1 Introduction

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1.1 Introduction

Radio frequency microelectromechanical systems (RF MEMS) can offer unsurpassed RF performance over more conventional solid-state electronic devices and can help to implement advancements within a broad range of applications; from ubiquitous smart sensor networks to mobile handsets. Moreover, they can substantially reduce the size, weight and cost of reconfigurable subsystems; making this an important enabling technology for the twenty-first century.

MEMS technologies are already firmly established within high-volume commercial markets. Examples include inertial sensors/accelerometers (e.g. used in car airbag sensors, gaming accessories and mobile handsets), disk drive read/write heads, ink-jet printer nozzles, microphones and digital light projectors. In contrast, MEMS for RF applications has been relatively slow to move out of the laboratory and into commercial products. Indeed, the first RF MEMS papers started to appear over three decades ago. For example, a truly landmark paper was published on electrostatically actuated cantilever-type ohmic contact switches back in 1979 [1]. Over the past decade, however, a raft of interesting components and circuits has been demonstrated. Some of these developments have been reviewed from the perspective of enabling technologies [2], while the real founding principles have been described in some detail within the established textbooks by Santos [3], Rebeiz [4] and Varadan *et al*. [5]. More recent articles of noteworthy merit have also appeared on technologies, testing, reliability and applications associated with general RF MEMS [6–8].

1.1.1 Defining terms

It is useful to introduce the underlying concepts of RF MEMS by first defining some common nomenclature. The term *microsystems technology* is generally used within Europe and this represents specific micromachined components (e.g. static-micromachined, self-assembled and vibrational), microelectromechanical systems (e.g. those actuated using electrostatic, piezoelectric, electromagnetic or electrothermal mechanisms) and microfluidic technologies. It can be stated without ambiguity that MEMS components

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are micromachined components, but not necessarily vice versa. Having said this, some non-MEMS micromachining technologies have been mislabelled as MEMS. The subtle distinctions will be discussed in this section.

In the context of MEMS, RF covers the frequency spectrum from direct current (dc) to submillimetre wavelengths. This distinguishes itself from optical MEMS technologies that encompass the mid-infrared to the ultra-violet parts of the frequency spectrum. Therefore, with RF MEMS technology, lumped-element and distributed-element transmission line components are the norm. This does not, however, exclude the possibilities of implementing quasi-optical techniques that are reminiscent of those found in optical MEMS. A notable example of the former is the two-dimensional (2D) matrix of RF MEMS shorted variable delay lines used to make up reflectarray antennas [9], whereas a ubiquitous example of the latter is found with Texas Instrument's digital light processing (DLP™) front projectors [10].

Within this book, the focus of interest has been deliberately narrowed down to what will be referred to as *true RF MEMS* technologies. Here, *microelectromechanical systems* will relate to the following literal interpretation: *systems* corresponds to the integration of both the functional RF component and its associated actuator; *mechanical* relates to both the physical displacement of and mechanical interaction between the RF component and its reconfigurable actuator; *electro* corresponds to the actuator's electrical bias control that normally does not depend on the input RF signal; and *micro* corresponds to the micron-scale dimensions of critical features within the RF component and/or its actuator.

As a result, *self-assembled, micromechanical* and *vibrational* technologies will not be covered in much detail. The *self-assembled* category may include inductors [11, 12] and antennas that exhibit movement during the latter stages of manufacture, but are not intended to move once assembled. *Micromechanical* components can include separable RF connectors [13] and lumped/distributed-element components that can be designed to move by physical manipulation but then remain stationary for the duration of their working lifetime. A good example of a distributed-element micromechanical component is the sliding planar backshort (SPB) impedance tuner reported by Lubecke *et al*. [14]. *Vibrational* components include micromechanical resonators, carbon nanotube (CNT) forest resonators, thin-film bulk acoustic resonator (FBAR) filters, surface acoustic wave (SAW) devices and even quartz crystal resonators. Within this specific category, the components are self-excited by the input RF signal in order to produce physical vibrations. Therefore, these generally non-tuneable technologies have no independent reconfigurable actuator and, within the limited scope of this book, this category is not considered *true RF MEMS*.

1.1.2 Enabling technology roadmap

A unique visual roadmap, associated with RF MEMS, highlighting the main enabling technologies and their interdependencies is shown in Fig. 1.1. The first important area to be considered is fabrication technologies, comprising surface and bulk micromachining and packaging. These technologies are strongly interrelated to other areas identified in Fig. 1.1. For example, if only the non-MEMS RF components are considered, surface micromachining has been used to realise three-dimensional (3D) planar spiral inductors

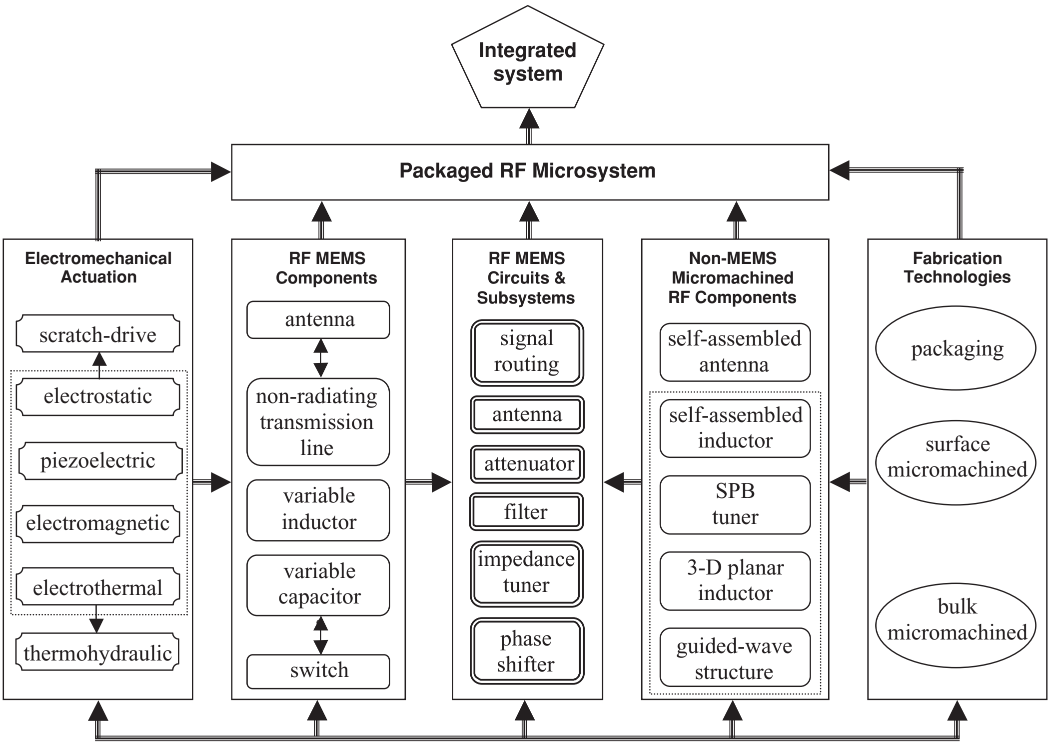

Fig. 1.1 Roadmap of enabling technologies for RF MEMS (based on [2])

and transformers, self-assembled components, guided-wave transmission lines and SPB impedance tuners; but bulk micromachining has been used to implement 3D planar spiral inductors and guided-wave structures (e.g. transmission lines, cavity resonators and horn antennas). High-performance non-MEMS RF components are vital for implementing RF MEMS circuits to preserve the advantages offered by the individual RF MEMS components.

When considering an RF MEMS component, in addition to the RF element, an electromechanical actuator is required; the most appropriate choice of which depends greatly on the fabrication technologies available. By far, the most common actuation mechanism is electrostatic, followed by piezoelectric, electromagnetic and electrothermal. In addition to these generic forms, the scratch drive represents a subset of the electrostatic microactuator. In contrast to scratch drives, thermohydraulic actuators [15–18] – which may be considered a subset of the electrothermal microactuator – offer much larger displacements and forces.

In terms of RF MEMS components, four main generic types have been reported so far: (i) *switches*, (ii) *variable capacitors*, (iii) *non-radiating transmission lines* and (iv) *antennas*. By far, the single most important true RF MEMS component is the switch. This is because it can be used to implement high-performance digitally controlled components (e.g. *R*-, *L*-, *C*-lumped elements and *delay-line, impedance-transforming, resonator*-distributed elements), reconfigurable circuits (e.g. phase shifters, impedance matching networks (i.e. tuners), filters, attenuators and antennas) and subsystems (e.g. signal routing for implementing same-circuit selection and redundancy switching, transmit/receive (T/R) modules and also sectorised and beam-forming antenna arrays).

The RF MEMS tunable or variable capacitor (varicap) is a lumped-element component that can find applications in analogue-controlled reconfigurable circuits. While the RF MEMS switch can offer a superior RF performance over the *p*-type/intrinsic/*n*-type (PIN) diode [19], the variable capacitor has the potential to supersede the simple variable reactor (varactor) diode, especially in terms of phase modulation to amplitude modulation (PM-to-AM) conversion, intermodulation distortion (IMD) and RF power handling.

It is worth mentioning that attempts have been made to implement tunable or variable inductors (variometers). An excellent review, with a notable example of optimised design, has been given by Kim and Peroulis [20]. Based on a transformer configuration, tuning is implemented by varying the separation distance between the inductor and a magnetically coupled short-circuited loop. By electrothermal actuation, a 2:1 variation in inductance has been demonstrated over a dc to 25 GHz frequency range.

A non-radiating transmission line structures can also be represented as a generic RF MEMS component. Examples of these distributed-element components include the SPB (with scratch-drive microactuators) [21] and RF-coupled cantilever inverted-microstrip resonator (under electrostatic actuation) [22].

Finally, an antenna can represent a generic RF MEMS component, with its radiating elements that physically move under some form of actuation mechanism. It is worth making a distinction with RF MEMS antennas that combine fixed-position radiating elements that employ RF MEMS switches or variable capacitors to alter the electrical behaviour of the radiating elements. These RF MEMS antennas would not be considered generic components because, in essence, they are RF MEMS circuits. These are covered in Chapter 11.

With the main non-MEMS RF components and RF MEMS components and circuits being identified, it is appropriate to link them all to the critical issue of packaged RF microsystems. As can be seen in Fig. 1.1, what underpins all the blocks discussed so far are the fabrication technologies available to the designers. With the appropriate choice of packaging solution, which greatly depends on many factors (e.g. RF interconnect performance, seal integrity, material compatibility, process availability, cost, etc.), RF MEMS can be integrated into systems that can offer a much greater RF performance and enhanced functionality over conventional solutions.

1.2 Fabrication technologies

Before RF MEMS technologies are discussed further, fabrication technologies used in commercial hybrid and monolithic integrated circuit manufacture will be briefly introduced [2]. Various RF microsystems have evolved as a result of the continual advancements being made in a number of different manufacturing technologies that have merged together, leading to a blurring in their otherwise distinctive characteristic features. For example, traditional RF MEMS is generally associated with surface micromachining on silicon or glass-like substrates, using microfabrication processing techniques adapted from the silicon integrated circuit (IC) industry. It is possible that future RF MEMS technologies may include ultra-low-cost manufacturing techniques, such as screen printing [12, 23] or low-temperature cofired ceramic (LTCC) processes, where high performance is not of paramount importance and cost is the most important driver.

The manufacture of hybrid and monolithic integrated circuits can be broadly partitioned into traditional *multilayer* and *micromachining*, which have both been used in the production of RF circuits since the 1970s. Advanced passive components found within radio frequency integrated circuits (RFICs), monolithic microwave integrated circuits (MMICs) [24], hybrid microwave integrated circuits (HMICs) and multichip modules (MCMs) [25], rely on multilayer thin-film microfabrication techniques. An interesting example of one such component is a miniature metal-pipe rectangular waveguide (MPRWG) [25–30]. Here, a dielectric or metal layer is first deposited and then a photolithographic process is used to pattern the layer; these steps are then repeated for the next layer, and so on. In recent years, thick-film processing based on screen printing has evolved into high-resolution photoimageable and advanced 3D LTCC manufacturing techniques [31]. With basic screen printing, self-assembled inductors have been demonstrated [12]; while photoimageable techniques have been used to create lumped – and distributed-element components; for example, as used to make MPRWGs [29, 30].

In essence, surface micromachining has evolved from basic multilayer microfabrication; the important difference is that sacrificial layers are used. Here, micromachining is generally not applied to the substrate material, but to the dielectric and/or conducting layers above it. Bulk micromachining generally relies on selective crystallographic etching techniques of silicon wafer substrates, exploiting differential etch rates between the crystallographic directions because of the orientation of the silicon crystal planes. In addition, the Technical University of Darmstadt has for many years been pioneering micromachined structures with III-V materials [32]. Here, in contrast with silicon, crystallographic etching techniques cannot be employed, so wet chemical etching is one alternative, but it is at the expense of poorer precision and profile definition.

1.3 Electromechanical actuation

By demonstrating a functional Planar Backshort impedance tuner within a fully monolithic submillimetre-wave-integrated circuit, Lubecke *et al*. [14] reported a noteworthy example of a RF micromechanical component, although it is not considered as a true RF MEMS component. Here, two moveable impedance tuners were integrated by use of coplanar waveguide (CPW) transmission lines in a quasi-optical detector circuit operating at 620 GHz. The tuning elements were used to vary the power delivered to the detector over a range of 15 dB by adding a variable reactance in a series with an input antenna and a variable susceptance in parallel with the detector.

With true RF MEMS components and circuits, many additional constraints have potentially numerous conflicting requirements that need to be considered early on in the design process. Some of the more obvious interrelated constraints are listed:

(i) Modelling (e.g. circuit, electromagnetic, control bias, mechanical, electrostatic, thermal, failure modes and yield analysis)
(ii) Intrinsic RF performance (e.g. insertion loss, isolation, return loss, tuning linearity, power linearity and maximum power handling)
(iii) Actuation mechanism (e.g. electrostatic, piezoelectric, electromagnetic and electrothermal)
(iv) Control parameters (e.g. voltage/current, hysteresis, power, residual energy and speed)
(v) Layout (e.g. area, volume, topology and topography)
(vi) Fabrication technologies (e.g. surface/bulk micromachining, material selection, wafer bonding and assembly)
(vii) Packaging (e.g. assembly, parasitic effects, seal/hermeticity integrity, standardisation and testing)
(viii) Subsystems integration (e.g. external environment, self-actuation and cost)
(ix) Metrology (e.g. circuit, control bias, mechanical, thermal, vibrational, reliability and standardisation)
(x) Patent infringement and overall cost benefit

While RF MEMS technology can offer unprecedented levels of RF performance – at intrinsic device level and also at homogeneous (e.g. electronically scanned arrays (ESAs)) and heterogeneous (e.g. reconfigurable transceivers) subsystems levels – a significant limitation in any one of the above requirements can mean the success or failure of its implementation or commercial viability. For this reason, RF MEMS components and circuits can be subjected to very severe practical trade-offs in their designs [33]. Indeed, although many initial designs may seem appropriate, it is not until all of these requirements have been carefully considered that a much smaller number of candidate solutions remain for the next phase of detailed computer-aided design (CAD) simulations.

The prototype CAD stage can be fraught with problems that are attributed to the multiscale and multiphysics nature of RF MEMS. For example, nickel has for many decades been used for realizing ferrites and ferromagnets because of its high magnetic permeability at low frequencies. However, in recent years, electroplated nickel has been used as a structural material in RF microfabricated circuits [34], RF MEMS switches [35–37] and antennas [38]. At approximately 30 GHz, weakly magnetised nickel has twice the surface resistance of silver or copper, but is chemically and mechanically more robust [34]. Moreover, it has a relatively small deleterious effect [34]. When used in electrothermal buckle-beam microactuators, with its thermal expansion coefficient being approximately five times greater than that of polycrystalline silicon (also known as polysilicon or poly-Si), the same displacements can be obtained at much lower temperatures [37]. Unfortunately, while nickel is used as a structural material in RF MEMS, its complex magnetic permeability has still not been accurately characterised in the microwave frequency range [39], leading to unknown uncertainty levels in CAD simulations.

Another example relates to dielectric layers commonly used in the microelectronics industry: silicon dioxide (SiO_2) and silicon nitride (Si_3N_4). Both materials can be used to realise capacitive membrane switches, but their tuning hysteresis behaviour is still difficult to model. As a final example, warping effects and even buckling of thin structures, due to residual stresses, may not have been foreseen during the prototype CAD stage. Such issues may occur during fabrication and, because of localised heating effects, during operation.

Simulations can be performed by using a combination of different software tools; for example, using electrostatic, electromagnetic, circuit, mechanical and thermal simulators. Attempts to integrate such tools into "multiphysics" simulators are only now being developed commercially. However, to completely avoid the problems found with the conventional piecemeal approach to multiphysics CAD, a consortium led by Purdue University has created the US Department of Energy's National Nuclear Security Administration (NNSA)-funded Center for **P**rediction of **R**eliability, **I**ntegrity and **S**urvivability of **M**icrosystems (PRISM) [40]. This consortium is in partnership with the University of Illinois (Urbana-Champaign) and University of New Mexico. The objective of the PRISM centre is to significantly accelerate the development of MEMS technologies for civilian and military applications through the use of predictive, validated science and petascale computing, using supercomputers to perform 10^{15} floating point operations per second (petaflops) on real applications. The centre seeks to understand, control and improve the long-term reliability and survivability of MEMS by using multiscale multiphysics simulation – from atoms to complete micromachined devices – to address fundamental failure mechanisms. The main focus is on RF MEMS capacitive switches. The work to be undertaken by PRISM is divided into the following five thrusts: (i) contact physics, (ii) multiscale modelling of MEMS response, (iii) multiscale models for aerodynamic damping, (iv) uncertainty quantification and (v) integration of models and numerics.

In practice, by use of the conventional approach, once the intrinsic level of RF performance of the MEMS component or circuit has been decided, then appropriate methods of actuation can be investigated. Electrostatic actuation can implement relatively small components that are robust and simple to fabricate. They are also relatively fast and tolerant to environmental changes. In principle, they consume almost no bias control power, with the exception of when they are switching between states, although some residual energy is required to hold them in their actuated state. The main disadvantage with electrostatic actuation is that it is difficult to create large physical displacements and sufficient contact force. Moreover, with some designs, self-actuation by the RF signal itself can be a serious problem.

Piezoelectric actuation is typically based on a bimorph cantilever or membrane, where a differential contraction due to the piezoelectric effect causes the structure to bend. Here, relatively fast actuation speeds are possible. Care must be taken to avoid the differential thermal expansion of different layers, which can result in unwanted thermal self-actuation. To avoid this, the structure can be designed to be symmetrical with respect to the thermal characteristics of the layers. Integrating piezoelectric materials into a MEMS environment can also be problematic, because films are difficult to pattern and the processing involves high crystallisation temperatures.

Both electromagnetic and electrothermal actuation offer the advantages of low control voltages and high contact force. Unlike electrostatic and piezoelectric actuators, they are slow, draw a relatively high current and dissipate significant levels of bias control power when held without some form of latching mechanism. Moreover, electromagnetic actuators tend to be relatively large, because they require either a large area and/or volume for their actuation coils.

1.4 Generic RF MEMS components

All the enabling technologies, identified in Fig. 1.1, needed to implement RF MEMS circuits and subsystems have been introduced. Before practical demonstrators can be cited, it is important to understand the key requirements for each component.

1.4.1 Switches

For the past few decades, RF switching has been performed by PIN diodes within HMICs and switching-field-effect transistors (FETs) within RFIC/MMICs. The former can deliver excellent RF performance. For example, M/A-COM's MA4AGSW1 aluminium gallium arsenide (AlGaAs) single-pole, single-throw (SPST) reflective PIN diode switch can achieve a measured ON-state insertion loss of less than 0.4 dB, from dc to 50 GHz; OFF-state isolation better than 45 dB, from 18 to 50 GHz; and return losses better than 15 dB, from dc to 50 GHz [41].

The switching FET is the result of the inherent compatibility with active-FET processing, but the RF performance is much worse, in general, than that obtained with PIN diodes. With any active device solution, intermodulation distortion presents serious limitations at higher RF power levels. Having said this, the Peregrine Semiconductor's PE42671 UltraCMOS^{TM} is being marketed as the world's most linear single-pole, seven-throw (SP7T) solid-state switch [42]. Having a quoted third-order intermodulation intercept point (IP_3) of +68 dBm, while requiring an operating voltage of only 2.75 V, this switch technology seems ideal for duplexer applications within multistandard mobile phones. These solid-state diode and FET switch examples give performances that are formidable and serve as useful benchmarks in the evaluation of realistic RF MEMS solutions.

System architectures can be greatly enhanced – in terms of (i) greater performance, (ii) functionality, (iii) reduced complexity, and (iv) cost – if the RF switch characteristics can be improved even further with the use of MEMS technology [43]. The RF performance of a switch can be crudely represented by the following artificial cut-off frequency figure-of-merit:

$$f_c = \frac{1}{2\pi R_{on} C_{off}} \tag{1.1}$$

where, R_{on} is the ON-state resistance, effectively representing the ON-state insertion loss, and C_{off} is the OFF-state capacitance, effectively representing the OFF-state isolation.

There are two generic types of RF MEMS switch: (i) *ohmic contact* (metal-air-metal, MAM), also simply referred to as *ohmic switches*; and (ii) *capacitive membrane* (metal-insulator-metal, MIM), also simply referred to as *capacitive switches*. The main advantages of the former are that very low ON-state resistance and OFF-state capacitance can be achieved, resulting in extremely high-performance figures-of-merit. For example, Goldsmith *et al*. [44] reported switches having an extracted $f_c = 2$ THz, way back in 1995; which represents improvement of at least a two orders of magnitude over that attainable with PIN diodes. This is because only a relatively small ohmic contact area is needed to exhibit a reasonably low ON-state insertion loss. This small area, in turn, has only a small parasitic capacitance when the electrodes are separated and, thus, good OFF-state isolation can be achieved.

Unfortunately, considerable force is required to create a good metal-to-metal contact and this may not be possible under certain types of actuation. Ohmic contact switches are highly susceptible to corrosion and microscopic bonding of the contacts' metal surfaces. Moreover, contact adhesion due to "static friction" (or stiction), which represents residue contamination, electrostatic, Van der Waals and hydrogen bonding forces, is also a very significant problem.

With the capacitive membrane switch, a trade-off has to be made; increasing the electrode surface area improves the ON-state insertion loss, but compromises the OFF-state isolation. As a result, electrode separation needs to be maximised and this may not be possible with certain actuation mechanisms. The main advantages of the capacitive membrane switch are the (i) potential for higher peak RF power levels of operation, (ii) reduced damage during hot-switching, and (iii) longer lifetime, typically several orders of magnitude more than that of an ohmic contact switch. Another advantage is that the ON-state insertion loss is independent of the contact force, which relaxes the requirement for the actuation mechanism. Having said all this, there are still serious issues of stiction and switching hysteresis effects because of trapped charges associated with the dielectric membrane.

Nearly all RF MEMS switches are based on an in-plane suspension bridge or cantilever design, under electrostatic actuation. Here, the condition of snap-down (also known as pull-down or pull-in) occurs, theoretically, when the electrode separation decreases below two-thirds of the normally fully open condition. It is important to be able to calculate the actuation voltage, V_S, at which snap-down occurs – the point where the inward electrostatic attracting force is equal to the outward linear restoring spring force.

With basic theory, it can be easily shown that the cantilever offers the important advantage of a factor of 8 reduction in the actuation voltage, when compared with that required by the suspension bridge [2]. Reducing the effective spring constant decreases the actuation voltage, but also increases the switching time and, hence, a trade-off exists between the actuation voltage and speed of operation. Practical considerations set a lower limit to the actuation voltage, such as stiction, sensitivity to microphonics and self-actuation when a switch is designed so that the bias control voltage is superimposed onto the RF signal. Moreover, sensitivity to transverse acceleration of a cantilever can be important if they are too long. There is a discrete set of vibration modes that may be supported, and these modes clearly get excited at different natural mechanical resonance frequencies. The beams behave as a complicated *mass-spring-damper* system, with each mode behaving as if it had a different mass, spring stiffness and damping coefficient [22].

In practice, the actuation voltage for simple suspension bridge designs is too high for many applications, unless dc-to-dc converter chips can be employed, and so meandering can be introduced to lower the effective spring constant. Pacheco *et al*. [45] demonstrated a 9 V electrostatically actuated switch, having a five-meander arm at each of the four corners of the capacitive membrane bridge. Here, the capacitance ratio = 2.5 pF/47 fF = 43; insertion loss = 0.16 dB at 40 GHz; isolation = 26 dB at 40 GHz; and self-actuation occurs with a mean RF power of 6.6 W.

Failure due to stiction can occur when the stiction force is greater than the restoring force of the spring when it is in the 'closed' position. It is difficult to predict the stiction force, because this depends on the surface quality of the electrodes as well as on the environmental conditions (e.g. humidity and surface contamination of the electrodes). With low actuation voltage switches, stiction can be a serious problem. For this reason, reliability and hermetic packaging issues are now of the highest priority among manufacturers.

In addition to electrostatically actuated switches, RF MEMS technology has been used to implement electromagnetically and electrothermally actuated switches. With the former, a micromachined magnetic latching switch has been demonstrated by Ruan *et al*. [46] operating from dc to 20 GHz and with a worst-case insertion loss of 1.25 dB and an isolation of 46 dB. The device is based on preferential magnetisation of a nickel-iron magnetic alloy (permalloy) cantilever within a permanent external magnetic field. A short current pulse, through an integrated coil underneath the cantilever, can achieve switching between two stable states. This switch technology will be discussed in more detail in Chapter 4.

Blondy *et al*. [47] demonstrated an electrothermally actuated millimetre (mm)-wave switch. The switch is constructed using a stress-controlled dielectric bridge which buckles when heated. Here, resistors are fabricated into both beam supports. When a 5 V bias is applied to the switch, the resistors heat up and the beam buckles, thus, closing the switch. The insertion loss has been estimated to be 0.2 dB at 35 GHz and the turn-ON and turn-OFF times were measured to be 300 μs and 50 μs, respectively.

1.4.2 Variable capacitors

Variable capacitors are essential for direct reactance control and indirect control of frequency or transmission phase angle. With the latter, resonant frequency tuning is employed in applications such as antennas, filters and voltage-controlled oscillators (VCOs). With filters and VCOs, maximising the capacitor's quality (Q)-factor is of paramount importance to ensure minimal loss and optimal noise performance. Until relatively recently, only varactor diodes could provide direct voltage control for an integrated capacitor. However, while solid-state devices are useful for frequency agile applications, they have low Q-factors and exhibit poor PM-to-AM conversion, IMD and RF power handling characteristics.

RF MEMS capacitors can overcome some, if not all, of the disadvantages of varactor diodes, but at the expense of much slower control speeds. In principle, the switch is a special case of a variable capacitor. As a result, the variable capacitor is commonly