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RF MEMS: Maturing Technology is Getting Ready for Prime Time

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Here is an overview of RF MEMS technology, providing and update on its development and implementation in production quantity components

This article reviews the technological advancements and breakthroughs achieved in RF MEMS. This technology has already made inroads in cellular segments in a big way and is now posed to bring another revolution in the telecommunications industry. The next segment that will immensely benefit from this technology is the military and space segment. Moreover, recently NASA started qualifying MEMS oscillators for their space exploration missions. RF-CMOS concept leading toward SoC has also gained attention of the semi-conductor industry and major industries are focusing all their effort towards making it a reality in the coming future.

Introduction

MEMS devices employed in RF applications are termed as RF MEMS. MEMS technology is on the verge of revolutionizing RF and microwave applications. As semiconductor technology continues to progress toward smaller, lighter and super-integrated components and devices, the RF and microwave industry is reaping the benefits of micro-electro mechanical systems (MEMS). The requirement of present and future RF systems is for lower weight, less volume, low power consumption and cost with increased functionality, flexibility in the frequency of operation and component integration, all of which are driving the development of new RF/microwave components and system architectures. The major advantage of RF MEMS devices is that many limitations exhibited by standard RF devices can be easily overcome using MEMS, enabling circuits with new levels of performance for present and future requirements.

MEMS technology got its early commercialization in inkjet heads, DLP chips from Texas Instruments, plus pressure and inertial sensors. RF MEMS development dates back to 1979 and created lot of hype, but did not make its mark until 2002. The next major breakthrough is imminent in the telecommunication industry in terms of improved performance, ease of reconfiguration and miniaturization. Major RF devices in which such a breakthrough has been achieved are: micro-switches, tunable capacitors, micro-transmission lines, micromachined inductors, micromachined antennas and resonators, including micro-mechanical resonators, bulk acoustic wave resonator (BAW), and cavity resonators. Mostly RF MEMS are manufactured using conventional 3D structure technologies like bulk and surface micromachining but LIGA and SCREAM are also used for the requirement of the higher aspect ratio. The material used as the substrate is Si but now GaAs, SiC and SOI are the other materials employed for realizing various MEMS devices. Figure 1 shows a comparison of RF MEMS with the other technologies.

In addition to the potential offered by RF-MEMS devices for integration and miniaturization, they also provide reconfigurability and tunability for multi-band and multi-standard operation. RF MEMS offers lower power consumption, lower losses, higher linearity and higher quality factor than conventional communication components. Next-generation telecommunication systems will use RF-MEMS devices to operate over a wide frequency range.

RF-MEMS Devices:

A. Bulk Acoustic Wave Devices

Bulk acoustic wave (BAW) devices are the most mature components. Agilent and Infineon have already established themselves in this technology and pushed it in cell phones. More than 70% of the CDMA mobile segment has been captured by the Agilent duplexer. As of late 2005, several other companies were close to commercialization of BAWs, including EPCOS and Fujitsu. Two RFIC companies, Skyworks and Triquint also have acquired BAW technology. BAW resonators are also used for building band pass filters, often replacing SAW filters.

B. MEMS Inductor

Traditionally, many discrete passive components, such as off-chip inductors and bulky filters, have been used for RF applications. Improving the gain, power dissipation or phase noise of these circuits has led to incorporation of MEMS based on-chip inductors. A common way to realize monolithic integration of inductors is to fabricate spiral inductors onto the substrate with air suspension to minimize substrate parasitics effects. A CMOS RF amplifier demonstrated by Chang et al (*IEEE Electron Device Letters*, 1993) shows improvement of approximately 12 dB in gain and a factor of two higher center frequency capability with the MEMS inductor. MEMS inductors have found new applications for power management and are commercialized by Enpirion for AC-DC converters.

C. Micro-Machined Cavity Resonator-Based Circuits

The Q of a cavity resonator is proportional to its volume. Therefore, at millimetric wave frequencies these resonators are an attractive option as both frequency and performance levels can be met. These circuits include oscillators, VCOs and filters. Recently a 33.2 GHz MMIC oscillator stabilized by a micromachined cavity was shown, which has an improvement of 18 dB over its MMIC free-running counterpart.

D. Micro Mechanical Resonators

At lower frequencies, cavity resonators become impractical due to their excessive large dimensions. Micromechanical resonators are an attractive option as their resonance frequency is proportional to the square root of their stiffness-to-mass ratio. These resonators use the mechanical vibrations of extremely small beams to achieve high-Q resonance. The Q achievable using this technology yields the value of >8000 and found out to be excellent solution for the reference clock circuits. Discera, Silicon Clocks and SiTime are some of the companies going in production of these resonators. These resonators are very promising as a replacement for conventional off-chip quartz reference oscillators. However this technology is new and will take time before rapid deployment.

Technology	Insertion Loss (dB)	Isolation (dB)	Linearity (dBm)	Return Loss (dB)	Power (mW)
CMOS	0.00	0	0	0	5
SOI	1.50	20	30	20	15
GaAs	0.90	35	48	35	35
RF-MEMS	0.45	40	70	40	<1.0

Figure 1 · Comparison of different technologies.

E. RF MEMS Switch

Switches have long attracted the most attention among RF MEMS products. The excellent performance of MEMS switches has demonstrated great potential for replacing lossy and power hungry semiconductor switches in numerous applications, including T/R switches, phase shifters, switchable filters, cross-bar/multiplexing, tunable antennas and phased arrays. RF MEMS switches can be categorized in two ways; actuation mechanism and type of contact. Some methods of actuation include: electrostatic, thermal, magnetic and piezoelectric. The most common so far is electrostatic actuation in spite of reduced power handling capability, but preferred due to low power consumption and fast actuation time. An RF MEMS switch can have either ohmic (DC) contact or a capacitive contact. They can further be classified under series and shunt configuration. The first commercially qualified MEMS switch was announced by Tera Victa Technologies in 2005. This switch based on high force disk actuator (HFDA) has typical mean cycle before failure (MCBF) of approximately 200 million cycles, 20 times higher than the best electromechanical relays. Radant switch for US department of defense had surpassed 200 billion cycles mark. The future of MEMS switches over next few years will be driven by three key factors: substantial improvement in reliability, significant reductions in size and cost, and a wide variety of products.

F. RF-CMOS Integration

With continuing miniaturization of electronic systems and the advancement of MEMS capabilities, design solutions continue to emerge with the integration of MEMS technology. Integration offers a number of benefits including cost, higher performance, reduced size and weight, and increased reliability. This, along with frequency agility offered by these devices, has great potential for wireless handsets, wireless networking, wireless internet and other platforms. MEMS device technology as discussed above is already being applied to inductors, capacitors, switches and filters. These devices when integrated with the RF chips, offer higher performance for applications such as VCOs, PLL and other RF functionality required for the advanced telecom systems. Basically the aim of this technology is to use batch processing which is possible by utilizing IC fabrication techniques. Fully compatible CMOS IC fabrication needs advancement in improving RF performance of silicon substrate. Silicon is the preferred medium not only due to mature technology, but its thermal conductivity is three times higher than GaAs. Moreover, the dielectric constant of Si is stable with frequency and temperature, surface smoothness is excellent, and silicon device integration is mature, so it is an ideal substrate for SoC concept. Two approaches to RF MEMS insertion are possible—bottom-up and top-down. In the bottom-up approach, one would proceed with direct component replacement as dictated by established system architecture. In the top-down scenario, one would begin by devising a system architecture not prejudiced by the usual limitations of conventional RF components, and would exploit to the highest degree possible their RF MEMS realizations. The recent trend is to use the bottom-up approach while slowly solving issues related to top-down approach (Figure 2).

By incorporating RF MEMS into CMOS process flow, WiSpry has readied a family of MEMS-tunable digital capacitors for antenna tuning, band programmable impedance matching, power amplifier tuning and tunable RF filters. These products integrate low-power CMOS control and voltage generation logic with an array of tunable RF-MEMS digital capacitors to offer an ultra linear, digitally programmable, variable capacitance on a single silicon die which will be commercially available in 2008.

G. Micro-Machined Transmission Lines

Transmission lines are versatile components in RF and microwave electronics, as they are key elements of many circuits and systems. A number of circuits on micromachined lines have been demonstrated.

Technical Issues

Despite the enormous progress made in the RF MEMS area still there are some issue which needs great attention and innovation to make it popular. The two main issues are *packaging* and *reliability*.

Packaging plays a major role in RF MEMS performance. They are needed, as the package provides physical protection of the component and also protection from contaminants such as moisture, particles or reactive elements. This requirement necessitates the use of hermetic sealing. Also for RF MEMS, the package must be small, inexpensive and high-performance. This requires wafer-level packaging (WLP) to package MEMS devices in the clean room environment but the challenge lies in packaging along with RF interconnects without sacrificing the performance. Epoxy, benzocyclobutene (BCB), and glass frit are reported for wafer bonding sealing materials. Many companies are working on this packaging option, and it is just a matter of time before it is optimized.

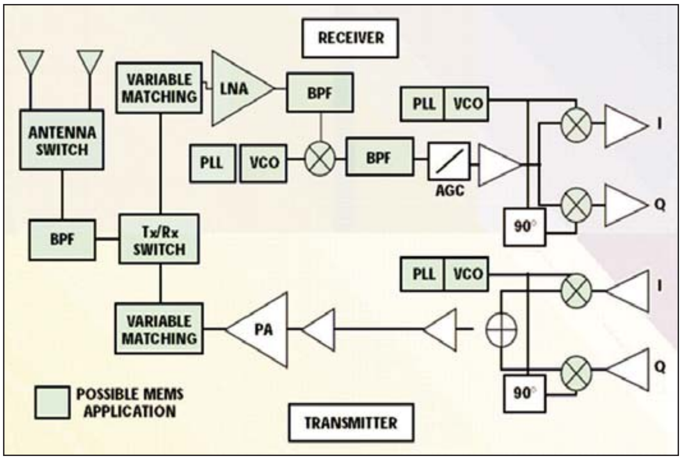

Figure 2 · The top-down approach to for RF MEMS examines how they might fit into a radio design like this.

Reliability is another area to be addressed in RF MEMS for its successful integration in spacecraft technology. This area's main concern is in active circuitry like switches, oscillators, etc., where thermal and mechanical processes can cause failures to creep in. Taking the typical case of a switch, the four main factors that affect the lifetime of a switch are: environment, contact degradation, dielectric stiction and mechanical failure. Any type of moisture or outgassing can create unwanted films on the contact surfaces possibly causing the contact to stick. Improvement in process cleanliness and package integrity, along with the elimination of contamination from the other materials will dramatically improve product lifetimes. But still, evaluation of the RF MEMS reliability is an issue. There is no known accelerated life testing method that has accurately predicted actual RF MEMS lifetime, and different failure modes may be prevalent for each type of switch.

Industry Trends

Military, space and instrumentation applications are ready to use RF-MEMS. The main drivers are the significantly better technical performance and reliability compared with the existing technology. Market volumes are small compared to mobile telephony; however companies are prepared to pay higher prices for components if technical performance is proven.

Band switching and filter switching in cell phones will probably be the first application for RF-MEMS switches, as future wireless receivers will need to operate at several bands coverings a wide range of frequencies. These bands or standards including DCS, PCS, GSM, EGSM, CDMA, WCDMA, GPS, and Wi-Fi have their own constraints and characteristics. RF MEMS switches can meet the challenges of integrating multiple bands while maintaining longer battery life and progressively reducing overall size of the handsets. About 75% of components in mobile phones are passive and can be replaced with the MEMS version.

Conclusion

RF MEMS are a major entry in the MEMS markets. More than the 120 industrial and research organizations work on RF MEMS worldwide. Along with the established markets for inkjet heads, digital micro mirrors and pressure sensors, RF MEMS technology represents one of the few MEMS markets that will exceed the US$1 billion mark. Mobile industries see immense potential in MEMS technology, while RF instrumentation, automated test equipment, as well as military markets are the best immediate prospects. SiTime Inc. already makes MEMS oscillators that operate as high as 125 MHz and is developing chips that gang multiple MEMS resonators on the same die to form the banks of RF filters needed to implement NASA's ultra miniature SDRs (software defined radios). NASA has begun qualifying MEMS oscillators for space exploration and has found that MEMS oscillators operate over a wide range of temperature from 100°C down to –110°C, a range that exceeds their specified –40°C to 85°C. Also MEMS offer radiation immunity, vibration tolerance and extreme longevity, a good fit for space missions.

RF MEMS have had an amazing effect on the way people think of RF and microwave systems. By combining high RF performance, low cost and low power consumption, RF MEMS devices allow system designers to explore new architectures and configuration which was not possible with the traditional technology. Reliability and packaging, the two issues daunting RF MEMS are on the verge of solution and soon this technology will bring another revolution.

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