TUTORIAL

MEMS FOR RF/MICROWAVE WIRELESS APPLICATIONS: THE NEXT WAVE

Microelectromechanical systems (MEMS) technology is on the verge of revolutionizing RF and microwave applications.[1] The requirements of present day and future RF/microwave systems for lower weight, volume, power consumption and cost with increased functionality, frequency of operation and component integration are driving the development of new RF/microwave MEMS components and system architectures.

Presented in two parts is an overview of RF/microwave MEMS technology. Part one begins with a brief discussion of RF/microwave system requirements, and then introduces the enabling potentialities of the MEMS arsenal to meet these requirements. In particular, MEMS fabrication techniques are addressed, and fundamental components, including inductors, varactors, resonators and transmission lines, as well as the design/CAD paradigm, are described.

> ***...a technology that can drastically reduce manufacturing costs, size, weight, and improve performance and battery life.***

Part two, to be published later, will expose the revolutionary possibilities afforded by MEMS in systems integration and novel architectures. In particular, the projected impact of MEMS in RF/microwave, from that resulting from direct component replacement to that enabled by circuit applications, including typical front-end circuits, will be addressed.

THE PROMISE OF MEMS TECHNOLOGY FOR RF/MICROWAVE APPLICATIONS

The recurring demand for ever more flexible and sophisticated, yet lightweight and low power wireless systems, has generated the need for a technology that can drastically reduce manufacturing costs, size, weight, and improve performance and battery life. Familiar examples of current and future applications exacting these qualities include wireless handsets for messaging, wireless Internet services for e-commerce, wireless data links such as Blue-

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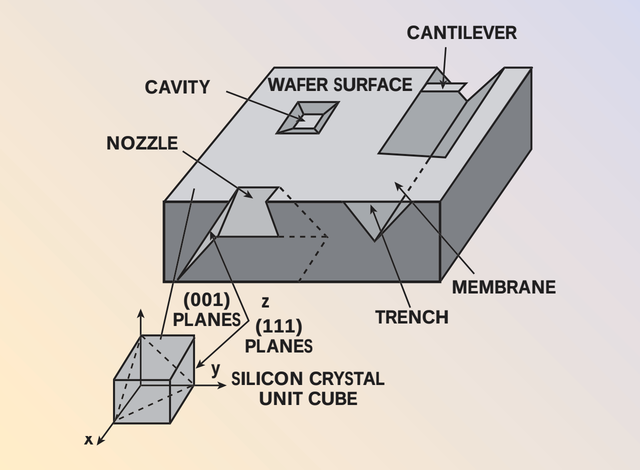


Fig. 1 A bulk-micromachined structure.

tooth and location services exploiting the Global Positioning System. With the potential to enable wide operational bandwidths, eliminate off-chip passive components, make interconnect losses negligible, and produce almost ideal switches and resonators in the context of a planar fabrication process compatible with existing IC and MMIC processes, RF MEMS is widely believed to be just that technology.

Brought to maturity, RF MEMS technology promises to enable on-chip switches with zero standby power consumption, nano-Joule-level switching power and sub-5V actuation voltage; high quality inductors, capacitors and varactors; highly stable (quartz-like) oscillators; and high performance filters operating in the tens of megahertz-to-several gigahertz frequency range. The availability of such an arsenal of first-rate RF and microwave components will provide designers with the elements they have long hoped for to create novel and simple (but powerful) reconfigurable systems. In this first paper, a review of the status of MEMS technology is provided, including fabrication, devices, circuits, systems applications, packaging and the new design paradigm the technology invokes.

FABRICATION TECHNIQUES: THE MEMS TECHNOLOGY TOOLBOX

MEMS fabrication techniques empower conventional integrated circuit fabrication processes to produce three-dimensional (3-D) mechanical structures. Accordingly, there are three main approaches, namely bulk micromachining, surface micromachining and LIGA.

Bulk Micromachining

In bulk micromachining, the 3-D structure is sculpted within the confines of a wafer by exploiting the anisotropic etching rates of different atomic crystallographic planes in the wafer. Alternatively, structures may be formed by the process of fusion bonding, which entails building up a structure by atomically bonding various wafers. ***Figure 1*** shows a bulk-micromachined structure.

Surface Micromachining

In surface micromachining, the 3-D structure is built up by the orchestrated addition and removal of a sequence of thin film layers to/from the wafer surface called structural and sacrificial layers, respectively. The success of this approach usually hinges on the ability to release/dissolve the sacrificial layers while preserving the integrity of the structural layers. ***Figure 2*** depicts a surface-micromachined structure.

LIGA

LIGA is a German acronym consisting of the letters LI (Roentgen-LIthography, meaning X-ray lithography), G (Galvanik, meaning electrodeposition) and A (Abformung, meaning molding). Accordingly, in this technique thick photoresists are exposed to X-rays to produce molds that are subsequently used to form high-aspect ratio electroplated 3-D structures. ***Figure 3*** depicts a junction of a CPW 6-dB coupler fabricated in a LIGA process.

MEMS-BASED COMPONENTS: INDUCTORS, VARACTORS, SWITCHES, RESONATORS

The ability of MEMS fabrication technologies to eliminate the substrate underneath passive structures, to elevate them over the substrate, or to enable high-aspect ratio/large cross-sectional area structures, places at the designer's disposal a large repertoire of techniques to help him combat the limitations of passive components. In this section, examples of the application of such techniques to inductors, varactors, switches and resonators is presented.

Micromachined High Q Inductors

Bulk micromachining has been applied to drastically reduce the parasitics plaguing conventional on-chip planar inductors, and that contribute to their low quality factor (Q) and self-resonance frequency, with the particular aim of approaching the performance of their off-chip counterparts. ***Figure 4*** shows an example of a bulk-micromachined inductor in which the substrate has been eliminated from underneath the spiral trace. Measured Qs range from 6 to 28 at frequencies from 6 to 18 GHz, with typical inductor values around 1nH. Similarly, surface micro-

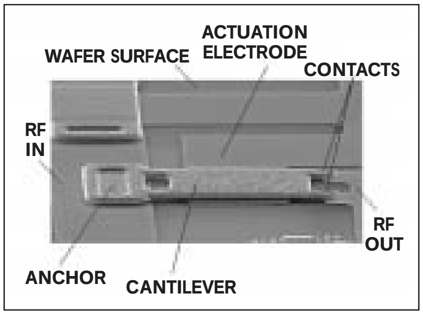


Fig. 2 A surface-micromachined structure (courtesy of Northeastern University).

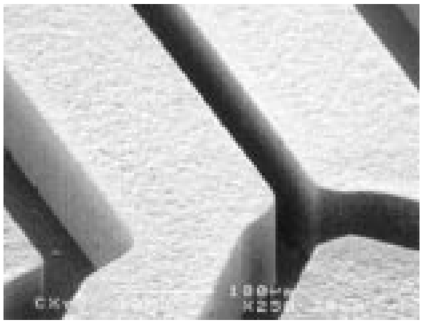
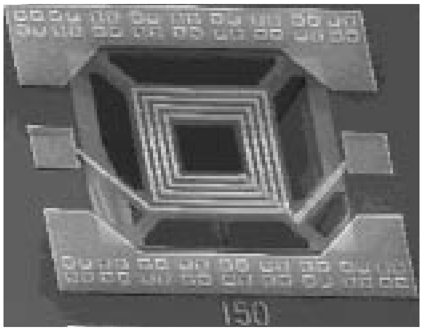


Fig. 3 Junction of a CPW 6 dB coupler fabricated in a LIGA process. © 1998 IEEE

Fig. 4 A bulk-micromachined inductor.



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machining has been exploited to create solenoid-like inductors above the substrate. ***Figure 5*** shows an example of such an approach. A quality factor of 25.1 at 8.4 GHz and an inductance of 2.3 nH were obtained. ***Figure 6*** summarizes the attained state-of-the-art inductor performance.

MEMS Varactors

Tunable capacitors have traditionally resisted monolithic integration due to a number of factors, particularly process incompatibility, which results in devices with sub-optimal properties (for example, low Q and self-resonance frequency). MEMS-based varactors take two forms — parallel plate, shown in ***Figure 7***, and interdigitated, shown in ***Figure 8***. In the parallel plate approach the top plate is suspended a certain distance from the bottom plate by suspension springs, and this distance is made to vary in response to the electrostatic force between the plates induced by an applied voltage. The parallel plate example has a measured nominal capacitance of 2.05 pF, a Q of 20 at 1 GHz and achieves a tuning range of 1.5:1, a tuning voltage range of 0 to 4 V and a self-resonance frequency greater than 5 GHz. In the interdigitated approach, shown in ***Figure 9***, the effective area of the capacitor is varied by changing the degree of engagement of the fingers of comb-like plates. Typical performance includes a Q of 34 for 5.19 pF at 500 MHz, a tuning range of 200 percent, a

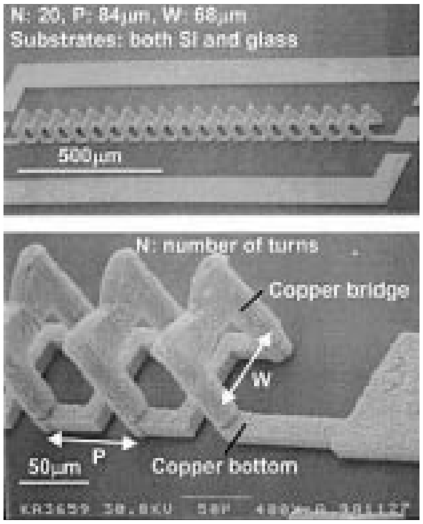

Fig. 5 Solenoid-like inductors.
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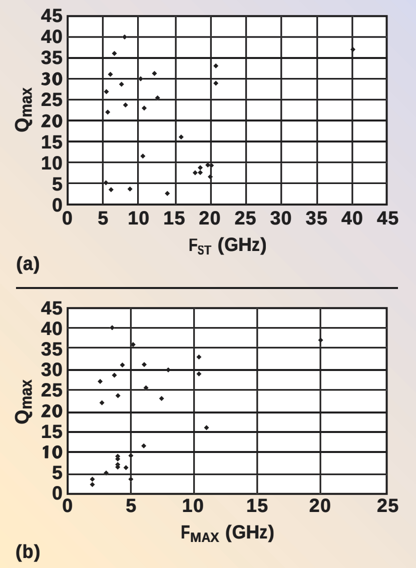
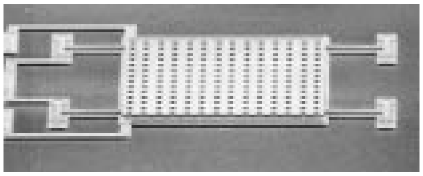


Fig. 6 Inductor Q_{max} *vs.*
(a) self-resonance frequency F_{sr} *and (b)* F_{max}.

Fig. 7 A parallel plate MEMS-based varactor.



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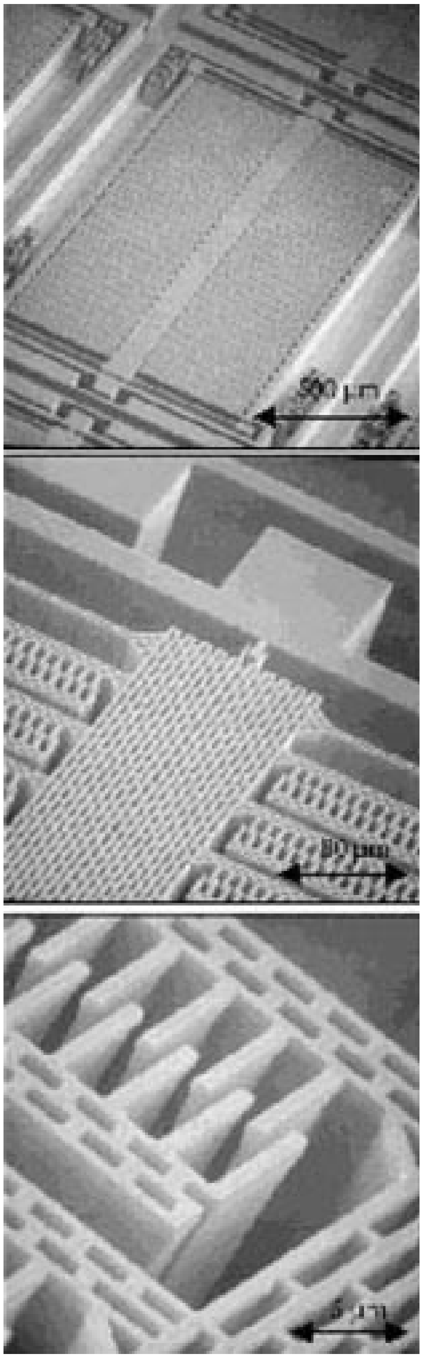

Fig. 8 Interdigitated MEMS-based varactors.
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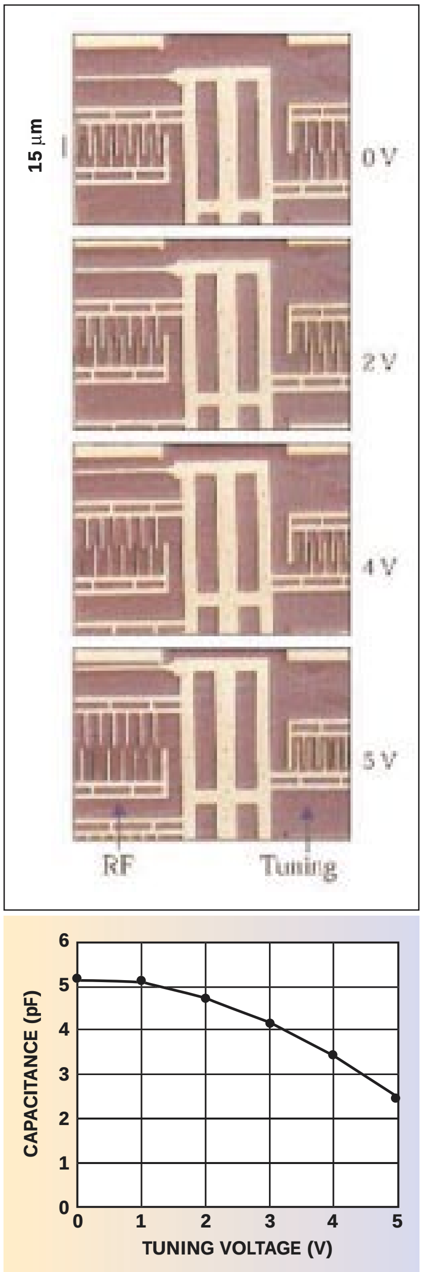

Fig. 9 The changing degree of engagement of the fingers of comb-like plates and the varactor's capacitance vs. tuning voltage characteristics.
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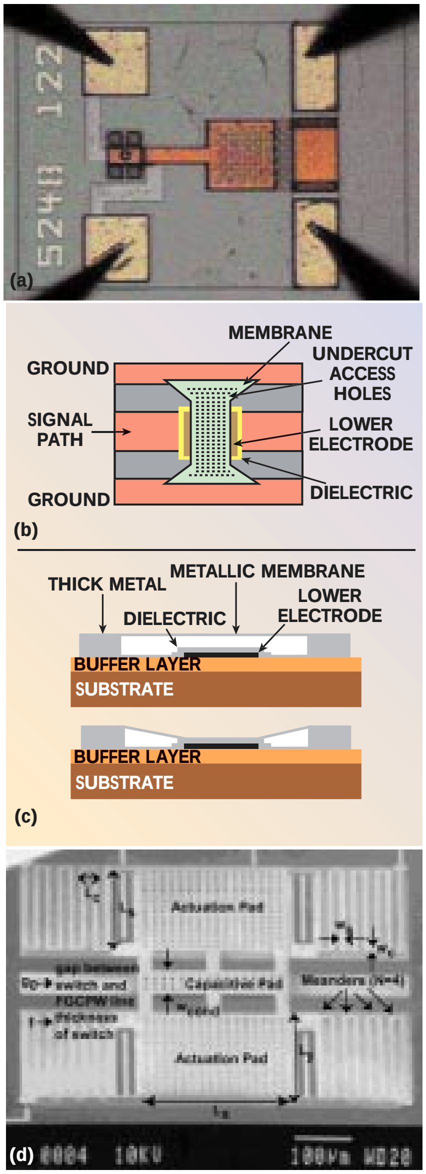

Fig. 10 A MEMS switch implementation.
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tuning voltage range of 2 to 14 V and a self-resonance frequency of 5 GHz for 5.19 pF. The reported linearity, as measured by the third order intermodulation product, is greater than +50 dBm.

MEMS Switches

Interest in MEMS switches centers on their potential for low insertion loss, high isolation and high linearity. Work is under way to achieve fast switching and low actuation voltage operation. Many switches, based on a number of actuation mechanisms and topologies, have been demonstrated. These include the cantilever, membrane, shape-memory alloy and multi-pole/multi-throw, shown in ***Figure 10***. A brief definition of the actuation mechanisms follows.

TABLE I

RF MEMS vs. PIN AND MESFET SWITCH COMPARISON

	MESFET	*PIN Diode*	*MEMS*
Series resistance (Ω)	3 to 5	1	< 1
Loss at 1 GHz (dB)	0.5 to 1.0	0.5 to 1.0	0.1
Isolation at 1 GHz (dB)	20 to 40	40	> 40
IP3 (dBm)	40 to 60	30 to 45	> 66
1 dB compression (dBm)	20 to 35	25 to 30	> 33
Size (mm^2)	1 to 5	0.1	< 0.1
Switching speed	~ ns	~ μs	~ μs
Control voltage (V)	8	3 to 5	3 to 30
Control current	< 10 μA	10 mA	< 10 μA

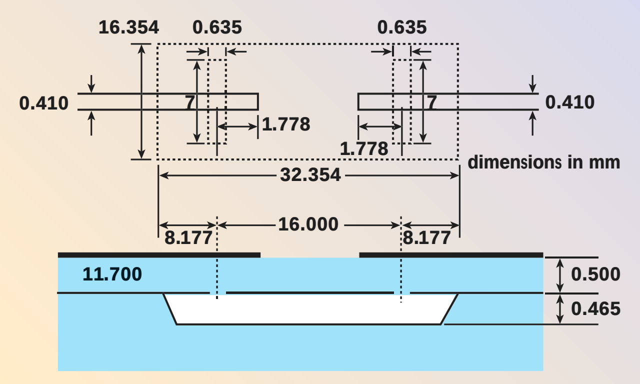

Fig. 11 An X-band micromachined cavity resonator.
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Electrostatic: positive and/or negative charges, set by applied voltages between certain structural members elicit Coulomb forces which produce motion.

Piezoelectric: applied voltages on structures induce fields which change their dimensions, with the physical dimensional change used to communicate motion.

Thermal: a current forced through an element causes it to heat up and expand, with the physical dimensional change used to communicate motion.

Magnetic: magnet-induced or current-induced magnetic forces produce motion.

Bi-Metallic (shape-memory alloy): materials that upon experiencing deformation at a lower temperature can return to their original undeformed shape when heated. During this process the physical dimensional change is used to communicate motion.

While a number of actuation mechanisms are under investigation for RF MEMS device applications, electrostatic actuation is the most mature, perhaps due to the fact that surface micromachining, the most common technology utilized to produce electrostatically-based actuators, is compatible with integrated circuit fabrication processes.

In addition to the type of actuation mechanism they exploit, switches are classified according to the type of contact they utilize. Thus, there are resistive or metal-to-metal contact switches, and capacitively-coupled switches, in which the contact is made via an insulating dielectric layer. While the resistive contact switch permits operation down to DC, the blocking capacitance inherent in the capacitively-coupled switch does not. Thus, the frequency of application and operation are intimately related to the type of switch design chosen. ***Table 1*** presents a comparative summary of the performance of MEMS switches and MESFET and PIN-diode switches.

Micromachined Cavity Resonators

The performance levels typical of macroscopic waveguide resonators may be approached at the microscopic planar level by exploiting micromachining techniques. As an example, ***Figure 11*** depicts a micromachined cavity resonator for X-band applications that is suitable for integration in the context of a planar microwave process. In this particular demonstration an unloaded Q of 506 for a cavity with dimensions 16 × 32 × 0.465 mm was obtained. This was just 3.8 percent lower than the unloaded Q obtained from a rectangular cavity of identical dimensions.

Micromechanical Resonators

The performance of bulky mechanical resonators, particularly the fact that they are capable of exhibiting Q in the 10,000-to-25,000 range, is well-known. Micromechanical resonators attempt to approach a similar level of performance in the context of a planar IC process. Accordingly, there are two main design approaches to accomplish this — the vertical displacement resonator, in which a cantilever beam is set into a diving board-like vertical vibration in response to an electrostatic excitation, and the lateral displacement resonator, in which the motion is elicited by exciting a comb-like structure. As of this writing, the maximum resonance frequency reported for these resonators is below 200 MHz. Applications requiring higher frequencies, that is, up to a few gigahertz, appear to be the domain of the film bulk acoustic wave resonator (FBAR) technology. An FBAR device, shown in ***Figure 12***, consists of a layer of piezoelectric material (for example, aluminum nitride) disposed between top and bottom metal electrodes. The typical Q and resonance frequency are over 1000 and between 1.5 and 7.5 GHz, respectively.

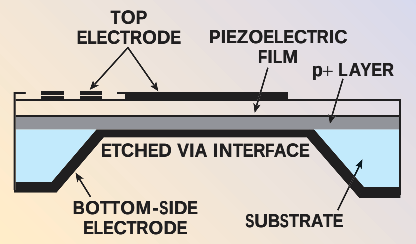

Fig. 12 An FBAR device configuration.
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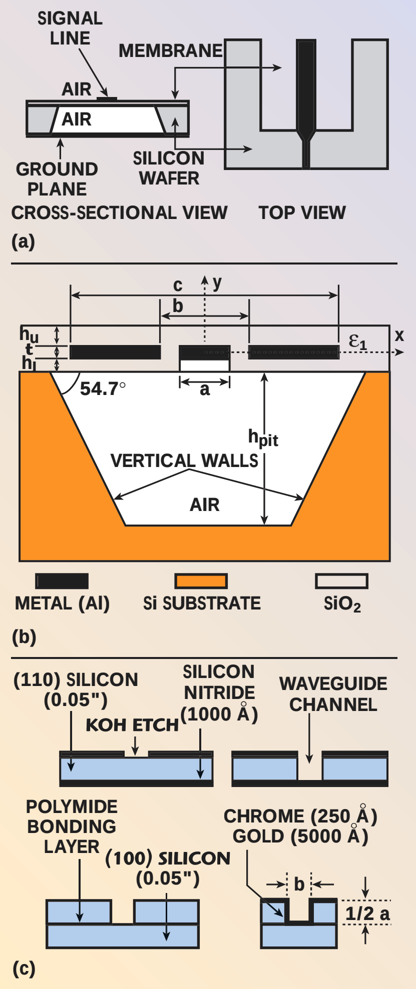

Fig. 13 MEMS transmission line configurations; (a) membrane supported microstrip, (b) top-side-etch coplanar waveguide and (c) micromachined waveguide.
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Micromachined Transmission Lines

Most of the limitations germane to transmission lines, such as frequency dispersion and, to a certain extent, insertion loss, originate in the properties of the substrate or media where they are defined. MEMS technology has been successfully exploited to diminish the influence of the substrate in four types of transmission lines, shown in ***Figure 13***. They are the membrane supported microstrip, coplanar microshield transmission line, top-side-etch coplanar waveguide and micromachined waveguide. In the membrane supported microstrip the transmission line is defined on a thin membrane, with dielectric constant close to unity, by bulk-etching the substrate underneath the trace via backside processing. A drawback of the membrane-supported microstrip line is that it possesses no intrinsic ground plane. The coplanar microshield overcomes this limitation by including the ground planes defining the ground-signal-ground structure. The top-side-etch coplanar waveguide does away with the potential complications of backside etching of the membrane and microshield lines, and instead relies on opening etch windows through the top passivation layer to create a pit underneath the line. Finally, there is the micromachined waveguide, in which micromachining and wafer-bonding techniques are aimed at overcoming the lower-dimension bound of conventional machining techniques.

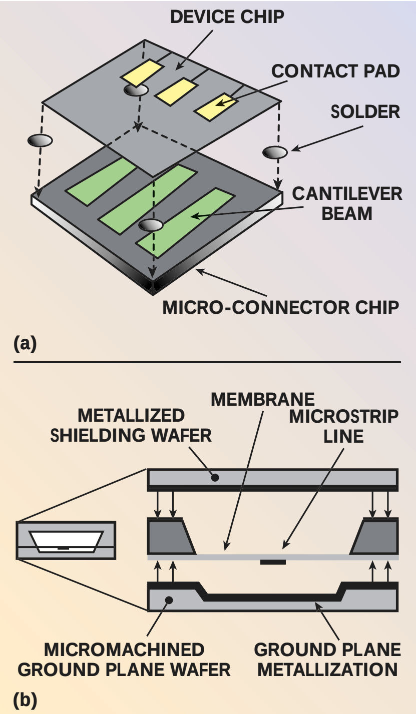

Fig. 14 RF MEMS packaging examples; (a) flip-chip assembly and (b) self-packaged.
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MEMS PACKAGING

As is well-known, good packaging practice is essential for the successful performance of conventional RF and microwave components. The case for RF MEMS is no different. Indeed, in addition to ensuring the absence of unwanted resonances and electromagnetic interference and coupling, RF MEMS packaging techniques aim at preventing moisture and particulates, which may impair the movement of freestanding MEMS structures, as well as the various types of energy losses (for example, acoustic and thermal). Two examples of RF MEMS packaging approaches are shown in ***Figure 14***. The first is based on the flip-chip assembly technique, whereas the second utilizes the self-packaged technique in which devices are enclosed in cavities formed by bonding multiple wafers.

MEMS DESIGN TOOLS

In the past many RF MEMS designers relied on lengthy and expensive prototyping cycles to achieve MEMS designs. Today accurate, easy-to-use, commercially available MEMS design tools enable shorter time-to-market and lower design costs. The need for these tools is driven by the nature of MEMS devices leading to multi-domain design aids that can solve true-coupled analysis (such as electrostatic, mechanical and thermal). Successful RF MEMS designs must take in to account device layout, construction (including packaging), modeling and sim-

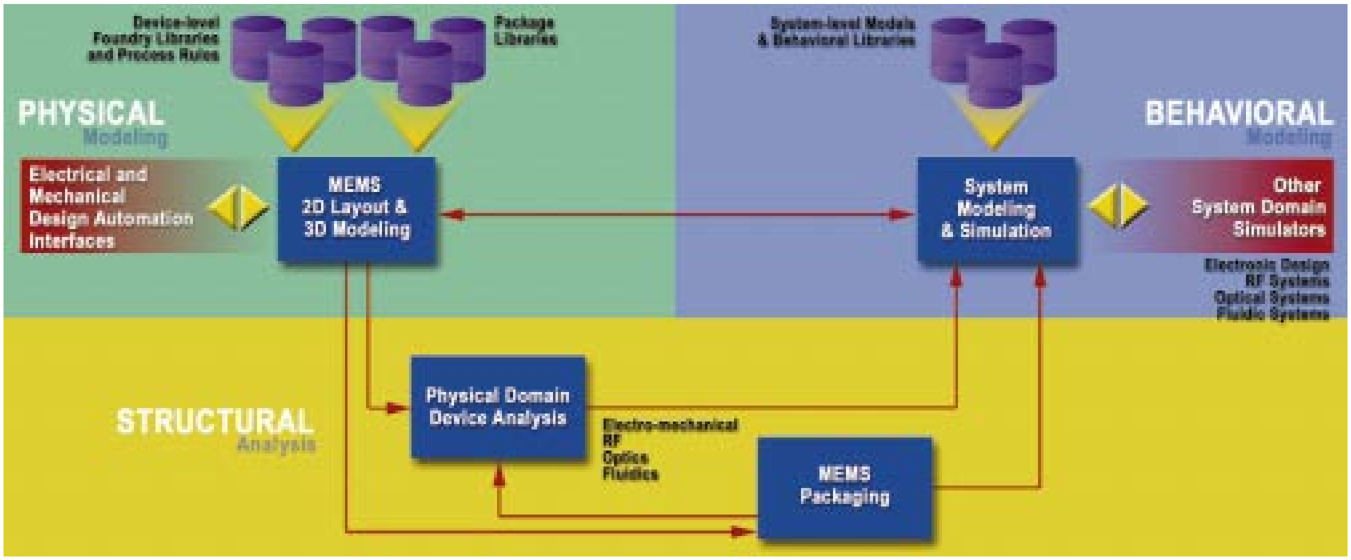


Fig. 15 Design methodology for MEMS-enabled device development.

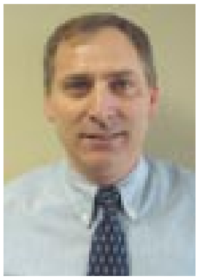
ulation, as well as system modeling and simulation, particularly if the RF MEMS devices are to be integrated. A design methodology for the complete end-to-end development of MEMS-enabled devices is shown in ***Figure 15***.

CONCLUSION

Part one of this article has presented an overview of RF/microwave MEMS technology that enable small, low cost, integrated, RF MEMS devices, including the RF MEMS fabrication processes, devices and design considerations, and packaging.

References

1. H.J. De Los Santos, *Introduction to Microelectromechanical (MEM) Microwave Systems*, Artech House, 1999, pp. 4–9.
2. A.S. Holmes and S.M. Saidam, "Sacrificial Layer Process with Laser-driven Release for Batch Assembly Operations," *Journal of Microelectromechanical Systems*, Vol. 7, No. 4, December 1998.
3. T.L. Willke, E. Onggosanusi and S.S. Gearhart, "Micromachined Thick-metal Coplanar Coupled-line Filters and Couplers," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 1, 1998, pp. 115–118.
4. Y. Sun, H. van Zeijl, J.L. Tauritz and R.G.F. Baets, "Suspended Membrane Inductors and Capacitors for Application in Silicon MMIC's," *Microwave and Millimeter-wave Monolithic Circuits Symposium Digest of Papers*, IEEE, 1996, pp. 99–102.
5. J.B. Yoon, B.K. Kim, C.H. Han, E. Yoon and C.K. Kim, "Surface Micromachined Solenoid On-Si and On-glass Inductors for RF Applications," *IEEE Electron Device Letters*, Vol. 20, No. 9, September 1999, p. 487.
6. A. Dec and K. Suyama, "Micromachined Electro-mechanically Tunable Capacitors and Their Applications to RF IC's," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 46, No. 12, December 1998, p. 2587.
7. J.J. Yao, *Topical Review: RF MEMS from a Device Perspective*, J. Micromech. Microeng. 10 (2000) R9-R38.
8. S.P. Pacheco, L.P.B. Katehi and C.T.C. Nguyen, "Design of Low Actuation Voltage RF MEMS Switch," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 1, 2000, pp. 165–168.
9. J. Papapolymerou, J.C. Cheng, J. East and L.P.B. Katehi, "A Micromachined High X-band Resonator," *IEEE Microwave and Guided Wave Letters*, Vol. 7, No. 6, June 1997.
10. S.V. Krishnaswamy, et al., "Compact FBAR Filters Offer Low Loss Performance," *Microwaves & RF*, September 1991, pp. 127–136.
11. T.M. Weller, L.P.B. Katehi, M.L Herman, P.D. Wamhof, K. Lee, E.A. Kolawa and B.H. Tai, "New Results Using Membrane-supported Circuits: A Ka-band Power Amplifier and Survivability Testing," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 44, No. 9, September 1996, p. 1603.
12. M. Ozgur, V. Milanovic, C. Zincke, M. Gaitan and M.E. Zaghloul, "Quasi-TEM Characteristic Impedance of Micromachined CMOS Coplanar Waveguides," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 48, No. 5, May 2000.
13. W.R. McGrath, C. Walker, M. Yap and Y.C. Tai, "Silicon Micromachined Waveguides for Millimeter-wave and Submillimeter-wave Frequencies," *IEEE Microwave and Guided Wave Letters*, Vol. 3, No. 3, March 1993, p. 61.
14. D.C. Miller, W. Zhang and V.M. Bright, "Microrelay Packaging Technology Using Flip-chip Assembly," *The Thirteenth Annual International Conference on Micro Electro Mechanical Systems*, 2000, pp. 265–270.
15. S.V. Robertson, L.P.B. Katehi and G.M. Rebeiz, "Micromachined Self-packaged W-band Bandpass Filters," *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, 1995, pp. 1543–1546.



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