Discussion Article

Utilisation of Microsystems Technology in Radio Frequency and Microwave Applications

Owen Casha*, Joseph Micallef, Ivan Grech and Edward Gatt
Department of Electronic Systems Engineering, Faculty of Engineering, University of Malta, Msida MSD 06, Malta.

Summary. *The market trends of the rapidly growing communication systems require new product architectures and services that are only realisable by utilising technologies beyond that of planar integrated circuits. Microsystems technology (MST) is one such technology which can revolutionise radio frequency (RF) and microwave applications. This article discusses the enabling potential of the MST to meet the stringent requirements of modern communication systems. RF MST fabrication technologies and actuation mechanisms empower conventional processes by alleviating the substrate effects on passive devices and provide product designers with high quality versatile microscale components which can facilitate system integration and lead to novel architectures with enhanced robustness and reduced power consumption. An insight on the variety of components that can be fabricated using the MST is given, emphasizing their excellent electrical performance and versatility. Research issues that need to be addressed are also discussed. Finally, this article discusses the main approaches for integrating MST devices in RF and microwave applications together with the difficulties that need to be overcome in order to make such devices readily available for volume-production.*

Keywords: *MST, Micromachining, MEMS, RF Integrated Circuits*

Introduction

The rapidly growing communication systems entail demands for a wide range of radio frequency (RF) and microwave transceivers, and as a consequence, the research and development of such systems has dramatically increased in these last years. Amongst the common demands of present day and future RF and microwave applications, one finds the need for lower weight, low power consumption and low cost with increased functionality, frequency of operation and component integration. Consumers also demand for highly personalised, ever-present access to information together with growing volumes of data traffic and the need of higher quality products.

Such market trends require new product architectures that are enabled by technologies beyond that of planar integrated circuits (ICs). Microsystems technology (MST) is one such technology and is on the verge of revolutionising RF and microwave applications (Hilbert & Morris 2002). RF MST provides product designers with high quality versatile three-dimensional (3-D), microscale design components that can be manufactured using traditional IC batch fabrication techniques. These components have the potential for enhancing performance and robustness together with the reduction of power consumption and size of modern wireless architectures (Nguyen 2005).

RF MST components are generally classified into two categories: micromachined components and micro-electro-mechanical systems (MEMS). The difference between them is that in an RF MEMS component, in addition to the micromachined RF element, there is an electromechanical actuator which is able to convert a voltage or current signal into a mechanical movement to provide re-configurability to the device. RF MEMS are generally actuated using electrostatic, piezoelectric, magnetic or electro-thermal mechanisms. In contrast to European terminology, in the US and Asia, the term MEMS loosely represents microsystems technology (Lucyszyn 2004).

Very high quality factor (Q) passive devices, such as tunable capacitors with Q values up to 300 at 1 GHz (Young & Boser 1996, Yoon & Nguyen 2000) and inductors with Q values up to 85 at 1 GHz (Van Shuylenbergh *et al.* 2002), transmission line structures (Daneshmand *et al.* 2004, Kintis & Berenz 1997), mechanical resonators (Wang *et al.* 2004a, 2004b) and switches with insertion loss as low as 0.1 dB (Yao *et. al* 1999) are achievable using MST. Such devices can be implemented as discrete components or, for highly-integrated portable applications, merged with ICs through post-processing manufacturing techniques. MST components have been a very interesting area for research and development showing their excellent performance at microwave and even at mm-wave frequencies (Milosavljevic 2004). Such excellent performance comes from the possibility of the MST to limit the substrate coupling effects and the availability of metal structures with low parasitic capacitance and contact resistance.

RF MST structures are already being developed for switching applications such as transmit/receive duplexers (TDD) and band/mode selection which is fundamental for modern wireless multi-mode multi-standard applications. Also micromachined film bulk acoustic resonators (Otis & Rabaey 2003) are already carried in many mobile handset platforms for two-way voice and data traffic (Coventor Inc. 2005). New applications are emerging as

* *Corresponding Author: e-mail: oecash@eng.um.edu.mt Telephone: (+356) 2340 2388 / (+356) 7905 0635 Fax: (+356) 2134 3577*

the existing technology is applied to the miniaturisation and integration of conventional devices. Also its flexibility is starting to be exploited to overcome the limitations exhibited by standard planar integrated RF devices. The ultimate goal in the utilisation of MST structures in RF and microwave applications is to propagate the device-level benefits all the way up to the system level to attain new levels of performance not achievable otherwise.

Having said that, to date communication system designers are still finding some difficulty in utilising RF MSTs since they usually rely on non-standard design methods that require custom processes together with specialist knowledge resulting in long development cycles with relatively high risk and cost (Hilbert & Morris 2002). From the industry's perspective, the overall implementation cost is the most important factor determining the utilisation of such RF MST structures (Lucyszyn 2004). Packaging and reliability determines the cost of such structures and in fact these issues are currently the subjects of an intense research effort, since together with process and material characterisation, will eventually determine how and when MST structures are readily available for volume-production (Milosavljevic 2004, Coventor Inc. 2005).

Fabrication Technologies

RF microsystems have evolved as a result of continual advances in a number of different manufacturing technologies that have merged together. These can be broadly categorised into multilayer and micromachining technologies (Lucyszyn 2004). The three characteristic features of MST fabrication are miniaturisation, multiplicity and microelectronics. Miniaturisation enables the production of compact, fast-responding devices. Multiplicity or batch fabrication, allows millions of structures to be easily and concurrently fabricated. Thirdly, microelectronics provides the intelligence to the MST structures. In particular for MEMS structures it allows the monolithic merger of sensors, actuators and electronic circuitry to build a unified component or system. MST fabrication techniques empower conventional IC fabrication processes to produce 3-D mechanical structures not achievable by conventional machining techniques.

Multilayer Technologies

Multilayer technologies are used to increase package densities, by implementing traditional planar 2-D components with 3-D geometries (Robertson & Lucyszyn 2001). Two main approaches are used in multilayer fabrication: microfabrication and substrate bonding. In microfabrication technologies, a dielectric or metal layer is first deposited and then a photolithographic process is used to pattern the layer. This is then repeated for any other required layer. Since sub-micron feature sizes can be obtained, this technology is normally associated with monolithic circuits (Lucyszyn 2004). Lumped-element components, 2-D and 3-D transmission lines and multi-chip modules are possible structures which can be realised through this technology. With substrate bonding techniques, high purity dielectric substrates are bonded together, using flip-chip technology in order to create both electrical and thermal contacts between the substrates (Lucyszyn 2004). Note that in this technique there is no etching of the substrate other than for via holes.

Micromachining Technologies

There are three main approaches used in micromachining fabrication, namely bulk micromachining, surface micromachining and micromoulding.

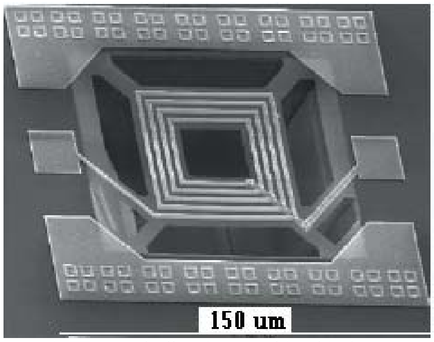

Figure 1: A bulk-micromachined inductor
(Source: Sun Y *et al.* 1996)

Bulk micromachining is an extension of IC technology for the fabrication of 3-D structures, in which they are sculpted within the confines of a wafer by exploiting the anisotropic etching rates of the different atomic crystallographic planes in the wafer (Moore & Syms 1999). In addition to this, the Technical University of Darmstadt has been working on micromachined structures developed from III-V semiconductor materials (Miao *et al.* 1995, Beilenhoff *et al.* 1999). In this case crystallographic etching techniques cannot be employed as in the case of silicon. Chemical etching is a possible alternative but poorer precision and profile definition is achieved (Lucyszyn 2004). Another approach is to form structures by means of fusion bonding, i.e., building a structure by atomatically bonding various wafers. The work in McGrath *et. al* 1993 demonstrated a W-band micromachined air-filled metal-pipe rectangular waveguide, realised by using a two-wafer sandwich approach. A measured level of insertion loss of only 0.04 dB/λg at 100 GHz was achieved. Wafer bonding continues to advance, with vertically integrated micromachined filters being demonstrated at frequencies in the 10 GHz range (Harle & Katehi 2002). Figure 1 shows an example of a bulk-micromachined inductor in which the substrate has been eliminated from underneath the spiral trace to reduce substrate associated parasitics (Sun *et al.* 1996).

3-D structures in surface micromachining are built up by the controlled addition and removal of a sequence of thin film layers to/from the wafer surface called structural and sacrificial layers, respectively. The substrate is used primarily as a mechanical support upon which the micromechanical elements are fabricated. For instance, in Treen & Cronin 1993 a 600 GHz air-filled metal-pipe rectangular waveguide structure, realised using a single wafer is presented. A very thick layer of SU-8 photoresist was used to define the waveguide. Gold was deposited onto an SU-8 former, the sacrificial layer of SU-8 was removed to leave a 3-D metal structure. The success of this approach usually depends on the ability to release or dissolve the sacrificial layers while preserving the integrity of the structural layers. Figure 2 depicts an RF switch implemented as a surface-micromachined structure (Richards and De Los Santos 2001). Other possible structures are variable capacitors, V-antennas, rectangular waveguides and microstrip filters.

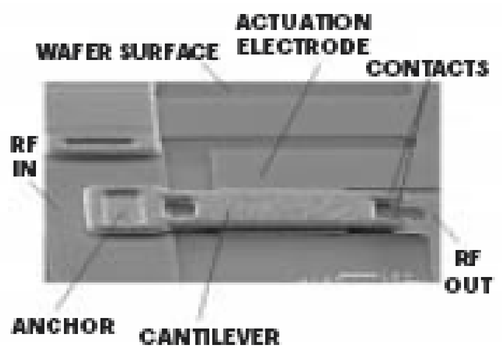

Figure 2: A surface-micromachined RF switch
(Source: Richards and De Los Santos 2001)

In the micromoulding process, microstructures are fabricated using moulds to define the deposition of the structural layer. The structural material is deposited only in those areas constituting the micro-device structure, in contrast to the previous approaches. After structural layer deposition, the mould is dissolved using a chemical that obviously does not attack the structural material.

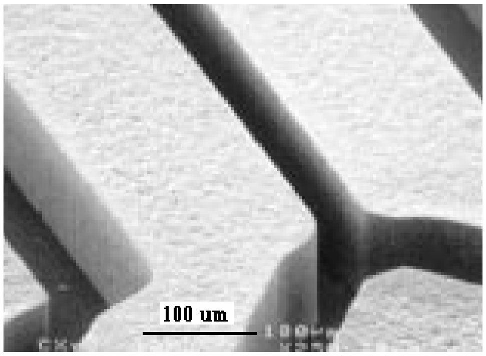

Figure 3: Junction of a CPW 6-dB coupler fabricated in a LIGA process (Source: Willke *et al.* 1998)

A common type is the LIGA process, where LIGA is a German acronym consisting of letters LI (RoentgenLIthography, mean X-ray lithography), G (Galvanik, meaning electrodeposition) and A (Abformung, meaning moulding). In the LIGA process thick photoresists are exposed to X-rays to produce the moulds. Figure 3 shows a junction of a coplanar waveguide (CPW) 6-dB coupler fabricated in a LIGA process (Willke *et al.* 1998).

RF MST components and applications

The MST fabrication possibilities provide solutions to the designer to develop new components that do not carry the limitations of conventional ones. In this section, an insight on the variety of both true-RF MEMS and micromachined components that can be fabricated using the MST is given, together with the applications in which they can utilised, emphasising their excellent electrical performance and versatility. These include switches, variable capacitors, variable and fixed inductors, transmission lines, resonators and antennas.

RF Micromachined Components

Micromachined High-Q Fixed Inductors

Inductors are key passive components which determine the noise and power consumption performance of tuned circuits, such as voltage-controlled oscillators (VCOs), low noise amplifiers (LNA) and impedance matching networks. Conventional IC planar spiral inductors lie on their host low resistivity substrate and as a result suffer from unwanted effects such as low self-resonant frequency, low Q (< 10) and limited operating bandwidth. As a consequence, circuits requiring high performance inductors usually use off-chip components. Using micromachining it is possible to reduce the parasitics affecting conventional on-chip planar inductors, thus providing high performance inductors which can be integrated.

Figure 1 shows an example of a bulk-micromachined inductor in which the substrate has been eliminated from underneath the spiral trace (Sun *et al.* 1996). Removing the substrate reduces parasitic capacitances, thus increasing Q-factor and the self-resonating frequency and removes the associated capacitive dielectric losses. Induced eddy currents in the substrate and associated energy lost due to Joule's heating are also minimized (Lucyszyn 2004). The measured Q values range from 6 to 28 at frequencies from 6 to 18 GHz, with typical inductor values of around 1 nH. Questions have been raised regarding their robustness to withstand subsequent wafer processing, lack of good RF ground and susceptibility of their characteristics to electromagnetic coupling (De Los Santos 2002). These issues were addressed in the structure proposed in Jiang *et al.* 2000, where the structure consists of an elevated inductor suspended over a 30 μm deep copper-lined cavity etched in a silicon bulk.

While substrate removal and shielding together with spiral elevation do improve inductor performance, the ultimate limitation on improvement is dictated by the remaining parasitic capacitance, between metal traces and the substrate. This approach yielded a Q of 30 at 8 GHz on a 10.4 nH inductor with a self-resonating frequency of 10.1 GHz. Solenoid-like inductors above the substrate, as that shown in Figure 4 have been developed using surface micromachining (Yoon *et al.* 1999) yielding a Q of 16.7 at 2.4 GHz on 2.67 nH inductors and exhibiting a linear relationship between the inductance and the number of turns having the shape of a solenoid. In (Ribas *et al.* 2000) the inductor is located on a platform which is then raised above the substrate using scratch-drive actuators.

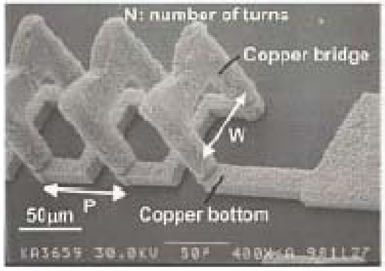

Figure 4: Solenoid-like inductor (Source: Yoon *et al.* 1999)

Another approach uses the self-assembly principle, in which planar inductor structures are brought perpendicular to the substrate, aimed at decoupling the inductor properties from those of the substrate (Chen *et al.* 2003, Dahlmann *et al.* 2001a, 2001b, 2002, Zou *et al.* 2001a). As a consequence of this the designer has a greater possibility to increase the number of turns (maximize inductance) or conductor track width (minimize series resistance). A typical example is shown in Figure 5.

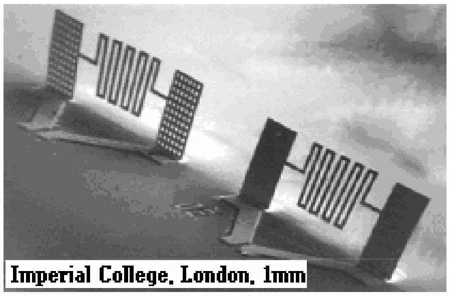

Figure 5: 4.5-turn meander inductor after self-assembly (Source: Dahlmann *et al.* 2001)

There are three major methods of actuation that are used during the manufacturing process to create nearly vertical inductors: plastic deformation magnetic assembly (Zou *et al.* 2001a), tensile stress (Lubecke *et al.* 2001a, Van Shuylenbergh *et al.* 2002, Chua *et al.* 2003) and surface tension (Dahlmann *et al.* 2001a, 2001b, 2002). Very high Q-factors were demonstrated as those in Chua *et al.* 2003 and Van Shuylenbergh *et al.* 2002 in which Q values of 70 and 85 at 1 GHz were demonstrated.

Further improvement of the Q-factor of micromachined inductors in order to achieve values as high as 300, for applications such as multi-band filters is an important challenge for future research (Nguyen 2005).

Micromachined Resonators

The performance of macroscopic waveguide (cavity) resonators and bulky mechanical resonators are well known, in particular the fact that they are capable of exhibiting Q values in the 10,000-to-25,000 range. By means of the available micromachining techniques it is possible to approach a similar level of performance in the context of a microscopic planar IC level.

The work in Papapolymerou *et al.* 1997 proposed a micromachined cavity resonator for X-band applications, in which an unloaded Q of 506 for a cavity of 16x32x0.465 mm was obtained. It can be seen that such resonators are very advantageous in applications such as emerging millimetre-wave commercial applications, whose performance levels and frequency cannot be met otherwise. For instance, a 33.2 GHz monolithic microwave IC (MMIC) oscillator was stabilised by a similar micromachined cavity, in which the obtained phase noise is −113 dBc/Hz at a 1 MHz offset from the carrier (Kwon *et al.* 1999). An 18 dB improvement over its MMIC free-running counter was obtained.

At lower frequencies, cavity resonators become impractical due to their excessively large dimensions. Micromechanical resonators, in turn, become very attractive especially in the 1 kHz-1 GHz range, where they can be used to design ultra stable oscillators (Lin *et al.* 2004) and low loss circuit functions, such as bandpass filters (Bannon *et al.* 2000) and mixers (Wong & Nguyen 2004), for a wide range of transceiver types. There are two main design approaches to design such resonators: 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 obtained by exciting a comb-like structure. The typical maximum resonance frequency of such resonators is about 200 MHz with a Q value of almost 9400 under vacuum conditions. In Nguyen 2005 a short review of high-Q vibrating mechanical resonators is presented. Micromechanical resonators usually require some form of transduction mechanisms so that they can be interfaced to an electrical circuit. Capacitive transduction is commonly employed, but resonators using piezoelectric (Piazza *et al.* 2005) and magnetomotive methods (Roukes 2000) also exist. The choice of transduction method greatly effects the achievable Q, impedance of the devices and also the amenability of their implementation.

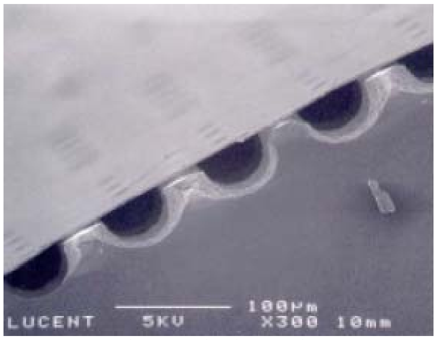

Figure 6: SEM photograph of a membrane-type FBAR (Source: Lubecke *et al.* 2001b).

Applications requiring higher frequencies up to a few gigahertz appear to fall in the domain of film bulk acoustic wave resonator (FBAR) technology. An FBAR device basically consists of a layer of piezoelectric material sandwiched between metal electrodes. Such technology is one of most promising for high-Q integrated wireless filters (e.g. wireless PCS duplex filters (Bradley *et al.* 2000), since it can provide sharp cut-off characteristics, compact size and a practical fabrication. It can also be employed in very stable oscillators such as that presented in Otis and Rabaey 2003, where a 1.9 GHz CMOS oscillator was designed using such a micromachined resonator. In Lubecke *et al.* 2001b a review of such resonators is presented describing resonator design and fabrication together with performance and circuit considerations. Two types of such resonators are the membrane based resonator (see Figure 6) and the acoustic mirror type resonator.

Micromachined Transmission Lines

Transmission lines are flexible components in RF and microwave electronics and are utilised very often in many circuits and systems. Unfortunately conventional transmission lines, have some limitations such as frequency dispersion and to a certain extent insertion loss, originating from the properties of the substrate or the environment in which they are constructed. Similarly to the design of the other micromachined passive devices, MST can be utilised to design transmission lines in which the influence of the substrate is reduced.

There are three main approaches how a micromachined transmission line can be designed: membrane supported microstrip, coplanar microshield and the top-side-etched coplanar waveguide. In the membrane supported microstrip the transmission line is defined on a thin membrane, in which the substrate underneath the trace is bulk-etched via backside processing, to achieve a dielectric constant close to unity. The coplanar microshield was proposed to overcome the limitation exhibited by the membrane supported microstrip which has no intrinsic ground plane, by including the ground planes defining a ground-signal-ground structure. The top-side-etched coplanar waveguide relies on opening etch windows through the top passivation layer to create a pit underneath the line, thus simplifying the substrate etching process when compared to the first approach. Micromachined waveguide uses micromachining techniques which are aimed at overcoming the lower-dimension bound of conventional machining techniques (Richards and De Los Santos 2001).

Typical uses of micromachined transmission lines are in the design of impedance tuners (Lubecke *et al.* 1998, Chiao *et al.* 1999b) and filters (Kim HK *et al.* 1999, 2002). Such applications usually require some form of tuning arrangement: the most common form is to make use of MEMS surface micromachined switches or variable capacitors. Another approach was used in the design of an impedance tuner in a coplanar stripline technology, in which a sliding planar backshort on top of a coplanar transmission lines forms a moveable short circuit and allows for variations in the length of short circuit transmission line stubs using a scratch-drive actuator (Chiao *et al.* 1999b).

RF MEMS Components

Actuation Mechanisms

The appropriate choice of an electromechanical actuator to be used in an RF MEMS component depends a lot on the available fabrication technologies and the requirements of the application being considered. There are mainly four types of actuation mechanisms: electrostatic, piezoelectric, magnetic and electrothermal. The scratch-drive actuator (SDA) is a direct drive actuator that can be based on one of these actuation mechanisms. It has become a common means of achieving mechanical movement in RF MEMS components (Li *et al.* 2002, Minotti *et al.* 1998). Electrostatic actuation is the most commonly employed mechanism because it gives the facility to produce small components that are robust, simple to fabricate, relatively fast and which consume almost no control power. Table 1 provides a comparison between these four actuation mechanisms. More details on these mechanisms can be found in Lucyszyn 2004 and Richards & De Los Santos 2001.

Actuation Mechanism	**Actuation Voltage**	**Power Demand**	**Structure**	**Actuation Speed**
Electrostatic	Can be quite high in particular for the design of good isolation switches	Low	Simple Robust to changes in the environment	Fast
Piezoelectric	Lower than that required in Electrostatic Actuation	Low	Can suffer from parasitic thermal expansion of the layers being used	Fast
Magnetic	Low	High	Bulky Difficult to fabricate	Slow
Electro-thermal	Low	High	Provide High Contact Force	Slow

Table 1: Comparison of RF MEMS actuation mechanisms

Switches

The switch is considered as the most important RF MEMS component (Lucyszyn 2004). The excellent performance of prototype MEMS switches demonstrated in Yao 2000 (insertion loss of 0.1 dB, isolation of 50 dB from DC to 4 GHz and high linearity) shows their great potential for replacing lossy and power hungry semiconductor switches (e.g. Pin-diode switches or GaAs-based FET), such as in numerous applications such as switchable filters, tunable antennas, high efficiency RF power amplifiers and other reconfigurable RF circuits (DeNatale 2004). System architectures can be greatly enhanced, in terms of greater performance and functionality and reduced complexity and cost, if switch performance can be improved even further (Lucyszyn 2004).

They achieve such impressive performance characteristics because of their micromechanical construction, which not only provides a mechanical operation mechanism much like that of macroscopic mechanical switches, but allows the use of metal materials with substantially lower resistivity than semiconductors (Nguyen 2005). Current research is studying new structures with fast switching and low actuation voltage together with improving reliability, packaging and cost issues that can be tolerated in many telecommunication applications (Milosavljevic 2004, Nguyen 2005).

Nearly all RF MEMS switches are based on out-of-plane electrostatically actuated suspension bridge or cantilever-type as shown in Figure 2. The condition of pull-down occurs when the electrode separation decreases below two-thirds of the fully open condition (Lucyszyn 2004). In practice, the actuation voltage for such designs is too high for many applications and so meandering can be introduced to lower the effective spring constant (Pacheco *et al. 2000*, Peroulis *et. al* 2003) since the actuation voltage is proportional to the square root of the spring constant. Other ways of lowering the actuation voltage are described in (Milosavljevic 2004); where a review on RF MEMS switches is also presented.

There are two generic types of RF MEMS switch: (i) the ohmic contact (metal-air-metal, MAM) or series switch (De Los Santos 1999) and (ii) the capacitive membrane (metal-insulator-metal, MIM) or shunt switch (Muldavin & Rebeiz 1999, 2000, Park *et al.* 2000). The advantages of the series switch are that a very low ON state insertion loss and very high OFF state isolation can be achieved. On the other hand, such switches are very susceptible to stiction, corrosion and microscopic bonding of the contact electrodes' metal surfaces and usually require a considerable force to create a good metal-to-metal contact. The advantages of the capacitive membrane switch are that it has a longer lifetime and that the insertion loss is independent of the contact force relaxing the requirements of the actuation mechanism. With such a switch a trade-off between insertion loss and isolation exists (Lucyszyn 2004).

Although electrostatic actuation is the most commonly used type since such switches are usually fabricated using surface micromachining which is most compatible process technology with IC fabrication processes, other actuation mechanism are sometimes employed. RF MST has been used to implement magnetically actuated and thermally actuated switches. With the former, a micromachined magnetic latching switch has been shown in (Ruan *et al.* 2002) operating from DC to 20 GHz and with a worst-case insertion loss of 1.25 dB and an isolation of 46 dB. In (Blondy *et al.* 2001) an electrothermally actuated mm-wave switch is demonstrated, constructed using a stress-controlled dielectric bridge which buckles when heated. The insertion loss has been estimated to be 0.2 dB at 35 GHz. Lower speeds are reached which such actuation mechanisms when compared to the electrostatic form.

Variable Capacitors

Variable capacitors or varactors are essential components wherever circuit tunability is required, like for instance, in variable frequency matching circuits, VCOs and phase shifters. For such applications, having a high Q is very important for maximising noise performance and minimising loss. Varactors have traditionally resisted monolithic integration due to their process incompatibility which results in devices with sub-optimal properties such as low Q, low self-resonating frequency, high sensitivity to even medium RF power levels and generally do not exhibit linear frequency tuning characteristics.

A number of publications demonstrate the performance improvement achieved by MEMS varactors (Young *et al.* 1998, Chen *et al.* 2003, Kassem and Mansour 2004, Liu 2002, Mehmet 2004, Yoon & Nguyen 2000) over conventional integrated diode or MOS varactors. For instance, the work in Yoon & Nguyen 2000 demonstrated a 1-4 pF varactor with a Q ≈ 300 at 1 GHz. MEMS based varactors usually take two forms: parallel plate and interdigitated. 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 (Kim *et al.* 2002) or by using two SDAs located at the opposite sides of the capacitor (Chiao *et al.* 1999b). Another possible version is a structure in which the dielectrics can be electrostatically positioned between the two metal plates (Yoon & Nguyen 2000). Although not so common, development of electrothermally actuated RF MEMS varactors is possible as demonstrated in Hirano *et al.* 1995 and Feng *et al.* 1999.

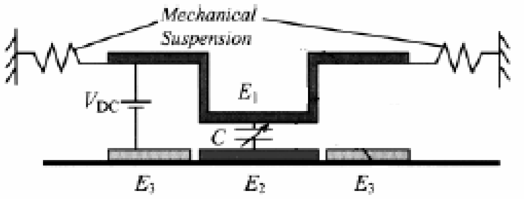

Figure 7: A variable MEMS capacitor in which the actuation electrodes (E_1-E_3) are spaced differently from the capacitor plates (E_1-E_2). (Source: Zou J. *et al.* 2001b)

Although such structures are very convenient to build due to simplicity of their fabrication, such types of MEMS capacitors have a maximum theoretical tuning range of 50% due to the collapse of the capacitor structure as the voltage in increased beyond a certain value (pull-in voltage). This problem can be minimised with the use of a passive series feedback capacitance to remove this instability (Seeger & Crary 1997). A MEMS parallel-plate capacitor with a wider tuning range was proposed in Chen *et al.* 2003, Liu 2002 and Zou J. *et al.* 2001b by spacing the actuation electrodes differently from the capacitor's plates, yielding a theoretical 100% tuning range as shown in Figure 7. However in practice, the obtained tuning range was of about 70%. In Kassem & Mansour 2004 a two movable-plate nitride loaded MEMS varactor gave a tuning range of about 250%-280% whilst in Cai Y. *et al.* 2005 , a multi-step actuator is proposed to increase the tuning range of the standard parallel plate MEMS varactor.

Generally traditional MEMS varactors require lengthy cantilever beams to attain low valued stiffness constants (and so low activation voltages) such that in these designs there is a trade-off between Q and actuation voltage. The work in Sani *et al.* 2007, breaks this trade-off by proposing two novel structures for tunable MEMS capacitors which do not require lengthy beams. When linearity of tuning is more important than dynamic range, circular parallel-plate variable capacitors similar to that proposed in Chiao *et al.* 1999b are preferred. In this case the gap between the two plates is fixed and the overlapping area can be varied by means of two circular SDA.

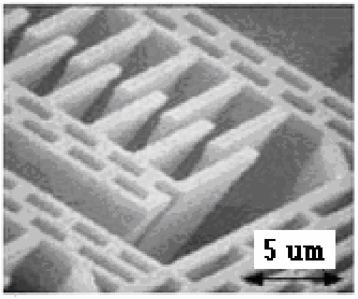

Figure 8: Interdigitated MEMS-based varactor (Source: Borwick *et al.* 2003)

In the interdigitated approach, shown in Figure 8, the effective area of the capacitor is varied by changing the degree of engagement of the fingers of the comb like plates, similar to the macro-scale variable capacitors used in radio receivers (Borwick *et al.* 2003). While interdigitated MEMS capacitors do not suffer from the pull-in voltage limitation, have a high tuning linearity and are generally more compact, they exhibit low-Q values and a low self–resonance frequency in comparison with the parallel-plate capacitors.

The most important research issues related to RF MEMS varactors are improvement in tuning range, lowering of actuation voltages and improvement in actuation speed together with reduction of microphonics and providing reliable packaging (Nguyen 2005).

Variable Inductors

Very few attempts to build tunable true-RF MEMS inductors have been reported in literature to date. In Sun *et al.* 2001, the inductor is divided into four segments and a relay network made of MEMS switches change the overall inductance depending on the switching configuration. Although MEMS devices are used in such a structure to provide tuning, one may argue that these are not true-MEMS tunable inductors (Lucyszyn 2004). An approach to design a true-MEMS variable inductor is presented in Lubecke *et al.* 2001a. The inductor consists of two loops, that are self-assembled above the substrate using the residual stress between the polysilicon and gold layers, with a relative angle between them, as shown in Figure 9.

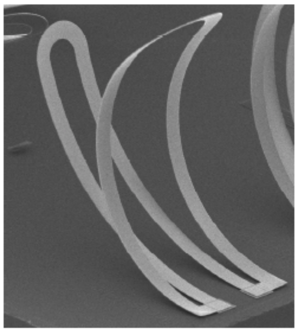

Figure 9: Self-assembling variable inductor: mutually coupled loops (about 1200 μm long) bend at different rates when heated to allow controlled variation of inductance (Source: Lubecke *et al.* 2001b)

The two loops can be thermally controlled. The differential motion results from a cross-member corrugation structure in the inner loop that causes it to bend with temperature at a different rate than the outer loop. The motion affects the mutual component of the total inductance of the structure, thus a variation in inductance is achieved when a DC current flows through the structure. This technique offers a continuous tuning range of 18 %. The main problem with such approach is that the original angle separating the two inductors depends a lot on the deposition temperature of gold during the fabrication and is very hard to control (Abidine *et al.* 2003).

To alleviate this problem, in Abidine *et al.* 2003 the tunability of the inductance mutual component is achieved with the use of thermal actuators that control the spacing between the main and secondary inductor. In this case the inner inductor is again off the substrate because of the residual stress between the metal and the polysilicon layer whilst the outer inductor is attached to a beam that is connected to an array of thermal actuators. When the array is actuated, the beam buckles and lifts up the outer inductor, thus varying the angle separating the two inductors. In this case the tuning range achieved was of 13 %.

Steerable Antennas

In terms of true RF MEMS components, steerable antennas are the most difficult to implement and reach the desired performance. Antennas are very sensitive to the presence of adjacent structures: actuation mechanism in the antenna structure can easily interact with the antenna to distort the desired radiation pattern. Also if the radiating elements are detached from the supporting substrate, the size reducing property of the dielectric cannot be fully exploited (Lucyszyn 2004). Steerable antennas give the possibility of far-field radiation beam-steering and also beam-shaping. In Chiao *et. al* 1999a a 17.5 GHz reconfigurable Vee antenna has been reported, in which the arms of the Vee antenna used to form the radiating aperture are moved, using linear scratch drive actuators. In Baek *et al.* 2003 2-D beam steering is achieved using magnetic actuation.

RF MST Structures: Design and Implementation

In the early days of RF MST structures development, designers used to rely on expensive and time consuming prototyping cycles. Today, a lower risk approach is possible because of the commercially available RF MST design tools, which are user-friendly and enable shorter time development and thus lower design costs.

In particular, the nature of RF MEMS structures necessitates such design tools that can solve true-coupled physical analysis such as electrostatics, electromagnetic, mechanical and thermal. Whilst developing RF MEMS, designers must also take into consideration the device layout, construction and packaging together with their effect on the system performance, in particular if the RF MEMS structures will be used within an IC framework. This is again facilitated through the use of available design tools. As a matter of fact, RF MEMS design tools usually provide modelling and analysis on both a behavioural, physical and structural level.

Successful performance of RF and microwave integrated systems depends a lot on how good is the packaging of the integrated circuits. In RF MEMS development, apart from ensuring that unwanted electromagnetic interference and coupling together with unwanted resonances are not present, designers should aim at developing packaging techniques that prevent moisture and particulates, which may impair the movement of freestanding MEMS structures. Reduction of energy losses such as acoustic and thermal must also be considered. For example the reliability of an RF switch, which is very important for long-term applications (Rebeiz & Muldavin 2001, Campbell 2001, Cass 2001), is limited by organic deposits and contamination around the contact area. These can be eliminated by a clean hermetic packaging environment, but unfortunately this is generally the most expensive step in the production chain and determines the cost of the switch, challenging volume-production. It is likely that the RF switch will continue to be most important RF MEMS component (Lucyszyn 2004) and as a matter of fact there is currently a large effort to develop low cost reliable wafer-scale packaging techniques which are compatible with MEMS switches (Rebeiz & Muldavin 2001). Two commonly used RF MEMS packaging approaches are the flip-chip assembly technique (Miller *et al.* 2000) and the self-packaged technique (Robertson *et al.* 1995).

RF MST Utilisation

There exist two main approaches for integrating RF MST devices into RF and microwave applications: the bottom-up approach and the top-down approach. In the bottom-up approach the designer uses an already established transceiver architecture and replaces the main components by RF MST structures. For example in a conventional transceiver architecture, whether it be super-heterodyne or homodyne, the off-chip passive components, switches, filters, VCOs, mixers and diplexers can all be replaced by their MST counterparts. Indeed, even just direct replacement of components via MST-based ones can lead to significant performance increases. For example, analyses before and after replacement of off-chip high-Q passives by higher Q MST versions in a super-heterodyne architecture often show dramatic improvements in receiver noise figure, e.g. from 8.8 dB to 2.8 dB (Nguyen 2005).

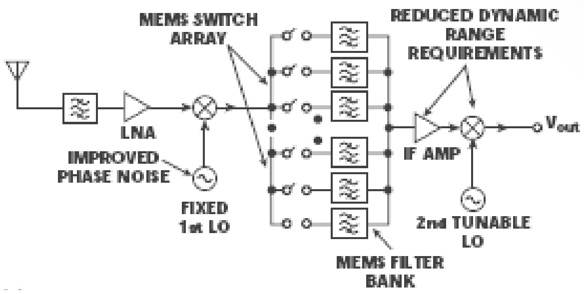

Figure 10: RF MEMS based receiver (Source: Larson 1999)

In the other approach, the designer begins the development by actually devising a new system architecture that is not biased by the usual limitations imposed by conventional RF components. Such architecture would take the advantages provided by MST realisations, such as their microscale size and zero dc power consumption, and use them in massive quantities to enhance robustness and trade Q for power consumption (Nguyen 2005). For example shown in Figure 10, is a receiver architecture proposed in Larson 1999 which utilises an acoustic resonant intermediate frequency (IF) filter bank aimed at simplify the implementation by eliminating the need for a tunable first local oscillator (LO), by replacing it with a fixed LO which can be designed to have a better phase noise response and exploiting the switchable filter bank to affect IF band selection. From the industry's perspective, the overall implementation cost is the most important factor determining the utilisation of such RF MST structures. Although using the bottom-up approach can provide superior RF performance to a conventional transceiver architecture, there is no overall economic gain in replacing conventional devices with RF MST counterparts. On the other hand, utilising the top-down approach there may be cost benefits from new architectures that are enabled with RF MST structures (Lucyszyn 2004).

RF MST Challenges

Although MST has already demonstrated its superior RF performance over conventional approaches, the difficulty in matching the future requirements of the RF designer with the limitations of commercial foundry processes should be taken in consideration (Lucyszyn 2004).

Due to the fact that MST offers many degrees of design freedom than conventional ICs and that most of the available MST products are fabricated in confined foundries, it will be difficult to have a MST “standard process” in the IC sense. As a matter of fact, to date communication system designers are still finding some difficulty in making use of the benefits of RF MST structures, also because the development of such devices requires specialist knowledge. To alleviate this issue MST development platforms (MDP) are being introduced, where an MDP is a reusable MST design component that has been designed, manufactured and validated. Making use of already proven design elements on an IC-compatible process technology platform provides broad access to MST even for non-specialists (Hilbert and Morris 2002).

However, the rapid growth of the MST industry has been impeded by a general lack of reliable material properties, understanding of processing effects on materials and process variables. Standardisation needs to be applied to the methods of characterising a process and its material properties to guarantee volume-production feasibility (Coventor Inc. 2005). Moreover special packaging techniques are required for reliable operation of such devices, especially in the case of RF MEMS structures. Packaging determines the cost of the product and since prices are still very high, it is proving to be one of the major challenges to volume-production feasibility.

There are also inherent problems associated in particular with RF MEMS: for instance at low microwave frequencies, resonant structures are relatively bulky and can be difficult to move under electromechanical actuation (Lucyszyn 2004). Another drawback of RF MEMS is that the actuation voltage required is still relatively high when compared to the always decreasing supply voltage of ICs and the speed of the actuation is not always adequate to every application. Another issue that may present difficulty to chip manufactures is the fact that to take advantage of the benefits of micromachining in RF design, incurs extra processing steps. Nevertheless, since these fabrication techniques, may be implemented as post processing steps, chip manufacturers are not required to modify their high-volume fabrication processes, thus making RF MST structures extremely appealing (De Los Santos 2002).

Conclusion

The recurring demand for wireless systems, such as wireless data links and Internet services, to be more flexible and sophisticated, yet consume very little power and occupy less space, has generated the need for a technology that can effectively reduce manufacturing size, weight and cost and improve performance together with increasing the battery life.

RF MST is widely believed to be one of the technologies that can cater for all these needs by eliminating off-chip passive components, enabling wide operational bandwidths, reducing interconnect losses and producing almost ideal switches and resonators. These provide designers with the necessary elements and features to create novel reconfigurable systems with new levels of performance not achievable otherwise.

The availability of reliable material properties, processing effects and variables during design and manufacturing, together with accurate, easy to use, commercially available MST design tools enables shorter time-to-market and lower design costs. Also, the use of MDP enables a semi-custom design methodology built on the reuse of already proven design elements on an IC-compatible process technology platform, thus providing broad access to the MST allowing non-specialists to take the benefits of integrating MST components into their designs. Availability of low cost hermetic packaging techniques will surely facilitate the volume-production of MST components, in particular for RF MEMS components.

References

Abidine IZE, Okoniewski M and McRory JG (2003), A new class of tunable RF MEMS inductors, *Proc. of the International Conference on MEMS, NANO and Smart System,* 114- 115.

Baek CW, Song S, Park JH, Lee S, Kim JM, Choi W, Cheon C, Kim YK and Kwon Y (2003), A V-band micromachined 2-D beam-steering antenna driven by magnetic force with polymer based hinges, *IEEE Trans. Microwave Theory Tech.*, **51** (1), 325-331.

Bannon FD III, Clark JR and Nguyen CTC (2000), High frequency micromechanical filters, *IEEE Journal of Solid-State Circuits*, **35** (4), 512-526.

Beilenhoff K, Mutamba C, Pfeiffer J, Peerings J, Simon A, Lin C and Hartnagel HL (1999), III-V semiconductor structuring for mm and sub-mm waves, *Workshop M-FrW3 European Microwave Week.*

Blondy P, Mercier D, Cros D, Guillon P, Rey P, Charvet P, Diem B, Zanchi C, Lapierre L, Sombrin J and Quoirin JB (2001), Packaged millimetre wave thermal MEMS switch, *Proc. 31st European Microwave Conf., London*, 283–286.

Borwick RL, Stupar PA, DeNatale JF, Anderson R and Erlandson R (2003), Variable MEMS capacitors implemented into RF filter systems, *IEEE Trans. Microw. Theory Tech.*, **51** (1), 315–319.

Bradley P, Ruby R, Larson J, Oshmyansky Y and Figuerdo D (2000), A film bulk acoustic resonator (FBAR) Duplexer for USPCS Handset Applications, *IEEE MTT-S Int. Microwave Symposium,* **1**, 367 – 370.

Cai Y, Wang J, Ativanichayaphong T and Chiao JC (2005), Multi-step Actuators for RF MEMS varactors and capacitive switches, *TexMEMS, VII International Conference on MEMS, Mexico.*

Campbell T (2001), MEMS Switch Technology Approaches the “Ideal Switch”, Applied Microwave & Wireless, **13** (5), 100-107.

Cass S (2001), Large Jobs for Little Devices, *IEEE Spectrum,* **38** (1), 72-73.

Chen J, Zou J, Schutt-Aine JE and Kang SM (2003), Design and Modeling of a Micromachined High-Q Tunable Capacitor with Large Tuning Range and a Vertical Planar Spiral Inductor, *IEEE Transactions on Electron Devices,* **50** (3), 730-739.

Chiao JC, Fu Y, Chio IM, Delisio M and Lin LY (1999a), MEMS reconfigurable Vee antenna, *IEEE MTT-S Int. Microwave Symposium, Anahein,* 1515-1518.

Chiao JC., Fu Y, Choudhury D, and Lin LY (1999b), MEMS millimeterwave components, *Proc. IEEE MTT-S Int. Microwave Symposium, Anaheim,* 463-466.

Chua CL, Fork DK, Van Schuylenbergh K, Lu JP (2003), Out-of-plane high Q inductors on low resistance silicon, *Journal of Microelectromechanical Systems*, **12** (6), 989-995.

Coventor Inc. (2005), Micro-electro-mechanical systems move toward standardization, Internet address: http://www.coventor.com/media/papers/standardization.pdf (Accessed: 20th December 2006).

Dahlmann GW, Yeatman EM, Young PR, Robertson ID, and Lucyszyn S (2001a), MEMS High Q Microwave Inductors Using Solder Surface Tension Self-Assembly, *IEEE IMS Digest of Papers,* **1**, 329-332.

Dahlmann GW, Yeatman EM, Young PR, Robertson ID and Lucyszyn S (2001b) ‘High Q achieved in microwave inductors fabricated by parallel self-assembly’. *Proc. 11th Int. Conf. on Solid-State Sensors and Actuators (Transducers Eurosensors XV), Munich, Germany,* 1098–1101.

Dahlmann GW, Yeatman EM, Young PR, Robertson ID and Lucyszyn S (2002), Fabrication, RF characteristics and mechanical stability of self-assembled 3D microwave inductors’, *Sen. Actuators*, 215–220.

Daneshmand M, Mansour RR and Sarkar N (2004), RF MEMS Waveguide Switch, *IEEE Transactions on microwave theory and techniques,* **52** (12), 2651-2657.

De Los Santos HJ (1999), *Introduction to Microelectromechanical (MEM) Microwave Systems*, Artech House, Boston – London.

De Los Santos HJ (2002), On the Ultimate Limits of IC Inductors - An RF MEMS Perspective, *Proceedings of the 52nd IEEE Electronic Components and Technology Conference. San Diego, CA*¸1027-1031.

DeNatale J (2004), Reconfigurable RF Circuits Based on Integrated MEMS switches, *ISSCC 2004*, **1**, 310-311.

Feng Z, Zhang W ,Su B , Harsh KF, Gupta KC, Bright V and Lee YC (1999), Design and modelling of RF MEMS tunable capacitors using electro-thermal actuators, *Proc. IEEE MTT-S Int. Microwave Symposium*, Anaheim, 1507–1510.

Harle L and Katehi LPB (2002), A vertically integrated micromachined filter, *IEEE Trans. Microw. Theory Tech.*, **50** (9), 2063–2068.

Hilbert J and Morris A, (2002), RF MEMS Switch Platforms Expedite MEMS Integration and Commercialization, *COMMS 2002, Ypsilanti, Michigan, USA.*

Hirano M, Nishikawa K, Toyoda I, Aoyama S, Sugitani S and Yamasaki K (1995), Three-dimensional passive circuit technology for ultra compact MMICs, *IEEE Trans. Microwave Theory Techniques*, **43** (12), 2845–2850.

Jiang H, Wang Y, Yeh JLA and Tien NC (2000), Fabrication of High-Performance On-Chip Suspended Spiral Inductors by Micromachining and Electroless Copper Plating, *2000 IEEE IMS Digest of Papers, Boston, MA*, **1**, 279-282.

Kassem MB and Mansour RR (2004), Two Movable-Plate Nitride-Loaded MEMS Variable Capacitor, *IEEE Transactions on Microwave Theory and Techniques,* **52** (3), 831-837.

Kim HK, Park JH, Kim YK and Kwon Y (1999), Millimeterwave micromachined tunable filters, *Proc. IEEE MTT-S Int. Microwave Symposium, Anahein,* 1235–1238.

Kim HK, Park JH, Kim YK, and Kwon Y (2002), Low-loss and compact V-band MEMS-based analog tunable bandpass filters, *IEEE Microwaves Wireless Components Letters*, **12** (11), 432 –434.

Kim Y, Lee SG and Park S, Design of the two-movable plate type MEMS voltage tunable capacitor, *NSTI 2002 Nanotechnology Conference, Santa Clara.*

Kintis M and Berenz JJ (1997), MEMS switched resonators for VCO applications, *United States Patent No.: 5,994,982.*

Kwon Y, Cheon C, Kim N, Kim C, Song I and Song C (1999), A Ka-band MMIC Oscillator Stabilized with a Micromachined Cavity, *IEEE Microwave and Guided Wave Letters*, **9** (9), pp. 360–362.

Larson LE (1999), Microwave MEMS Technology for Next-generation Wireless Communications – Invited Paper, *IEEE MTT-S Digest*.

Li L, Brown JG and Uttamchandani D (2002), Study of scratch drive actuator force characteristics, *Journal of Micromechanics and Microengineering*, **12**, 736-741.

Lin YW, Lee S, Li SS, Xie Y, Ren ZY and Nguyen CTC (2004), Series resonant VHF micromechanical resonator reference oscillators, *IEEE Journal of Solid-State Circuits*, **39** (12), 2477-2491.

Liu C (2002), Wide Tuning Range Variable MEMS capacitor, *United States Patent No.: 6,418,006.*

Lubecke VM, Barber B, Chan E, Lopez D, Cross ME and Gammel P (2001a), Self assembling MEMS variable and fixed RF inductors, *IEEE trans. on Microwave Theory and Techniques*, **49** (11), 2093-2098.

Lubecke VM, Barber BP and Fetter LA (2001b), High-Q MEMS for Wireless Integrated Circuits, *5th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Service*, **1**, 203-209.

Lubecke VM, McGrath WR, Stimson PA and Rutledge DB (1998), Micromechanical tuning elements in a 620-GHz monolithic integrated circuit, *IEEE Trans. Microwave Theory Tech*., **46** (12), 2098–2103.

Lucyszyn S (2004), Review of radio frequency micromechanical systems technology, *IEE Proc.-Sci. Meas. Technol.*, **151** (2), 93-103.

McGrath WR, Walker C, Yap M, and Tai YC (1993), Silicon micromachined waveguides for millimeter-wave and submillimeterwave frequencies, *IEEE Microw. Guid. Wave Lett.*, **3** (3), 61–63.

Mehmet G (2004), Method of making an integrated electromechanical switch and tunable capacitor, *United States Patent No.: 6,969,630*.

Miao J, Hartnagel HL, Wilson RJ and Weiss BL (1995), Improved free standing semi-insulating GaAs membranes for sensor applications, *Electronic Letters*, **31** (13), 1047-1049.

Miller DC, Zhang W and Bright VM (2000), Microrelay Packaging Technology Using Flip-chip Assembly, *The 13th Annual International Conference on Micro Electro Mechanical Systems*, 265–270.

Milosavljevic ZD (2004), RF MEMS Switches, *Microwave Review*, **10** (1), 2-8.

Minotti P, Bourbon G, Langlet P and Masuzawa T (1998), Arrayed electrostatic scratch drive actuators: Toward visible effects up to the human scale, *Journal of Intelligent material systems and structures*, **9**¸837-846.

Moore DF and Syms RRA (1999), Recent developments in micromachined silicon, *Electron. Commun. Eng. J.*, **11** (6), 261–270.

Muldavin JB and Rebeiz GM (1999), 30 GHz Tuned MEMS Switches, *IEEE MTT-S Int. Microwave Symp. Dig.,*Anaheim, *CA, USA,*1511-1514.

Muldavin JB and Rebeiz GM (2000), High-Isolation Inductively-Tuned X-Band MEMS Shunt Switches, *IEEE MTT-S Int. Microwave Symp. Dig., Boston, Massachusets*, *USA,* 169-172.

Nguyen CTC (2005), RF MEMS in Wireless Architectures, *DAC 2005, Anaheim, California, USA*, 416-420.

Otis B and Rabaey J, (2003), A 300-μW 1.9-GHz CMOS Oscillator Utilizing Micromachined Resonators, *IEEE Journal of Solid-State Circuits*, **38** (7), 1271-1274.

Pacheco SP, Katehi LPB and Nguyen CTC. (2000), Design of low actuation voltage RF MEMS switch, *Proc. IEEE MTT-S Int. Microwave Symposium., Boston, MA*, 165–168.

Papapolymerou J, Cheng JC, East J and Katehi LPB (1997), A Micromachined High Xband Resonator, *IEEE Microwave and Guided Wave Letters*, **7** (6), 168-170.

Park JY, Kim GH, Chung KW, Bu JU (2000), Fully Integrated Micromachined Capacitive Switches for RF Applications, *IEEE MTT-S Int. Microwave Symp. Dig., Boston, Massachusetts*, *USA,* 283-286.

Peroulis D, Pacheco SP, Sarabandi K and Katehi LPB (2003), Electromechanical Considerations in Developing Low-Voltage RF MEMS Switches, *IEEE Trans. on MTT,* **51** (1), 259-270.

Piazza G, Stephanou PJ, Porter JM, Wijesundara MJ, and Pisano AP, Low motional resistance ring-shaped contour-mode aluminum nitride piezoelectric micromechanical resonators for UHF applications, *18th IEEE International Conference on Micro Electro Mechanical Systems, MEMS' 05*, 20-23.

Rebeiz GM and Muldavin JB (2001), RF MEMS Switches and Switch Circuits, *IEEE Microwave Magazine,* **2** (4), 59-71.

Ribas RP, Lescot J, Leclercq JL, Karam JM and Ndagijimana F. (2000), Micromachined microwave planar spiral inductors and transformers, *IEEE Trans. Microw. Theory Tech*., **48** (8), 1326-1335.

Richards RJ and De Los Santos HJ (2001), MEMS for RF Microwave Wireless Applications - The Next Wave, *Microwave Journal*.

Robertson ID and Lucyszyn S (2001), *RFIC and MMIC Design and Technology.* IEE, London.

Robertson SV, Katehi LPB and Rebeiz GM (1995), Micromachined Self-packaged Wband Bandpass Filters, *IEEE MTT-S International Microwave Symposium Digest*, **3**, 1543–1546.

Roukes ML, Nanoelectromechanical systems (2000), *Solid State Sensor and Actuator Workshop, Hilton. Head, SC,* 367-376.

Ruan M, Tam G, Vaitkus R, Wheeler C and Shen J (2002), Micromagnetic latching RF switches, *Proc. Wireless Design Conf., London*, 59–66.

Sani EA, Nasirzadeh N and Dadshzadeh G (2007), Two novel structures for tunable MEMS capacitor with RF applications, *Progress in Electromagnetic Research (PIER 68)*, 169-183.

Seeger JI and Crary SB (1997), Stabilization of electrostatically actuated mechanical devices, *Proc. IEEE Int. Conf. on Solid-State Sensors and Actuators (Transducers), Chicago, IL,* 1130–1136.

Sun XQ, Zhou S and Carr WN (2001), A micro variable inductor chip using MEMS relay, *IEEE International Conference on solid-state sensors and actuators*, 1137-1140.

Sun Y, Zeijl H, Tauritz JL and Baets R (1996), Suspended Membrane Inductors and Capacitors for Application in Silicon MMICs, *IEEE Microwave and Millimeter-wave Monolithic Circuits Symposium Digest of Papers*, 99-102.

Treen SA and Cronin, NJ (1993), Terahertz metal pipe waveguides, *Proc.18th Int. Conf. on Infrared and Millimetre Waves*, London, 470–471.

Van Shuylenbergh K, Chua CL, Fork DK, Lu JP and Grifths B (2002), On-chip out-of-place high-Q inductors, *Proc. IEEE Conf. on High Performance Devices*, Palo Alto CA, 364–374.

Wang J, Butler JE, Feygelson T and Nguyen CTC (2004b), 1.51 GHz polydiamond µmechanical disk resonator with impedance-mismatched isolating support," *Proceedings*, *IEEE Int. MEMS Conf., Maastricht*, *The Netherlands*, 641-644.

Wang J., Ren Z. and Nguyen CTC (2004a), 1.156-GHz self-aligned vibrating micromechanical disk resonator, *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, **51** (12), 1607-1628.

Willke TL, Onggosanusi E and Gearhart SS (1998), Micromachined Thick-metal Coplanar Coupled-line Filters and Couplers, *IEEE MTT-S International Microwave Symposium Digest*, **1**, 115–118.

Wong AC and Nguyen CTC, Micromechanical Mixer-Filters Mixlers," IEEE/ASME J. Microelectromechanical Systems, **13** (1), 100-112.

Yao JJ (2000), Topical Review: RF MEMS from a Device Perspective, *Journal of Micromechanical Microengineering*, **10**, 9-38.

Yao ZJ, Chen S, Eshelman S, Denniston D, Goldsmith C (1999), Micromachined Low-Loss Microwave Switches, *IEEE/ASME J. Microelectromech. Syst*., **8** (2), 129-134.

Yoon JB, Kim BK, Han CH, Yoon E and Kim C.K. (1999), Surface Micromachined Solenoid On-Si and On-Glass Inductors for RF Applications, *IEEE Electron Device Letters*, **20**, 487.

Yoon JB and Nguyen CTC (2000), A high-Q tunable micromechanical capacitor with movable dielectric for RF applications, *Technical Digest, IEEE Int. Electron Devices Meeting, San Francisco, California*, 489-492.

Young D and Boser BE (1996), A Micromachined Variable Capacitor for Monolithic High-Q VCOs, *IEEE Solid-State and Actuator Workshop Proceedings*, *Hilton Head Island, SC,* 86-89.

Young DJ, Malba V, Ou JJ, Bernhardt AF and Bernhard EB (1998), A Low-Noise RF Voltage-Controlled Oscillator using on-chip High-Q Three Dimensional Coil Inductor and Micromachined Variable Capacitor, *Solid-state Sensor and Actuator Workshop Hilton Head Island, South Carolina*, 128-131.

Zou J, Chen J and Liu C (2001a), Plastic deformation magnetic assembly (PDMA) of 3D microstructures: technology development and application. *Proc. 11th Int. Conf. on Solid-State Sensors and Actuators, Munich, Germany*, 1582–1585.

Zou J, Liu C and Schutt-Aine JE (2001b), Development of a wide-tuning-range two-parallel tunable capacitor for integrated wireless communication systems, 322-329.