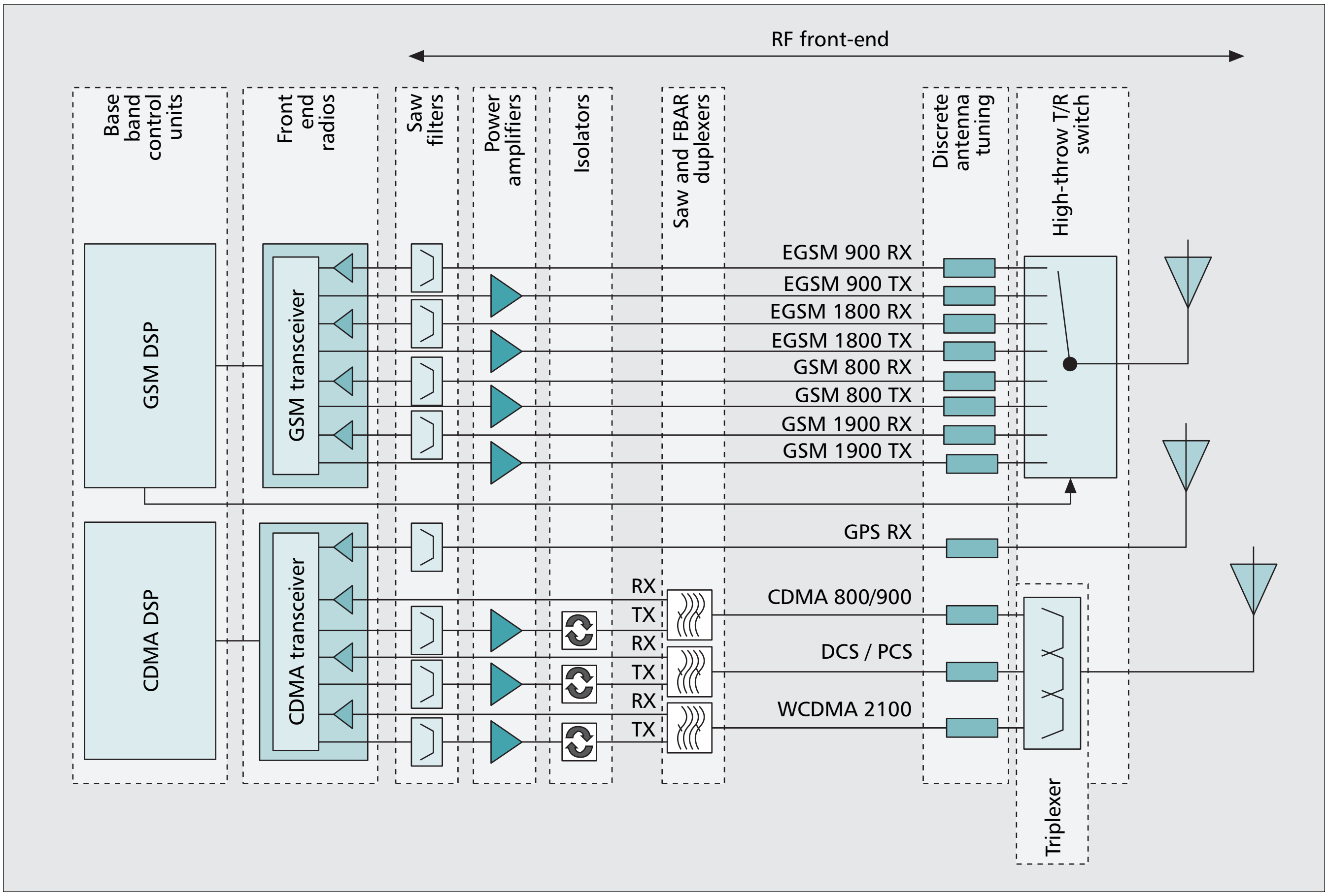


Figure 2. *Traditional multiradio handset architecture.*

contacting behavior desired when the beam is in the fully deflected position. Actuation voltage is also a function of the desired speed of operation and requirements for reliability and repeatability of operation. Electrostatic voltages can be quite high (e.g. 100 V), but as long as the techniques for generating such voltages are power-efficient, this actuation mechanism can be very attractive for portable battery operated devices since essentially zero current is involved in the operation of the device.

APPLICATIONS OF RF-MEMS IN CELLULAR COMMUNICATIONS

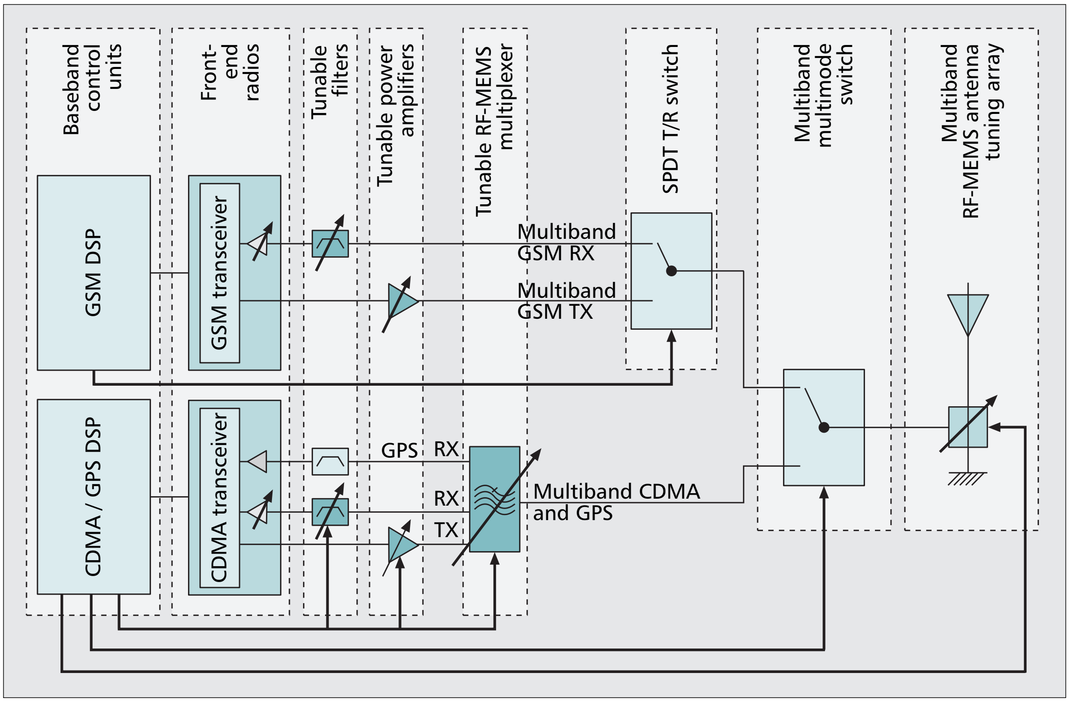
By 2010, global annual shipments of handsets are expected to reach the 1.5 billion mark, representing a CAGR of 9 percent for the period 2007–2010 [1]. During this same period the growth rate of cellular PDAs and "smartphones" or "converged devices" is expected to top 50 percent with such devices representing 28 percent of the total annual units shipped in 2010. These converged devices, along with other multifrequency band and "feature" phones, require multiple radios to be implemented in the handset and increasingly require more than one radio to operate in parallel. At the same time as the handset continues to evolve, carriers are poised to roll out a series of technology upgrades for their networks that will improve end-user data services, enhance voice capacity, improve data rates for two-way transmission, and enable support for multiple antennas and improved modulation schemes [1]. While all of the planned improvements in handsets and networks will significantly enhance the consumer experience, as mentioned earlier, they will also put tremendous time and cost pressure on the design of the RF front-end of the handset (and in the base station on the network side).

HANDSET RF DESIGN CHALLENGES

The architecture of a cellular handset radio can be thought of as having three major components:

1 An RF front-end
2 A transmitter/receiver (transceiver)
3 A baseband processor (Fig. 2)

As information proceeds from 1 to 3 (reception), the signal of interest is selected and strengthened, it is decoded, its frequency is substantially reduced, and it is then appropriately processed by general-purpose logic in the baseband processor. During transmission, the information is passed from 3 to 2 for encoding and frequency selection, and then onto 1 for amplification and final transmission through the antenna. A single baseband–transceiver pair may handle multiple RF front-ends, usually one for each operating frequency supported by the handset. The traditional approach to implementing a multiradio handset is shown in Fig. 2, which, for clarity, includes only major functional blocks of interest. This architecture includes seven radios (four for



■ **Figure 3.** *Tunable multiradio handset architecture.*

Over time, devices have been manufactured using a diversity of technologies including ceramics, magnetics, acoustics, gallium arsenide, silicon germanium, and very recently CMOS. Integration has been achieved through module-level assembly.

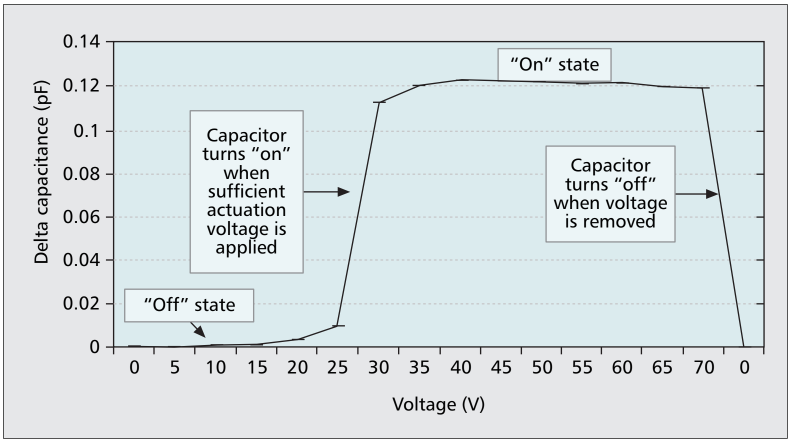
Global System for Mobile Communications [GSM] and three for code-division multiple access [CDMA]) and a GPS receiver integrated with two baseband–transceiver pairs. The RF front-end of each radio is implemented as one or two discrete chains of high-performance components, each of which is highly optimized for the specific frequency band and mode of operation of that particular radio. With the continued addition of functionality such as Bluetooth, Wi-Fi, and digital television reception, today's high-end handsets can have as many as 12 radios. While the addition of a new radio may or may not require the addition of a new baseband and/or transceiver, in the traditional implementation approach the number of RF front-ends scales directly with the number of radios, disproportionately adding cost, consuming power, taking space, and adding to the product design time. But why is this true? Due to the performance requirements of the devices in the RF front-end, they typically have not been able to be manufactured in complementary metal oxide semiconductor (CMOS) technology and as a result have not benefited from Moore's law scaling (or integration), as have the baseband and transceiver. Over time, devices have been manufactured using a diversity of technologies including ceramics, magnetics, acoustics, gallium arsenide, silicon germanium, and very recently CMOS (for power amplifiers). Integration has been achieved through module-level assembly.

A closer look at Fig. 2 reveals that many of the devices and functions in the RF front-end are passive and, as such, could potentially be implemented using MEMS or other types of micro-scale structures. These opportunities include, from right to left, the antennas, switches, antenna tuning, duplexers, and surface acoustic waveguide (SAW) filters in the figure. Additional opportunities exist in the baseband–transceiver area including inductors, oscillators, frequency synthesizers, mixers, and resonators for the replacement of quartz crystals [4–6].

An early example of the successful integration of a micro-scale structure into the RF front-end of the handset is the film bulk acoustic resonator (FBAR) filter. This device is implemented using piezoelectric materials and, as the name implies, uses an electrical-to-acoustic-to-electrical transduction to filter out the signal of interest. The FBAR represents a step toward implementing RF front-end devices using mainstream semiconductor fabrication techniques. The FBAR replaced a ceramic block filter whose height defined the thickness of the handset. As such, the FBAR became a key enabler of today's thin form factor cell phones. Today FBARs are shipping in the hundreds of millions of units per year for use as duplexers (transmit/receive filters) in CDMA phones. The FBAR is an example of a component replacement model where a new device is inserted in an existing location in a design. While benefits accrue from replacing one component with a better one, MEMS enable a more compelling opportunity — the opportunity to implement novel solutions based on tunable RF components.

TUNABLE RF COMPONENTS

Figure 3 demonstrates a potential reimplementation of the multiradio handset architecture of Fig. 2 using MEMS-enabled tunable RF components. The seven separate RF front-ends of Fig. 2 have been reduced to two front-ends, each with substantially fewer components, and the number of antennas has been reduced from three static elements to a single tunable multiband structure.



■ **Figure 4.** *Digital capacitor operation (measured data).*

By enabling tunable components, MEMS allow multiple discrete components to be replaced by a single component whose characteristics can be adjusted. These adjustments can be one-time (at the end of the assembly process), semi-dynamic (during operation based on static information), or dynamic (based on the current operating environment and data). Tuning behavior is effected by movement of MEMS devices, but movement in such a way that the required RF performance of the circuit is maintained before and after operation. As an example, the tunable filters shown in Fig. 3 could be implemented as LC networks using MEMS capacitors and inductors. Assume that the handset is operating in a specific frequency band and using a channel within that band so that those MEMS devices that are "off" are required to have high RF isolation and linearity, and those that are "on" require low RF insertion loss and high linearity to achieve the RF operating budget of the front-end. When the baseband processor requires the handset to move to a new channel, a command is sent to the tunable filter, causing certain capacitors and inductors to move and change value. This movement alters the location of the poles and zeros of the filter structure, producing a new optimum filter configuration for the new channel of operation. Finally, in the new state the MEMS devices are once again required to have high linearity, and high or low enough isolation and loss, respectively. Thus, as long as sufficient RF performance is maintained for each configuration of the MEMS devices, the capability for movement allows a single MEMS-enabled device to emulate the behavior and replace multiple discrete devices. The number of devices replaced and the range of operation are trade-offs typically made during the design process. Whereas a tunable RF filter is an example of a novel RF-MEMS enabled solution, there are other applications where MEMS simply provide a better solution in an existing component socket. This advantage may be in performance (e.g., switches) or size (e.g., resonators).

RF-MEMS technology provides significant competitive advantage to the handset supplier in meeting the growing challenge of cost, performance, power, size, and time to market constraints. Consumers will benefit in terms of higher quality of service, more functionality, and better battery life, while carriers will benefit from better network capacity and performance as the transmit (power) efficiency and receive sensitivity of handsets are improved in a more affordable fashion.

A TUNABLE RF-MEMS DIGITAL CAPACITOR

Leverage and scaling in the semiconductor industry have resulted from standardization and outsourcing of manufacturing processes, and design reuse facilitated by electronic design automation (EDA) tools and structured design methodologies. Historically, MEMS designs have been accomplished in a full-custom fashion with each new design requiring a unique new manufacturing process. As MEMS are increasingly manufactured in semiconductor foundries, the ability to utilize custom processes is disappearing. With commercial EDA tools for MEMS design now available, the time appears ripe to explore MEMS design reuse.

A review of potential MEMS applications in RF front-ends finds that a common element in many of the applications is a capacitor. A capacitor in its most common form is implemented as a pair of parallel plates with the total capacitance of the device determined by the dimensions of the plates and the properties of a dielectric material between them. A second important property of a capacitor is its quality factor or Q, which is the ratio of the energy stored to the energy lost per unit of time. Capacitors with fixed values can be implemented in semiconductor processes using the interconnect layers or the gates of transistors. Capacitors whose value varies in an analog fashion are called *variable capacitors* or *varactors* and are implemented using the junction capacitance of a diode controlled by a bias voltage. Unfortunately, at the frequency range of interest in handsets, varactor Qs are low, get lower with more total capacitance, and the feasible change in capacitance is on the order of 2–3X. Varactors require closed loop control to understand how to transition from one value to the next. They also tend to lack the linearity required in the RF front-end.

Although analog varactors have been implemented using RF-MEMS [6], a more flexible approach is to digitize the variable capacitance function. To do so, a parallel plate capacitor with fixed minimum and maximum values is implemented using an electrostatic actuator. One plate, fixed to the wafer surface, is coated with dielectric, while the other movable plate is attached to the bottom side of the actuator (Fig. 1). When the actuator is in the up state, the capacitor is at the minimum value, and when the beam is fully deflected, it is at its maximum value. The device only operates in a digital fashion — off or on. By appropriate choice of materials and geometries, the total amount of capacitance change that can be achieved in a reasonable area and voltage and maintained out to the package pins is on the order of 10X, as shown in Fig. 4. This data is from a 0.125 pF

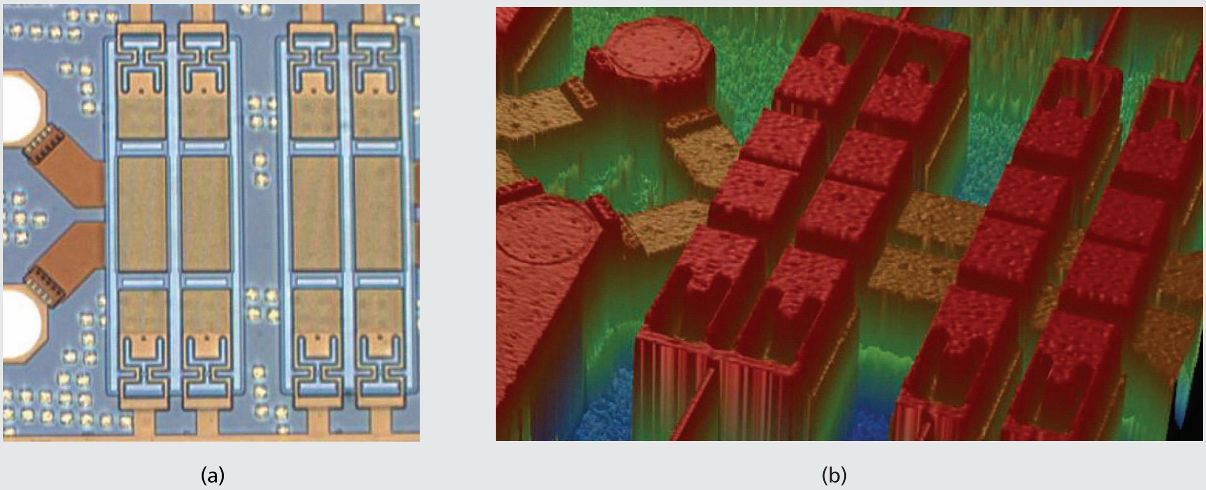


Figure 5. *Tunable RF-MEMS digital capacitor cell: a) die photo of four capacitance bits of a cell; b) 3D image of capacitance bits.*

digital capacitor implemented in an industry standard 180 nm RF-CMOS process.

A single capacitor can be reused as a "bit" to make a standard capacitor "cell" in a fashion analogous to transistors and logic gates for semiconductor devices. Figure 5 shows an example of a segment of a tunable RF-MEMS digital capacitor cell implemented using the capacitor bit whose performance was presented in Fig. 4.

Capacitor cells can be arrayed to form larger capacitors using metal interconnect on the die or connections on a substrate or package with the maximum practical amount of total capacitance limited by die size. Since the entire array is digital, it does not require closed loop control, and a new capacitance value can be selected by providing a digital control word to the array specifying which bits are on or off. Bit size can be adjusted to provide more or less precision, and bit sizes can be intermixed in an array along with series (floating) and shunt (one side grounded) configurations to make a very general variable capacitor structure. Bit sizes in the range of 0.005–0.25 pF and arrays with up to 40 pF of capacitance have been built in silicon. The devices are ultra linear with high isolation and low loss, maintain their 10:1 tuning range as total capacitance scales, are relatively insensitive to acceleration and shock, and exhibit minimum Q values of well over 100 at 2 GHz (a factor of at least 5 greater than a varactor diode). Tunable digital capacitor arrays similar to those already implemented in silicon are expected to find application as a design building block in a variety of front-end applications including antenna reconfiguration, matching, and filtering.

KEY LESSONS LEARNED

After almost a decade of working with RF-MEMS technology, a number of key factors that should be taken into account in any RF-MEMS project have become apparent. Perhaps most important is the selection of a manufacturing partner. A key decision here is the choice between a MEMS specialty foundry and a semiconductor foundry with MEMS experience. Typically, it is easier to develop and prototype in a MEMS foundry, and the developer should consider a hybrid approach of initial development in a MEMS foundry followed by a process transfer to a semiconductor foundry. Whether or not such a transfer is actually required will depend on product requirements in areas such as cost, volume, and silicon-level access to transistor technology. When selecting a manufacturing partner, look for foundries that have as much direct experience with your target market and customers, and the materials and unit processes required by your MEMS product as possible. Such direct experience is particularly important on the process side since experience in one area of MEMS process technology does not directly translate into expertise in a different application space.

Unlike the vast majority of integrated circuit (IC) designs today, MEMS designs are still device-level designs. As such, there is strong design–process interaction. To deal with this interaction in a cost- and time-effective manner, investments should be made in test structures, extraction and characterization methods, and the development of calibrated software simulation models to allow for design optimization and design of experiments work in software instead of on wafer. Several MEMS EDA software packages that provide these features are commercially available. Whenever possible, it is recommended that MEMS designs and processes be developed with an eye toward reuse. While this approach requires more time and cost up front (and is typically not the way MEMS have been developed), the capability of reusing design elements and designing into a fixed known process provide substantial cost and time advantages in the development of subsequent roadmap products. Overall, in the areas of product design, process development, and manufacturing partner interaction, be prepared to do more, take more time, and spend more than on a comparable IC design.

Packaging is a key consideration in MEMS design and should be taken into account upfront. Strong device-substrate mechanical interactions

Just as semiconductor transistor technology did for a wide variety of electronic products, RF-MEMS technology is poised to fulfill the promise of being a key enabler of future generations of more highly converged, cognitive, intuitive, and flexible consumer wireless products.

and/or hermeticity requirements for reliable operation can quickly dominate product yields. And meeting reliability requirements can be a challenge due to the absence of widely accepted test and acceleration procedures.

In general, for very high volume applications such as cellular handsets, we have found that maximizing the use of the existing semiconductor manufacturing infrastructure is the most effective way to bring an RF-MEMS product to market. In addition to cost advantages and access to transistor technologies, this approach addresses many perennial customer concerns with MEMS products including quality, capacity, yield, and security of supply.

CONCLUSIONS

Multiradio consumer wireless products continue to proliferate at a rapid pace. Short product development cycles and lifetimes, requirements for continuous cost reduction, consumer expectations and demands, and a complex and highly competitive market structure place increasing pressure on developers of such products from all sides. The RF front-end portion of multiradio architectures is one of the key areas under the most pressure today. Unlike the transceiver and baseband portions of the radio, the front-end has not enjoyed the scaling benefits of Moore's Law integration. As a result, these high-performance high-frequency front-ends now consume a disproportionate share of the cost, power, space, and design cycle for the radio and the end product.

RF-MEMS technology provides a new implementation approach that promises to reduce the pressure on the design of multiradio products. RF-MEMS technology enables a variety of novel functions and capabilities based on the concept of tunable RF. Tuning refers to adjusting various operating characteristics of a hardware component and is accomplished by the mechanical motion of micro-structures typically built on or above the surface of a semiconductor wafer. Due to their ability to move, usually under software control, RF-MEMS devices can allow a single hardware component to emulate the behavior of multiple discrete devices with as good as or better performance, and at comparable size and competitive cost.

Although tremendous progress has been made in RF-MEMS technology in recent years, a number of questions and challenges remain about the technology. These include questions in the areas of characterization and measurement techniques for new material properties; manufacturing supply and capacity; yield variability, modeling, and enhancement; availability of cost-effective, high-performance packaging options; and mechanical and materials reliability and field data. In one way or another, all of these questions relate to cost, always a key consideration in the consumer wireless space. As RF-MEMS engineers increasingly learn to utilize the existing semiconductor manufacturing infrastructure and a growing number of product designs are completed, these questions will be answered. Any remaining adoption barriers should be overcome in the next 12–18 months as RF-MEMS devices become widely deployed in cellular handsets on a global basis starting with so-called "3G/3.5G" multiband multistandard models, and the focus shifts from the technology itself to the enabling benefits it provides.

Just as semiconductor transistor technology did for a wide variety of electronic products beginning approximately 50 years ago, RF-MEMS technology is poised to fulfill the promise of being a key enabler of future generations of more highly converged, cognitive, intuitive, and flexible consumer wireless products.

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BIOGRAPHY

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