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Motivation and Background: RF Switches and the Need for a Non-Volatile RF Switch

1.1. Introduction

In electrical engineering, a switch, in general, is a device which opens, closes or regulates a current path at a desired event, like ON or OFF. Switches are an inevitable component of all electronic systems we come across in our life. Like the presence of salt in food, most of the time we are unaware of the presence of this mighty little electrical component that plays many roles in our daily life.

Even though the basic responsibility of a switch is to control (open or close or regulate) a current path when desired, it can perform multiple functions, such as a classic vintage mechanical electrical switch, a telephone keypad, a relay in an automatic bread toaster, a switching regulator in a room heater, a capacitive or resistive touch screen of a mobile phone, an integral part of signal modulation system for communication and Internet and so on.

In a broad sense, an electrical switch is identified by the associated actuation mechanism used to close, open, or regulate the current path through it. Electrical switching action is usually associated with the following actuation mechanisms: mechanical (mechanical toggle switches), electronic (PIN diodes, field effect transistor [FET], electromechanical relays), chemical (azobenzene photoelectric switches), magnetic (reed switches), light (opto-couplers), software defined (routers), ionic bridging (conductive bridging random access memory [CBRAM]), phase change and so on. This definition, however, is a very crude explanation of available switch technologies, which are in greater abundance than could be analyzed or differentiated in a single book.

In this book, we concentrate on non-volatile (which do not require a power supply to maintain their impedance state) switches for radiofrequency (RF) and microwave frequencies using nanoionic conductive-bridging metal–insulator–metal (MIM) switch technology, generally identified as CBRAM, for low-cost RF and microwave devices. Here, we focus on overcoming one of the significant shortcomings of passive RF and microwave devices, which is non-volatile electronic reconfigurability.

In this book, we propose techniques to make possible the integration of passive non-volatile switches with passive devices that primarily work in the frequency range of a few MHz to around 10 GHz. Referring to this frequency range, we assume the freedom to address the domain of this book as "RF" or "microwave" frequencies, interchangeably. This book aims to democratize the CBRAM/MIM switching technology for passive/low-power RF and microwave devices using a simple manufacturing process, which is compatible with mass production, at an economically efficient budget.

In this chapter, we discuss and give some examples about the need for such a study, and the background information available at the start of the research. We give a brief introduction on the available RF and microwave switch technologies. Then we present the state of the art in memristive CBRAM/MIM switch technology, and explain the reasons for choice of this technology in this research. We also provide in brief an introduction to targeted RF domains, which are the point of application of the developed CBRAM/MIM RF switching solutions.

1.2. Requirements and definition of a switch at RF and microwave frequencies

Modern life is predominantly dependent on electromagnetic energy propagations in the range 3 kHz–300 GHz on the electromagnetic spectrum, which is generally referred to as RF and microwave signals (Pozar 2005). The RF and microwave spectrum includes numerous application bands such as television, radio, mobile phone, GPS, Bluetooth, Wi-Fi, satellite and so on. RF and microwave radiations are also used for a lot of extended applications such as tracking, ranging and enhanced vision (radar and radio astronomy), heating (microwave ovens and heating in nuclear fusion reactors), imaging (microwave tomography), medical applications (microwave ablation of tissues) and so on. In essence, one could say that RF and microwave frequency signals find their application anywhere from a simple domestic kitchen to outer space.

High-frequency RF and especially microwave signals have very short free space wavelengths, typically of the order of a few tens to a few centimeters. Due to high frequency and small wavelengths, standard circuit theory and electronic circuit approaches are not enough to solve and define working phenomena in this domain (Jordan and Balmain 1968; Bahl 2003; Pozar 2005; Sadiku 2007). At these frequencies, classic lumped circuit element approximations defined by standard circuit theory prove difficult to hold onto, as at RF and microwave frequencies components are often associated with a number of distributed parameter effects arising from their geometry. This is because at these frequencies the phase of a voltage and current is significantly affected by the physical size of a device due to small wavelengths. Similarly, circuit parameters, such as inductance, capacitance and associated dielectric properties, are significant for circuit element sizes comparable to wavelengths. At these wavelengths and frequencies, electromagnetic field theory and broadly defined circuit theory, both described by Maxwell’s equations, are used for the analysis (Jordan and Balmain 1968; Bahl 2003; Pozar 2005; Sadiku 2007).

Similar to standard electronic circuits, switches are an integral and also inevitable part of RF and microwave circuits. However, some special care should be taken and some requirements should be satisfied for the design, development and applications of switches in this field. This is with respect to the previous explanations.

The performance and behavioral features desired for RF and microwave switches are not much different from those expected for any devices or circuit at these frequencies (Breed 2010). The most relevant of these requirements or performance factors are briefed as follows:

- bandwidth of operation of the switch;
- ON and OFF state insertion loss and isolation at frequencies of interest;
- switching speed;
- operating lifetime (number of switching cycles and reliability);

– figure of merit (product of OFF state capacitance and ON state impedance of the switch, typically expressed in THz);

– operating voltage and power consumption;

– power handling, stability and linearity;

– temperature and environmental dependence;

– isolation of biasing path from RF signal path;

– cross-talk and radiation isolation (isolation to other components in the circuitry).

These requirements vary according to a desired application, and are seldom obtained altogether in a single technology, but are a compromise defined with respect to a certain tradeoff, taking into account factors such as desired performance, accuracy requirements, cost, available physical space and so on.

This section and eventually this chapter chalks a boundary, helping our readers to understand and assess the outcome of the experimental results and associated discussions on CBRAM-based RF switching solutions presented herewith.

1.3. Review of RF and microwave switching technologies

A handful of switching technologies are available for RF and microwave switching, most of them with a unique distinctive feature. Some of the common technologies include PIN junction diode switches (Keysight Technologies 2019), FET switches (Keysight Technologies 2017a), hybrid switches like microwave monolithic integrated circuits (MMIC) (Mizutani and Takayama 2000; Keysight Technologies 2014), electromechanical RF switches like micro-electromechanical-systems (MEMS) (Analog Devices 2018) and so on.

New innovations such as memristive switches, including phase change memory (PCM) (Wang *et al*. 2014) or CBRAM (Pi *et al*. 2015), and engineered material switches, such as monolayer grapheme-based switches (Li and Cui 2015; Moldovan *et al*. 2015; Ma *et al*. 2016; Pan *et al*. 2017), are also in a budding stage to redefine the future of RF switching.

In this chapter, we discuss only the significant switching technologies of the above list. We also outline the state of the art of the topic in focus in this book, which is the memristive CBRAM/MIM switch technology. Here, we try to differentiate and compare this technology with the former counterparts.

Classically, RF and microwave switches could be broadly grouped into three main categories as follows:

1) electromechanical switches;

2) solid-state (semiconductor-based) switches;

3) memristive switches.

Electromechanical switches are similar to electrically actuated mechanical switches such as relays and were succeeded by more efficient technologies such as MEMS. Solid-state switches generally work on the basis of regulated electron flow through semiconductor or engineered materials, such as PIN diodes, FETs and hybrid semiconductor switches.

Technology (Right) Parameters (Down)	**Solid-state semiconductors**	**MEMS**	**Memristive switches**
ON state impedance	~1 Ω	~0.5–2 Ω	~2–10 Ω
Lower frequency limit	DC to a few kHz	DC	DC
Upper frequency limit	>100 GHz	>1 THz	>40 GHz
Switching time	10–100 ns	1–300 µs	1–10 µs
Figure of merit (THz)	1–4	10–300	0.015–38
Non-volatility	No	No	Yes
Fabrication complexity	High	Very high	High, low*
Commercial availability	Yes	Yes	No
Cost	Low	High	No commercial products
*High for classic fabrication techniques (Nessel and Lee 2011; Pi *et al.* 2015) and low for fabrication with polymer ion-conductors (Perret *et al.* 2015; Jian *et al.* 2017).			

Table 1.1. *Comparison of general categories of RF switching technologies*

Here, we take the privilege of introducing a third and emerging category called “memristive switches”, which is the focus topic of this book. We present this topic as a separate category for detailed discussion to highlight its relevance and unique characteristics.

A memristive switch could in a simple way be defined as a resistor with non-volatile memory, i.e. a resistor element that is capable of preserving its impedance states based on a preset former actuation, even after its withdrawal. This is achieved by techniques such as growing a metallic filament among two electrochemically asymmetric electrodes sandwiching an ion conductor layer as in CBRAM, changing the phase of a material from amorphous to crystalline that also inverses high to low impedance state as in PCM and so on. On a broader perspective, memristive switches are a subset of solid-state switches, but are considered here individually to highlight their significance and contrast from classic solid-state semiconductor switching technologies. In this section, we first we present a summary of the comparison of performance factors of all discussed RF switching technologies for a clearer understanding for the reader. This comparison is summarized from the discussion and references in the text, and is given in Table 1.1.

In the following sections, we explain in brief the main considerations, advantages and shortcomings of each of these switching technologies.

1.3.1. *Electromechanical switches: MEMS*

MEMS are a technology of fabrication of microscopic electronic devices with moving parts (Rebeiz 2004). Typically, MEMS are made up of components of size 1–100 µm, indicating the “micro” in MEMS. Generally, these devices are fabricated using micromachining technologies on substrates such as silicon, quartz, gallium arsenide and so on.

MEMS technologies were introduced in the 1970s for the realization of pressure and temperature sensors. After that, RF switches using MEMS technology were successfully presented in the late 1990s by the United States of America’s Defense Advanced Research Projects Agency (DARPA) (Rebeiz 2004). MEMS RF switches resemble classic electromechanical relay switches at a micrometer scale.

Today, ample amount of research has been done and it is still continuing on MEMS technology for RF switching, and several designs have been proposed in this domain that work up to THz frequencies (Goldsmith *et al.* 1998; Mollah and Karmakar 2001; Suzuki 2001; Chan *et al.* 2003, 2007; Rebeiz 2003; Unlu and Jarrahi 2014; Oberhammer 2017). Technological competence and reliability of MEMS technology are acknowledged by the fact that MEMS-based RF switches are now being trusted for a multitude of applications including medical and military equipment, and are widely released as commercial products (e.g. Analog Devices 2018). This technology is now used for a wide spectrum of RF switching applications including phase shifters (Rebeiz *et al.* 2002), multipole switches (Lee *et al.* 2005), reconfigurable antennas (Jung *et al.* 2006; Zohur *et al.* 2013), outer space and satellite communication applications (Souchon *et al.* 2017) and so on. There are several topologies of MEMS switches, implemented in series or shunt modes. Actuation mechanisms for MEMS switches are achieved through several techniques such as electrostatic, magnetostatic, piezoelectric or thermal means (Rebeiz 2004).

Broadly, two types of MEMS switch technologies are used extensively for RF switching, namely ohmic contact type and capacitive contact type. The former technology is used for frequency ranges from DC to 60 GHz and the later for 6–200 GHz, in general (Rebeiz 2004). These topologies are both implemented in series and shunt mode.

In terms of ohmic contact MEMS switches, the device consists of a micro-machined moving electrical contact arm, which is actuated to make or break an ohmic electrical contact (e.g. Chan *et al.* 2007). Figure 1.1 shows an illustration of an ohmic contact MEMS RF switch in series configuration. Here, the cantilever signal bridge (connected to signal line) is actuated to make or release an ohmic electrical contact with the isolated transmission line, respectively, for the ON and OFF states.

For capacitive contact MEMS switches, a variable capacitance contact system is made with the help of a suspended/spanning membrane to couple RF signal energy to a required transmission path, or to ground, for series and shunt configurations, respectively, through a capacitive contact (Goldsmith *et al.* 1998). Figure 1.2 shows an illustration of the working of a shunt mode capacitive MEMS RF switch built in a CPW transmission line configuration. Here, the suspended membrane bridge is actuated as shown in figure to touch and release from the dielectric slab to exhibit high and low capacitance values, respectively, to short circuit (OFF state) the power flowing through transmission line to ground for high capacitance values, and to revert (ON state) the signal flow in transmission line for low value. Capacitive contact MEMS switches are generally observed to exhibit more reliability than ohmic contact types (Rebeiz 2004). Ohmic contact type switches are prone to issues such as contact conductance degradation due to friction and oxide formations, cold welding at atomic level in metals leading to failure of switches and so on.

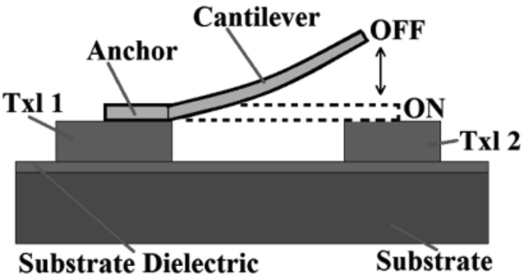

Figure 1.1. *Ohmic contact type MEMS RF switch in series configuration*

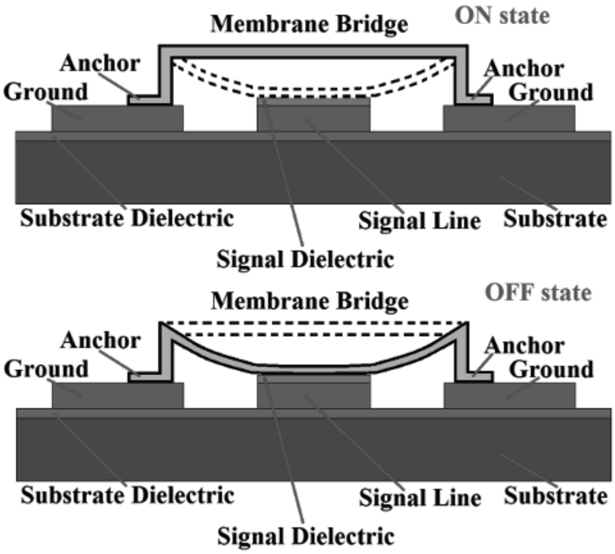

Figure 1.2. *Capacitive contact type MEMS RF switch in shunt configuration on a CPW line, showing ON and OFF states (cross-section view). For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

MEMS switches are known for their superior performance in terms of low insertion loss, high isolation and high linearity in comparison to solid-state semiconductor switches. However, MEMS switches are limited by factors including fabrication cost, size and robustness related to the reliability of moving parts, with respect to solid-state semiconductor counterparts.

1.3.2. *Solid-state semiconductor switches*

Solid-state semiconductor switches are based on regulation of RF energy flow through a semiconductor material (generally unheated) by controlling its electrical conductivity. This is done by introducing or inhibiting charge carriers (electrons or holes) in the semiconductor material by means of an external DC bias. The word "solid state" was introduced around 1960 and means that the switch involves only unheated solid semiconductor materials and no moving parts, as in the immediate counterparts like mechanical relays, nor vacuum tubes, which are now obsolete anyway. In this book, we provide detailed discussion only on solid-state semiconductor switches limited to RF and microwave applications. The most common and extensively used solid-state semiconductor RF switches are PIN diodes, FETs and hybrid switches, discussed in detail below.

Generally, solid-state semiconductor RF switches show more reliability and lifetime characteristics in comparison to MEMS RF switches or their ancient counterparts, the vacuum tubes. This is due to their remarkable resistance to shocks, vibrations and mechanical wear (Keysight Technologies 2017b). They also exhibit a faster switching time and are cheaper in cost, in comparison to MEMS. The adaptiveness of semiconductor devices to be batch produced in groups of thousands or more on a single wafer is one of the major reasons for their reduced cost. One of the drawbacks of semiconductor RF switches compared to MEMS is their higher ON state impedance, which leads to higher insertion losses.

1.3.2.1. *PIN diode RF switches*

A PIN diode is basically a semiconductor junction diode with layer architecture as indicated by its name. It has a high resistivity intrinsic (I) semiconductor layer sandwiched among a pair of highly doped P-type (P+) and N-type (N+) semiconductor layers as shown in Figure 1.3(a).

When this diode is forward biased, it starts functioning similar to a regular P-N junction diode. But due to the presence of the high resistivity intrinsic layer, charge carriers from their respective layers (electrons from N type and holes from P type) are injected into the intrinsic (I) layer and recombine there. However, due to the high doping concentration of P and N layers, and high resistivity of I layer, the charge injection rate is much higher than the recombination rate. This results in an accumulation of many charge carriers in the I layer despite recombination and leads to effective lowering of resistance of this layer. This establishes the RF-ON state of the PIN diode switch. During forward bias, a PIN diode could be represented as an RL network where the resistance R_F is the resistance of the diode under forward bias, and L_P is the parasitic inductance due to the associated package, as shown in Figure 1.3(b).

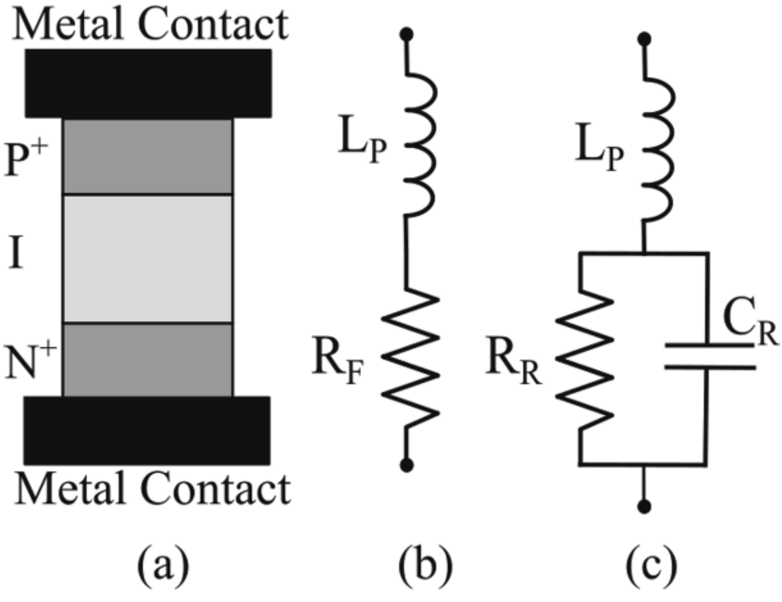

Figure 1.3. *PIN diode: (a) layer architecture of a typical PIN diode; (b) electrical equivalent circuit in forward bias (ON state); (c) electrical equivalent circuit in reverse bias (OFF state)*

During reverse bias (or no bias), the intrinsic region does not have any charge carriers and exhibit high resistivity, establishing an RF-OFF state of the diode switch. At this state, the electrical model of the diode could be represented as an RC parallel network in series with the parasitic inductance L_P, as shown in Figure 1.3(c). Here, R_R is the resistance measured across the diode in reverse bias and C_R is the diode junction capacitance. This junction capacitance is an important feature as it limits the maximum frequency of operation of the PIN diode switch. Nevertheless, typical commercial PIN diodes have usable frequency range up to 50 GHz (Keysight Technologies 2017b). The dielectric relaxation frequency of intrinsic (I) regions sets the lower frequency limit of a PIN diode, the typical values of which are around a few MHz. PIN diodes are basically current controlled devices, and in terms of power consumption, PIN diodes consume higher power than their immediate relatives, the FET switches. Another important characteristic of PIN diode RF switches is that in these devices, the DC biasing path is not different from the RF path, and hence special isolation circuits are necessary to prevent leakage and unwanted mixing of both these paths.

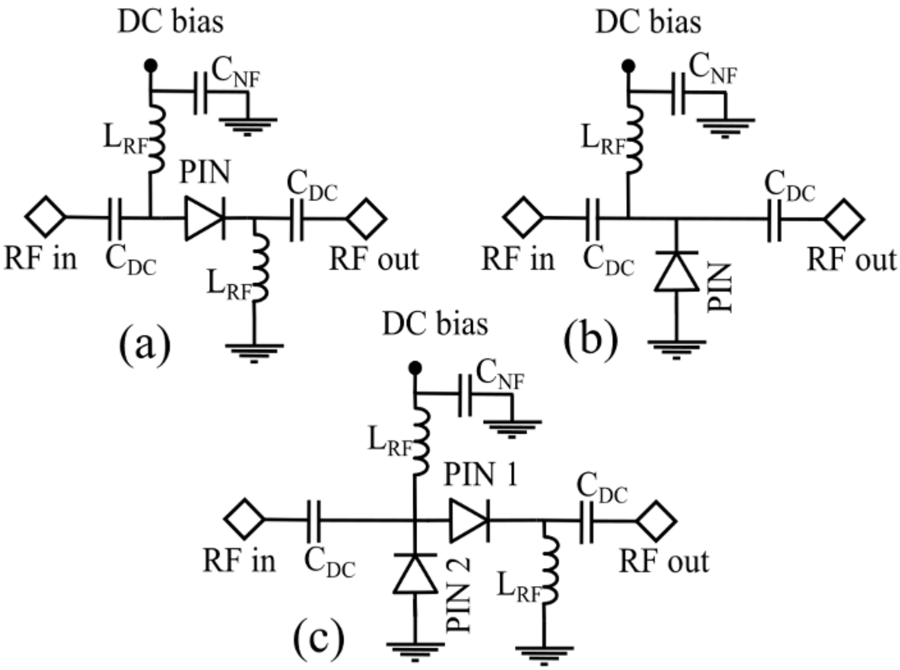

Figure 1.4. *Application of PIN diodes as switches in RF circuit: (a) series mode, (b) shunt mode and (c) series–shunt mode*

PIN diodes are used in circuits as RF switches in series, shunt and as a combination of series–shunt configurations, as shown in Figure 1.4, according to the application and performance requirements. Here, C_{DC} is the DC block capacitor to prevent mixing of DC biasing used for ON and OFF control of PIN diodes into the RF path, L_{RF} is the RF choke to prevent the leakage of RF power into the DC biasing path and C_{NF} is the noise bypass capacitor to discharge any unwanted noise pickup from the DC side of the circuit. Among these components, RF choke inductors are a factor that add significantly to the implementation cost of this circuit.

1.3.2.2. *FET-based RF switch*

FET are semiconductor devices in which the current flow in a heavily doped two terminal (source, drain) unipolar semiconductor block is regulated based on an applied electric field to an attached semiconductor layer (gate) of opposite polarity (Keysight Technologies 2017b). FETs are introduced with different layer architectures and technologies, depending on materials used, electrical contact among gate to drain and source, construction topology and so on; however, in most cases, the principle remains the same. Some of the notable models that are used commercially are MOSFET (metal oxide semiconductor field effect transistors), MESFET (metal semiconductor field effect transistors) and HFET (heterostructure field effect transistors) (Storm 1967).

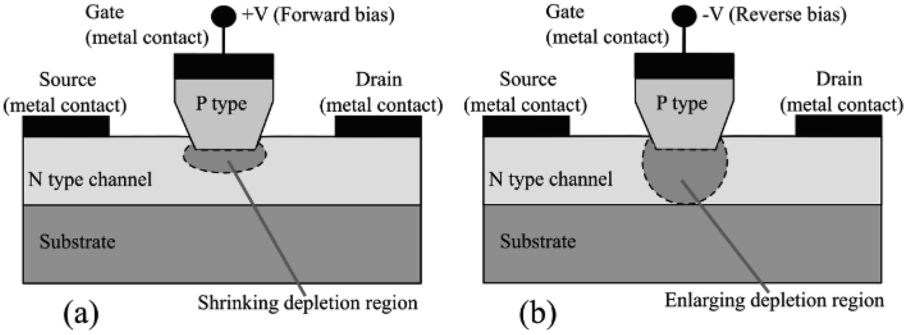

Figure 1.5. *Simplified layer architecture of an N-channel field effect transistor (FET) for RF switching applications. (a) ON state and (b) OFF state*

Similar to a PIN diode, a specially constructed FET (taking into account the requirements stated in section 1.2) could be used as an RF switch (Keysight Technologies 2014, 2017a, 2017b). Figure 1.5 shows a simplified layer diagram of an N-channel Gallium arsenide (GaAs) FET for RF application.

Here, the drain to source path offers a low resistance current path to an incoming RF signal during zero or forward bias, establishing the ON state of the switch, as shown in Figure 1.5(a). Inversely, one could see that a reverse bias voltage applied to the P-type gate material and one of the terminals (source or drain) enables the increase of the drain to source resistance by enlarging the highly resistive depletion region, establishing the OFF state of the switch as shown in Figure 1.5(b). Depletion of the conductive channel in this manner is referred to as a "pinch off" mechanism. This mechanism provides excellent isolation properties even at low frequencies and DC for an FET RF switch. The DC biasing path is different from the RF signal path for an FET, and this helps in reducing the circuit complexity by avoiding the use of comparatively expensive RF choke inductors and DC blocks.

FET is a voltage-controlled device, and it is characterized by low power consumption in operation, in comparison to a PIN diode switch. However, the ON state channel resistance of an FET is typically greater than that of a PIN diode, which results in higher insertion loss in comparison to the latter one. The operating frequency range of FET switches are also inferior to PIN diodes due to the presence of greater drain to source capacitance in reverse bias (OFF state), as a result of thinner depletion region. Figure 1.6 shows an example of a classic configuration of a series–shunt FET RF switch in an SPDT RF switching application.

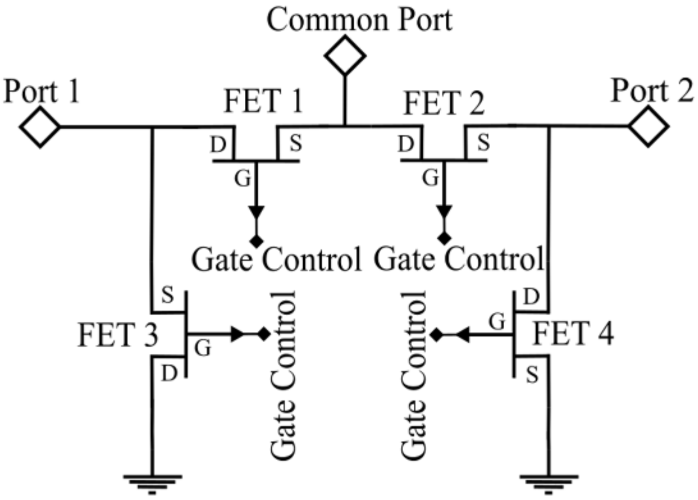

Figure 1.6. *Application of FETs as RF switches in a single pole double throw (SPDT) configuration*

We have seen the merits and demerits unique to both FET and PIN diode switches in previous sections. Engineers have combined these advantages to get best out of these technologies in the form of hybrid RF switches. Hybrid RF switches is a general nomenclature, given to a group of semiconductor switch technologies that aims at manufacturing of RF switches with optimized performance features using modified forms of PIN diodes and FETs. Extensive research has been done on this topic for a few decades, and today a number of excellent switching solutions have been reported. Some of the commonly used technologies are MMIC (Mizutani and Takayama 2000), SOI (silicon on chip) (Lee and Lee 2010; Jaffe *et al*. 2015), RF–CMOS (complementary metal–oxide–semiconductor) (Li *et al*. 2008) and so on. In commercial versions of these technologies, the switches are modular and are optimized for features such as input and output impedances, cross-talk and electromagnetic interference reduction, mechanical package stability and vulnerability to extreme environments and temperatures.

1.3.3. *Memristive RF switches*

Memristive RF switches are a new innovation among the classic and mature RF switching technologies explained above. As the name indicates, a memristor is a resistor with non-volatile memory (Chua 2011). This is a hypothetical electronic device, predicted by a circuit theorist called Leon Chua in his revolutionary article entitled “Memristor – The Missing Circuit Element” (Chua 1971). Chua predicted, based on the arguments of symmetry connecting basic electrical quantities, that there exists the possibility of a fourth fundamental element, which he named the “memristor”.

The theories of the memristor concept are too formal and too far from the evolved applications of memristive RF switches. However, this book would be incomplete without stating the general principle behind the focus topic of this publication, so we will state the general theory of the memristor, and then move on to memristive RF switching technologies.

Chua’s prediction of the memristor is described below as a generalized overview, and it is based on the following arguments of symmetry. The four fundamental variables of electricity and magnetism, the electric charge (q), magnetic flux (ϕ), voltage (v) and current (i), always co-exist, and these quantities except magnetic flux and charge are connected with each other by the so-called fundamental circuit elements resistance (R), inductance (L) and capacitance (C).

Chua stated that there should be a nonlinear relationship to connect the magnetic flux and charge, as shown in equation [1.1]. A circuit element called a memristor with a property called memristance (M) was modeled based on this theory, as shown in equation [1.2], which could be simplified by substituting flux as time integral of voltage and charge as time integral of current as in equation [1.3]. This concept is summarized in the form of an illustration in Figure 1.7. Figure 1.7 also shows the symbol of a memristor devised by Chua. From equation [1.3], the unit of a memristor could be extracted as the Weber per Coulomb (Wb/C) or simply Ohm (Ω).

$$f(\phi(t), q(t)) = 0 \qquad [1.1]$$

$$M(q) = \frac{d\phi}{dq} \qquad [1.2]$$

$$M(q(t)) = \frac{d\phi/dt}{dq/dt} = \frac{v(t)}{i(t)} \qquad [1.3]$$

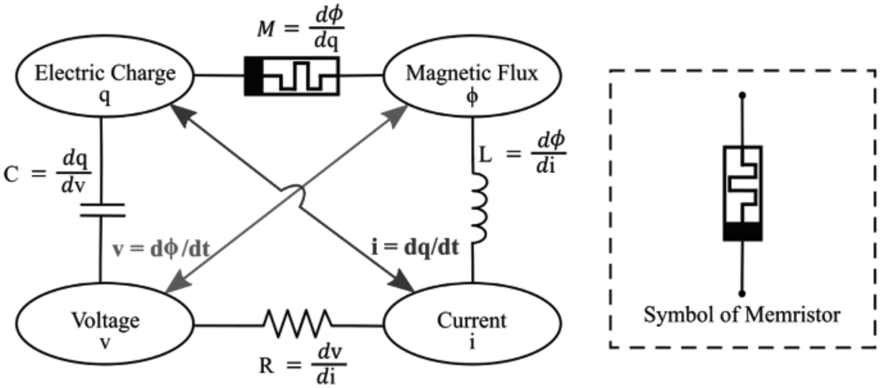

Figure 1.7. *Concept of relation among electric charge (q), magnetic flux (ϕ), voltage (v) and current (i) in terms of fundamental circuit elements: resistance (R), inductance (L) and capacitance (C), and the proposed memristor (M). Inset shows electrical symbol of a memristor*

Summing up the above theory, what is interesting for us is the concept of the memristor, which could be stated in a simplified way as follows. The memristor is an electrical resistance component/parameter with the following property: its resistance is not constant, but depends on the history or memory of previous current flow through this device (Chua 1971; Strukov *et al.* 2008). This makes the resistance of a memristor a function of past recollection of current flow, or amount of magnetic flux linked per unit charge, giving it a non-volatile memory property.

This non-volatile memory property of a memristor is the inspiration and principle behind memristive RF switches (Chua 2011). Memristive concepts were initially adopted for non-volatile data storage memory applications and some of the notable members of this family are given here in brief.

– ReRAM or RRAM (resistive switching random access memories): these are made up of memory cells that utilize the non-volatile change in resistance across a solid-state dielectric material for data storage memory applications (Chua 2011; Bocquet *et al.* 2014; Guy 2015; Leon 2018). CBRAM, oxide-based resistive random access memories (OxRAM) and PCM are a subset of this category.

– FeRAM (ferroelectric random access memory): this is a technology in which data are stored by utilizing the non-volatile dielectric polarization orientations in ferroelectric materials (Chanthbouala *et al.* 2012).

– MRAM (magnetic random access memory or magneto resistive random access memory): here, the magnetization in a stack of sandwiched magnetic and dielectric materials is utilized for non-volatile data storage (Daughton and Huang 1988).

Among these memory technologies, the concepts of CBRAM and PCM were later adopted and adapted for RF switching applications, and are explained in detail in the following sections.

1.3.3.1. *Phase change material-based RF switches*

Phase change material-based RF switches are a new upcoming innovation, inspired by the PCM applications. The center of this technology are the so-called phase change materials (Wuttig and Yamada 2007). Phase change materials are resistive materials that show a significant change in resistance upon a transition from crystalline to amorphous states and back, actuated by the application of heat pulses in a special manner. This phase transition is retained by the material even after the removal of heat pulse, thus making it a non-volatile switching technology. In this section, we discuss only the aspects of this technology related to RF switching applications to maintain brevity.

Phase change materials are integrated into the signal path of an RF circuitry to obtain an RF switch. Many material combinations have been reported to exhibit phase change characteristics, and are found suitable for RF switch applications. Some of the commonly used materials include germanium telluride (GeTe) (Gawelda *et al*. 2011; El-Hinnawy *et al*. 2014; Wang *et al*. 2014), vanadium dioxide (VO_2) (Dragoman *et al*. 2006; Hillman *et al*. 2014; Liu *et al*. 2019), yttrium hydride (Dragoman *et al*. 2006), germanium antimony telluride (GeSbTe), antimony telluride (SbTe) (Moon *et al*. 2018) and so on.

As mentioned above, the application of a controlled heat pulse results in a reversible transition of phase change material from an insulator to an electrical conductor. The magnitude, rise time and cooling time of the heat pulse determine the phase transition of these materials.

For example, phase change in the case of GeTe (El-Hinnawy *et al*. 2014) is achieved as follows, and is illustrated in Figure 1.8. Here, in a given phase of GeTe, the application of a short (~100 ns) high-temperature heat pulse, to raise the temperature above melting point, would result in liquidation of the material. In this liquid state, atoms are randomly distributed among themselves without any structural arrangements. A rapid (~100 ns) cooling at this state would freeze the material, leading to an amorphous state with very high electrical resistance, retaining the randomness of atomic distribution.

Inversely, the application of a broad pulse with a preset moderate amplitude to raise the temperature of this amorphous material above its crystallization temperature forces the atomic bonds to rearrange into a crystalline state with low electrical resistance, as illustrated in Figure 1.8. These narrow and broad heating pulses, used for phase transition, are called "quenching" and "annealing" pulses respectively.

PCM-based RF switches are developed by integrating such phase change materials into the RF signal path in series or shunt configurations, and are operated using heat pulses actuated using different electrical mechanisms. The requirements and challenges for an RF switch based on phase change materials are not different from the points stated in section 1.2. Over the past decade, a number of patents and remarkable articles have reported reliable

PCM RF switches that operate up to 100 GHz (El-Hinnawy *et al*. 2014; Hillman *et al*. 2014; Raieszadeh *et al*. 2016; Borodulin *et al*. 2017; Leon 2018). One important aspect in the design of a phase change material-based RF switch, after the selection of suitable material, is the technique for application of operating heat pulses. To the present date, different techniques are reported to be used for application of heat pulses to phase change materials as explained in the following.

In the initial stage of research in this domain, introductory designs reported using an oven for the application of operating heat pulses to the phase change materials.

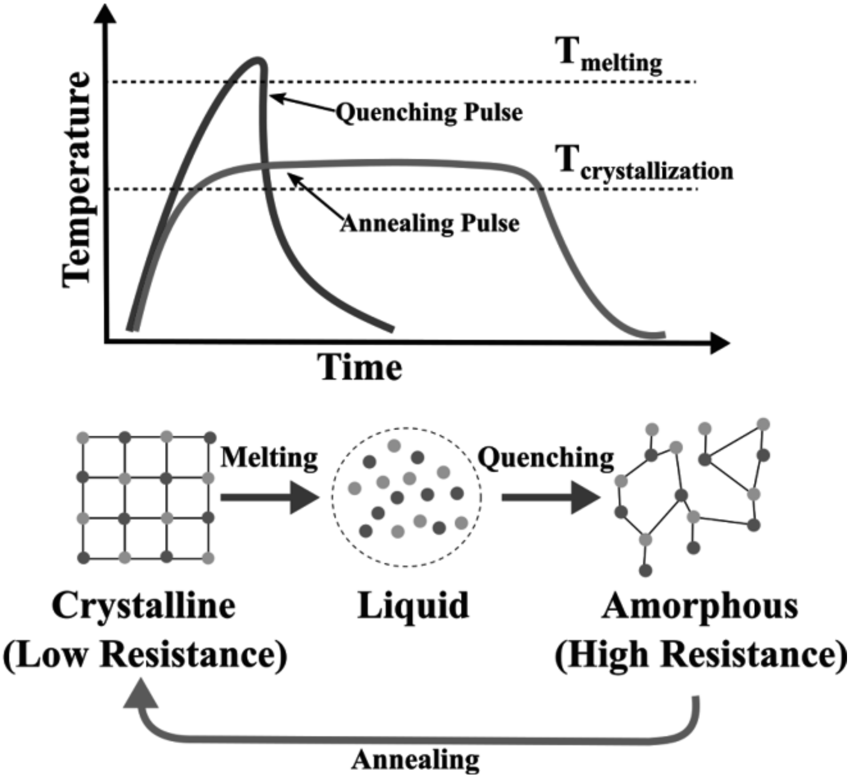

Figure 1.8. *Illustration of crystalline (low resistance) to amorphous (high resistance) reversible transition mechanism in GeTe phase change materials (idea conceived and redrawn from El-Hinnawy* et al*. (2014). For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

Nevertheless, today DC pulses for heating applications are applied to the device either directly through the RF signal path as in Shim *et al*. (2013) or using dedicated heater contacts as in El-Hinnawy *et al*. (2014). However, a design with dedicated heater contacts for application of heat pulses is simpler to implement (Mahanta *et al*. 2018). It is challenging in the former case to simultaneously maintain a low-resistance path for the RF signal and a high-resistance path for electrical resistive heating. Hence, most of the recent designs use an integrated heating element with compound alloys such as NiCrSi for the application of the heating pulses (El-Hinnawy *et al*. 2014; Wang *et al*. 2014; Raieszadeh *et al*. 2016). In addition, although not very common, some articles also have reported the use of pulsed femtosecond and nanosecond lasers for heating action (Gawelda *et al*. 2011).

Figure 1.9 presents the topology of a phase change material-based RF switch with dedicated contacts for application of heater pulses, similar to the design reported in El-Hinnawy *et al*. (2014). This design shows an ON state insertion loss less than 0.3 dB, and an OFF state isolation greater than 10 dB in the entire operating bandwidth, which is DC to 40 GHz.

At present, the phase change material-based RF switch technology is in its infancy stage, and it is progressing at a rapid rate. No commercial products are reported to date utilizing this technology for RF switching. Nevertheless, the current rate of advance in research and reliability of reported products would hopefully lead to commercial use of these switches in near future.

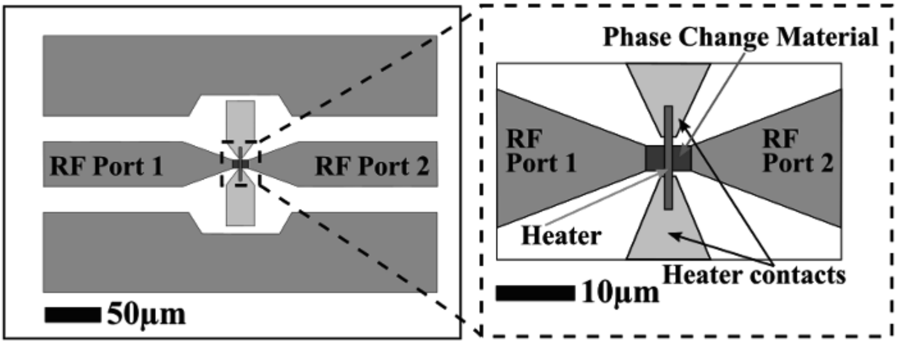

Figure 1.9. *Topology of a phase change material-based RF switch on a co-planar transmission line in series configuration. Inset shows zoomed image of switch area (idea conceived and redrawn from El-Hinnawy* et al. *(2014). For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

1.3.3.2. *CBRAM/MIM RF switches*

Application of CBRAM-based MIM switches to passive/low-power and low-cost RF microwave devices, using an optimized process compatible with mass production, is the focus topic of this book.

CBRAM/MIM switches are a subset of ReRAM. This technology depends on the memristive theory postulated by Chua (2011) and works on the principle of electrochemical formation and dissolution of a conductive filament, among two electrochemically asymmetric electrodes sandwiching a layer of solid ion conductor compound (Guy 2015).

Even though bistable resistive switching in metal–insulator–metal structures was observed implicitly or explicitly since the 1980s (Pagnia and Sotnik 1988), CBRAM technology in its current form was initially identified and invented in 1996 by Professor Michael Kozicki of Arizona State University. Professor Kozicki called these switches programmable metallization cells (PMC) and patented this technology with several variations and new innovations (Kozicki and West 1998, 2002; Kozicki 2002, 2010; Kozicki and Balakrishnan 2008). Initially, CBRAM technology was introduced as a fast and reliable non-volatile memory technology. Today several commercial memories are available utilizing CBRAM technology (Adesto Technologies 2016), and CBRAM is a registered trademark of Adesto technologies (Adesto Technologies 2020).

The relevance of this technology is well accepted even by the Defense Advanced Research Projects Agency (DARPA) of the United States Department of Defense, who acknowledged it by providing a grant to Adesto Technologies in 2010 for further advanced research on this topic (Adesto Technologies 2010). CBRAM is recognized and considered as a potential candidate to dominate future non-volatile memory applications in the International Technology Roadmap for Semiconductors (ITRS) report of 2011 (ITRS Reports 2011).

The potential of this technology as a non-volatile RF switching solution was soon revealed through some innovative research articles and patents in the recent decade (Nessel *et al.* 2008; Nessel and Lee 2011; Vena *et al.* 2012a; Pi *et al.* 2015, 2016; Xia *et al.* 2015; Dragoman *et al.* 2017). In this section, we discuss the RF and microwave switching applications of this technology. Device topology examples and state of the art in CBRAM/MIM RF switching technology are discussed separately later in this chapter.

A CBRAM-based MIM cell, as its name indicates, is formed of two electrochemically asymmetric electrodes sandwiching a layer of ion-conductor compound, which is also an electronic insulator. Figure 1.10 shows the layer architecture and working mechanism of a typical CBRAM/MIM switching cell. Here, one of the electrodes is an electrochemically active ion-donor such as silver (Ag) or copper (Cu), and the other is a relatively electrochemically inert ion acceptor such as aluminum (Al) or gold (Au). The switch action based on electrochemical formation and dissolution of a conductive filament in CBRAM/MIM cell is actuated and controlled using applied DC pulses.

The working mechanism of a CBRAM/MIM switching cell could be explained as follows. Initially, the electrical resistance across a CBRAM cell is very high due to the presence of an electrically insulating ion-conductor layer. Application of a positive DC electric voltage (with a sufficient current limit) with respect to the active electrode initiates a redox mechanism in the cell. On the basis of this, the active electrode surface in contact with the ion conductor starts to oxidize by losing electrons and liberates metal cations, as shown in Figure 1.10(a). These ions, under the influence of electric field induced due to the DC voltage, would migrate through the ion conductor layer to get reduced, by receiving electrons, to neutral metallic atoms at the inert electrode, and this process is called the forming process.

This reduction process at the inert electrode would result in the formation of a dendrite-shaped metallic filament at the inert electrode which will eventually touch the active electrode, thereby lowering the overall resistance of the MIM cell, thus establishing the “set” (or ON) state, as shown in Figure 1.10(b).

Conversely, the application of a sufficient reverse DC voltage (and current), that is, a voltage which is positive with respect to the inert electrode, would result in the reversal of this process. Here, the filament would start to dissolve due to the same redox mechanism, but this time in the reverse direction. Oxidization takes place on the metallic filament attached to the inert electrode and reduction at the active electrode. This would result in rupture of the conductive metallic filament, increasing the resistance of the MIM cell, thus establishing the “reset” (or OFF) state, as shown in Figure 1.10(c).

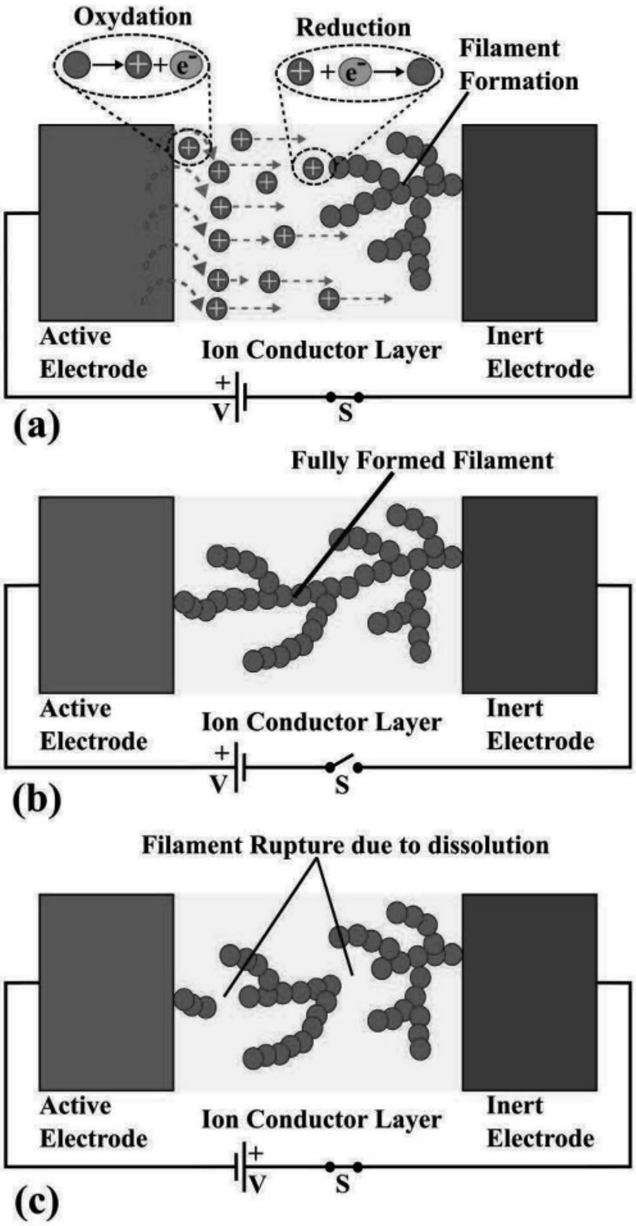

Figure 1.10. *Layer architecture of a typical CBRAM/MIM switch and its working mechanism. (a) Start of filament formation (forming process). (b) Fully formed filament (set or ON state). (c) Filament dissolution (reset or OFF state). For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

A CBRAM/MIM switch requires actuation in the form of DC pulses only to control the formation of a metallic filament and reach a desired impedance state, as explained above. The cell retains this impedance state even on withdrawal of the actuation mechanism, thus exhibiting non-volatile switching behavior. A power supply or actuation in the form of DC pulses is a requisite only when a change in present impedance state (ON or OFF) is desired.

Dissolution of metallic filament during reset process depends critically on the time duration of application of reverse voltage. A short pulse of sufficient amplitude and current (applied with right polarity) would lead to a high resistance reset state, by rupturing the filament, in its thinnest (or weakest) parts only. This is the consequence of a short pulse with high amplitude and current, which locally deforms the conductive filament at its weak parts due to localized heating. Then the actual dissolution mechanism as explained above would start. Here it is not necessary that the entire filament be dissolved back into the active electrode, but only that it be ruptured to break the current path, as seen in Figure 1.10(c). This is advantageous for the next set cycle as a rapid filament formation can be achieved by just making connections to the ruptured areas. This phenomenon brings significant difference in the characteristics of set pulses required for the first forming process and other set cycles, after the first reset following the forming process. Thus, for the subsequent set processes, a set voltage of smaller magnitude and shorter time period could be used to fill this small gap in the filament. In such a case, the gap between the inert electrode (which can be a part of a former filament connected to the inert electrode) and active electrode (which can also be a part of a former filament connected to the active electrode) is smaller than the initial gap.

One should also note that a prolonged application of reverse voltage would lead to more and more dissolution of the filament due to prolonged redox reactions (Yang *et al*. 2012). Similarly in the forming process, a prolonged exposure to set/ON voltage would lead to stronger filaments (Pi *et al*. 2015). Extensive research has been carried out to describe and observe the working mechanism of CBRAM/MIM cells, confirming the validity of above description (Nessel *et al*. 2008; Lin *et al*. 2011; Yang *et al*. 2012, 2014; Busby *et al*. 2015; Guy 2015; Pi *et al*. 2015; Yalon *et al*. 2015; Song *et al*. 2017).

It is worth noting however that, in some cases, especially for some ion conductors with low ion mobility/conductivity values (e.g. amorphous silicon [a–Si]), the direction of filament formation is reversed, i.e. the filament growth during forming and set process happens from the active electrode to the inert electrode, while all other mechanisms remain the same (Yang *et al*. 2012). Anyhow, such materials are seldom used and desired for RF switching, due to the requirement of fast switching speed and low ON state resistances.

Several metal combinations are found to be suitable as electrodes for CBRAM/MIM switching applications. This includes electrochemically active metals such as silver, copper and so on and relatively inert metals such as aluminum, gold, platinum, tungsten and so on (Pagnia and Sotnik 1988). The choice of ion conductor is a critical factor in the architecture of CBRAM/MIM switches. The choice of material and underlying process for the formation of this ion conductor layer influence factors such as switching speed, switching voltage and current, stability, cost of manufacture and so on (Yang *et al*. 2012). Several materials including doped chalcogenide glass (Kozicki and West 1998; Nessel and Lee 2011), semiconductor oxides (Vena *et al.* 2012a; Yang *et al.* 2012), ion conducting and metal doped polymers (Perret *et al*. 2015; Jian *et al*. 2017; Song *et al*. 2017), and several other material combinations (Pagnia and Sotnik 1988), including very precisely controlled air gaps (Pi *et al*. 2015), have shown ion-conducting properties suitable for CBRAM/MIM applications.

1.4. State of the art of CBRAM/MIM RF switching technology

CBRAM technology, as mentioned above, was originally introduced as a non-volatile memory technology. In addition, this technology is being investigated as an efficient and emerging RF switching solution and has produced a handful of promising results. In this section, before going into the details of state of the art accomplishments in this filed, it is interesting to mark the important aspects of expected performance parameters distinguishing among different applications of CBRAM technology: memory and RF switch. Table 1.2 summarizes some of the significant unique features (and their necessities) demanded by each of these applications of CBRAM/MIM technology.

CBRAM technology – memory application	**CBRAM technology – RF switch application**
Typically nanometric-sized cells.	Typically micrometer-sized cells.
ON and OFF states require only a notable distinction. A few kΩ at ON and a few MΩ at OFF states are well acceptable.	ON states should be necessarily less than a few ohms (e.g. <10 Ω) and OFF states should be greater than a few kΩ to ensure proper RF transmission and isolation.
Ion-conductor thickness is typically a few nanometers.	Ion-conductor thickness varies typically from a few nanometers to a few micrometer depending on application.
Write and read speeds are critical.	Linear behavior, RF compatibility and switching speed are critical.
Power handling capability is not a crucial factor.	Power handling capability is a crucial factor.
Packing density on a single wafer in a given space is vital.	Reliability as a stand-alone switching device is vital.

Table 1.2. *Performance parameter features distinguishing requirements for memory and RF switch applications of CBRAM/MIM technology*

RF switches utilizing CBRAM/MIM technology and operating up to 40 GHz have been recently proposed in the literature. Notable contributions identified as the state of the art include nanoionic RF switches based on silver (Ag)-doped germanium selenide ($GeSe_2$), invented by James Nessel *et al.* of NASA Glenn Research Center, USA (Nessel *et al.* 2008; Nessel and Lee 2011), and nanoscale memristive RF switches based on a 35 nm air gap invented by Shuang Pi *et al.* of the University of Massachusetts, USA (Pi *et al*. 2015, 2016; Xia *et al*. 2015). These two articles share the same principle of operation, but are unique in the choice of selection of ion-conductor for switching applications. The former uses a chalcogenide compound and the later use a precisely controlled air gap as the ion-conductor.

The work of Nessel *et al*. proposes a planar CBRAM/MIM switch topology on an RF transmission line, as shown in Figure 1.11 (recreated from Nessel *et al*. 2008).

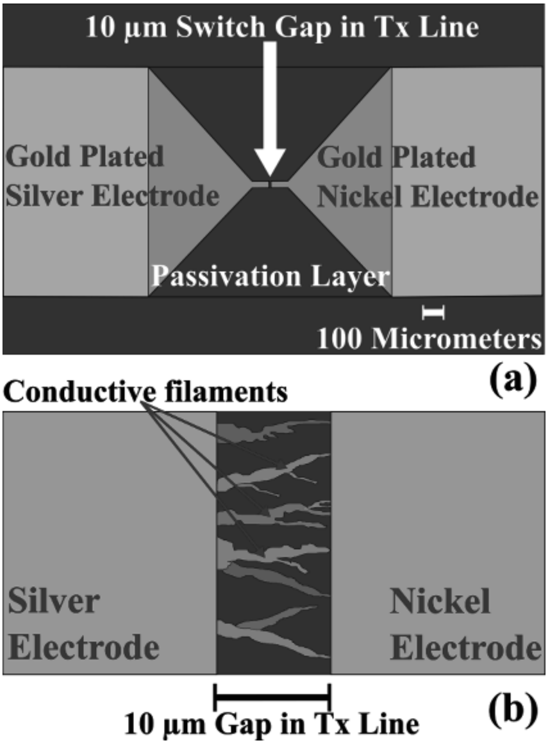

Figure 1.11. *Nanoionics-based RF switch (redrawn from Nessel et al. 2008). (a) Topology of nanoionic RF switch and (b) illustration of microphotograph showing filament formation among active (silver) and inert (nickel electrodes). For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

Here, a 10 µm wide planar gap in a RF transmission line filled with a chalcogenide composite of silver (Ag)-doped $GeSe_2$ as the ion conductor functions as the CBRAM/MIM switching mechanism. Gold-plated silver (Ag) and nickel (Ni), respectively, form the active and inert electrodes of the CBRAM/MIM cell in this device, as shown in Figure 1.11. Here, the CBRAM switch in summary operates in series configuration on the parent transmission line.

DC pulses of amplitude 1 V (ON process) and –1 V (OFF process), both with a compliance current limit of 10 mA, are used to operate the device. DC pulses are fed directly through the RF signal path using appropriate isolation networks. The device reports an ON or set state impedance around 10 Ω, and a higher resistance at OFF or reset state sufficient to provide a good RF isolation.

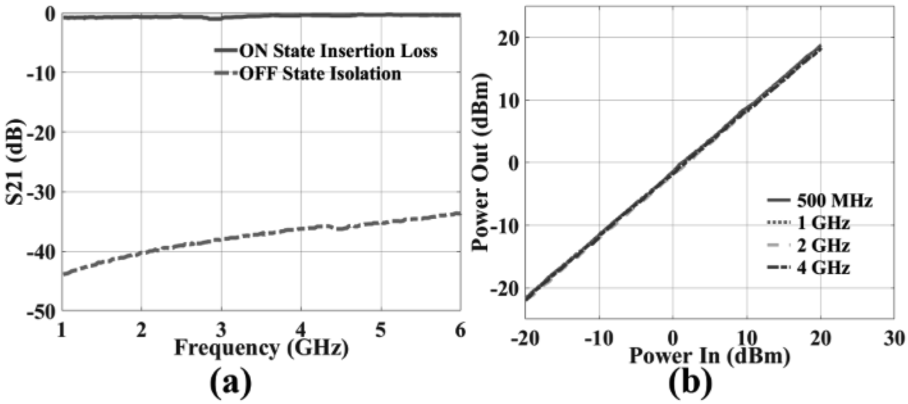

Figure 1.12. *RF performance characteristics of nanoionics-based RF switch shown in Figure 1.11 (redrawn from Nessel et al. 2008). (a) RF ON and OFF state insertion loss and isolation. (b) Relation among input and output RF power showing linearity characteristics. For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

Illustrations of microscope images exhibiting silver resistive filament in the ion conductor layer, formed as a result of switching action, among the silver active and nickel inert electrodes are shown in Figure 1.11(b) (redrawn from Nessel *et al.* 2008), validating the theory of CBRAM/MIM switching cells. This switch shows an operational frequency range of 1–6 GHz, with ON state insertion loss better than 0.5 dB and OFF state isolation better than 30 dB in the entire bandwidth as shown in Figure 1.12(a) (redrawn from Nessel *et al.* 2008). The switch also shows a linear operation in the given bandwidth for RF input power levels from –20 dBm to +20 dBm, as shown in Figure 1.12(b) (recreated from Nessel *et al.* 2008). Authors claim a switching speed of 1–10 μs for this device. Details on number repeatability of switching cycles or endurance cycles of the presented device are unknown.

The next state of the art design in this field is the work of Shuang Pi *et al.* This is a nanoscale memristive RF switch composed of gold (Au) and silver (Ag) electrode pairs separated by a 35 nm air gap, as shown in Figure 1.13 (redrawn from Pi *et al.* 2015). Low capacitance due to a lower dielectric constant of the air gap, in combination with chosen design geometry, provides an operating range of up to 40 GHz for this device.

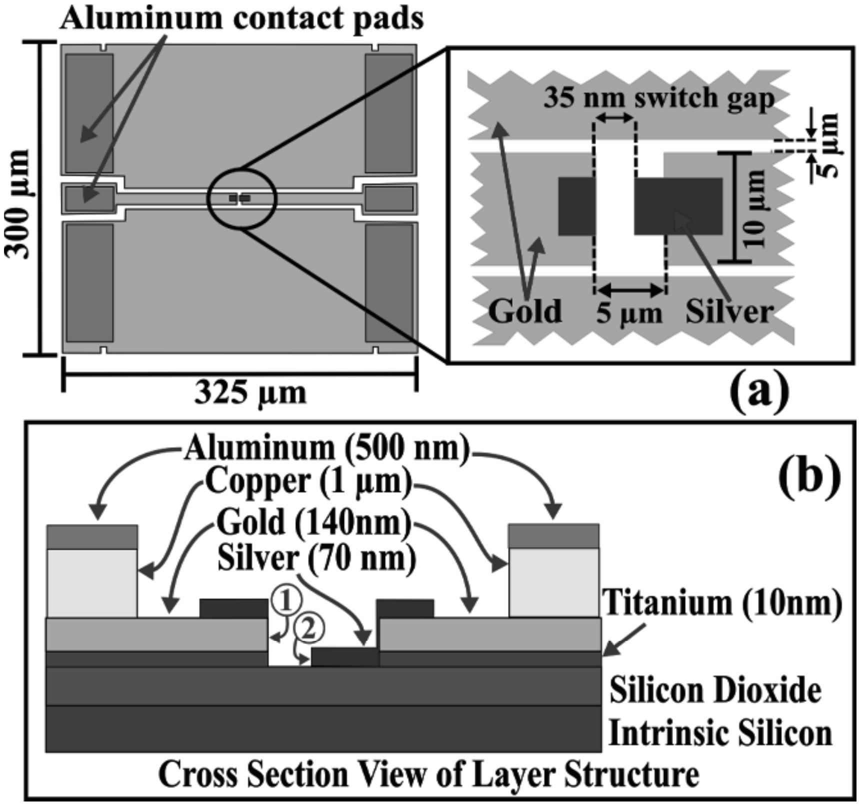

Figure 1.13. *Nanoscale memristive RF switch (redrawn from Pi* et al. *2015). (a) Topology of memristive RF switch, with zoomed inset showing 35 nm CBRAM/MIM switch gap. (b) Cross-section view showing layer structure of memristive RF switch. The filament formation is between gold and silver electrodes and marked as ① and ②. (Please note that the image is only an illustrative representation and the layers are not up to scale. Please refer to legends for dimensions). For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

Authors claim an ON state insertion loss less than 0.3 dB and an isolation greater than 30 dB from 10 to 40 GHz, respectively, for ON and OFF states of the switch, as shown in Figures 1.14(a) and (b) (replotted from Pi *et al.* 2015). DC voltage pulses with the mentioned polarity corresponding to the silver (active) and gold (inert) electrodes, respectively, are used to operate the device. Non-returning sweeps in the range of 0 to +4 V are used for the ON process and in the range of 0 to –0.4 V for the OFF process. A maximum compliance current limit of 50 mA is imposed for these voltages.

An average ON or set state resistance value of 3.6 Ω and a high resistance state in OFF or reset state which provides a good RF isolation is reported for this realization. This device also reports a linear power handling capability up to +17 dBm for the switch, above which the RF power is seen to induce self-switching characteristics. The maximum operating frequency of this switch is computed through full-wave electromagnetic simulation and reported to be 200 GHz, exhibiting ON state insertion loss and OFF state isolation values of less than 0.6 dB and greater than 17 dB, respectively, for the entire bandwidth. The presented device shows a switching cycle repeatability of around 80 cycles in a natural environment (which could be extended to around 700 cycles by protecting the switch area in deionized water) and a theoretically calculated ON/OFF state retention time of 3.3 years, as reported by the respective authors.

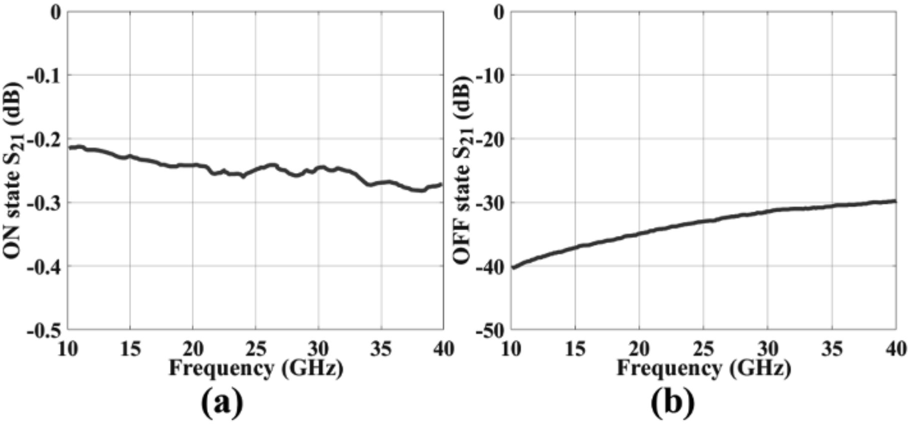

Figure 1.14. *RF performance characteristic of memristive RF switch, shown in Figure 1.13 (redrawn from Pi* et al. *2015). (a) ON state insertion loss. (b) OFF state isolation*

The presented state of the art devices present the capability and achievable performance of CBRAM/MIM technology for RF switching, even in its initial stage. Like in the infancy stage of any technology, CBRAM/MIM technology also has some challenges to be revamped through which these devices could promise a stunning future for RF switching.

One could note here that fabrications of both prototypes discussed above are accomplished using clean room procedures, and the available information on switching cycle repeatability or endurance shows that improvement is required in this aspect. Some of the improvements we try to address in this book include the introduction of simple processes for fabrication of non-volatile CBRAM RF switches and passive or low power RF and microwave devices with integrated CBRAM switches, through techniques compatible with mass production, at low cost. These processes should utilize materials that could be handled and operated in ambient environments, and not only in clean rooms, and free from any high temperature curing. Adaptation of these devices for an improved number of switching cycles is also a foreseen improvement.

1.5. Demand for a non-volatile RF switch and selection of CBRAM/MIM technology

In the previous sections, we have discussed different types of RF and microwave switching technologies their merits and demerits. From this discussion, it is clear that the choice of a switching technology is a compromise among different parameters such as type of application, required performance (e.g. switching speed), power consumption, operating bandwidth, cost and so on.

In this section, we discuss the potential areas of demand and requirement for a low-cost and non-volatile RF switching solution. An increase in demand for a non-volatile and fully passive low-cost RF and microwave switch has been intensified at present. Recent advances in the Internet of Things (IoT) backed by fifth-generation cellular communication (5G) technology have added to this yearning for a new breakthrough (Borkar and Pande 2016; Collela 2017).

The IoT is a technology that provides Internet connectivity to physical objects in our everyday life (Attaran and Rashidzadeh 2016; Borkar and Pande 2016). The 5G cellular network standard is a powerful broadband communication technology, a notable contribution of this era. 5G could be the foundation for implementation of the full potential of IoT. This combination would be a unique solution with high-speed connectivity, very low latency and ubiquitous coverage (Collela 2017). This would support smart homes, vehicles, transport infrastructure and so on, ranging from connected home appliances like a smart air conditioner at home, smart medical care like a smart band aid communicating the current condition of a wound, smart vehicular transport systems such as trucks and buses moving without human drivers on a busy highway, and even remote control of heavy machinery in hazardous and unreachable environments. These developments would contribute to improving quality of life, speed of service and safety standards. This technology is also very near to efficient extension of this idea to remote surgery and remote monitoring of implanted medical devices. All this is expected to be done through a group of smart wireless sensors, data processors and communication links working in harmony simultaneously.

It is estimated that more than 50 billion devices will be connected to the Internet in 2020 worldwide (Broadband Wireless Networking Lab 2019). However, for all these wireless systems to be truly "wireless" all the time, they should be passive or self-sufficient in terms of operating power supply. To meet such power supply or power storage regulations, one of the requirements is that these systems require a passive or low-power switching solution for needs such as reconfigurable antennas (which include 3D steerable MIMO systems, frequency agile antennas and similar), filters, resonators, object identifiers, stand-alone sensors, channel switches, power splitters and so on.

5G technology demands different types of RF switches, for example low-power consumption and high-performance switches for mobile phone base stations, low-cost non-volatile switches for battery-less or low-power stand-alone sensors and passive transponders and so on. At present, the former requirement (low-power consumption and high-performance switches) could be fulfilled using standard commercial CMOS switching devices. However, the latter requirement, i.e. low-cost non-volatile switches, is our area of interest of application of CBRAM/MIM switches.

A fundamental difference from 4G and one of the capital expectations for 5G communication technology is to provide connectivity to "things" through IoT concepts, utilizing smart low-power/passive sensors and transponders, attached to a connectivity seeking object. The object could in reality be anything which would like to pursue a certain degree of "smartness", such as an electronic home appliance requiring remote control, an everyday object like a wallet that could be tracked, a food package that could monitor the quality of its contents or a medical wound dressing that provides information on the status of a wound.

A very simple and primary step in making any object "smart" or connected is about attaching a "smart-label" that can identify itself, sense certain parameters and communicate to a base station. To keep it simple, a smart packet of yogurt or ice-cream could, upon request, identify itself to your mobile phone when proximal, tell you where it is in a supermarket, tell you its flavor, price, about its condition such as if it is consumable or rotten, etc.

Recent trends and advances in research in the field of passive RF and microwave devices show that RFID systems and especially chipless RFID systems could serve the purpose of requirements such as object identifiers and stand-alone sensors (Vena *et al.* 2011; Nair *et al.* 2013; Perret *et al.* 2013; Tedjini *et al.* 2013; Amin *et al.* 2014a; Perret 2014; Feng *et al.* 2015; Karmaker 2016; Bibi *et al.* 2017; Borgese *et al.* 2017; Vena *et al.* 2016). Chipless RFID technology could be used as a smart label which does not require any power supply or battery. It is often called the RF-Barcode due to similarities in appearance and operation to an optical barcode system, however in contrast it has a lot of additional functionalities such as non-optical line of sight reading (readability even if it is visibly hidden), electronic rewriteablity, sensing capabilities and so on.

Electronic rewriteablity of a chipless RFID tag is a unique feature which we try to address through this book. Electronic rewriteablity provides enormous flexibility and exceptional dominance to chipless RFID technology as a smart label which appreciates tag reuse, enabling mass production of similar blank tags in large quantities through techniques such as roll-to-roll processes, which could be pre-coded or written/rewritten to encode a desired identifier at time of application. In Chapter 3, we explain innovative approaches to the development of electronically rewritable chipless RFID tags with integrated CBRAM/MIM switches, with processes compatible with mass productions.

In addition, a lot of innovations have also been proposed recently in the field of pattern steerable and frequency agile antennas including MIMO systems, and in electronically reconfigurable filters (Zhang and Zhu 2011; Chaudhary *et al*. 2012; Ding and Wang 2013; Dragoman *et al*. 2017; Lin *et al*. 2017; Chen *et al*. 2018; Al-Yasir *et al*. 2019). These research advances are also backed by multidisciplinary engineering technologies including smart materials (Amin *et al*. 2014b; Bibi *et al*. 2016), 3D printing and conductive inkjet and thermal printing techniques (Cook *et al*. 2013; Ellinger *et al*. 2015; Chan *et al*. 2018; Ellinger *et al*. 2018; Saracho-Pantoja *et al*. 2018).

On the other hand, most of these devices cited above utilize classic volatile switching technologies such as solid-state semiconductors (PIN diode switches, MEMS switches, hybrid switches and similar) for electronic reconfigurability or mechanical solutions such as laser ablation and localized inkjet printing and similar in reconfigurable chipless RFID applications. The former (semiconductor switches) add to the power budget of the system, and furthermore make the presence of an onboard battery pack mandatory. The latter (mechanical solutions) are not efficient and reliable techniques.

For fulfilling the switching requirements of these devices, apart from commercially available volatile switching solutions such as solid-state semiconductor or MEMS switches, these switches should have certain unique characteristics as follows: non-volatile retention of impedance state, low power consumption, long time switch impedance state retention (stability), easy integration into target device and so on. A non-volatile RF switch with these desired characteristics would benefit every field of RF and microwave engineering, especially the above-stated domains, as illustrated in the form of a chart in Figure 1.15.

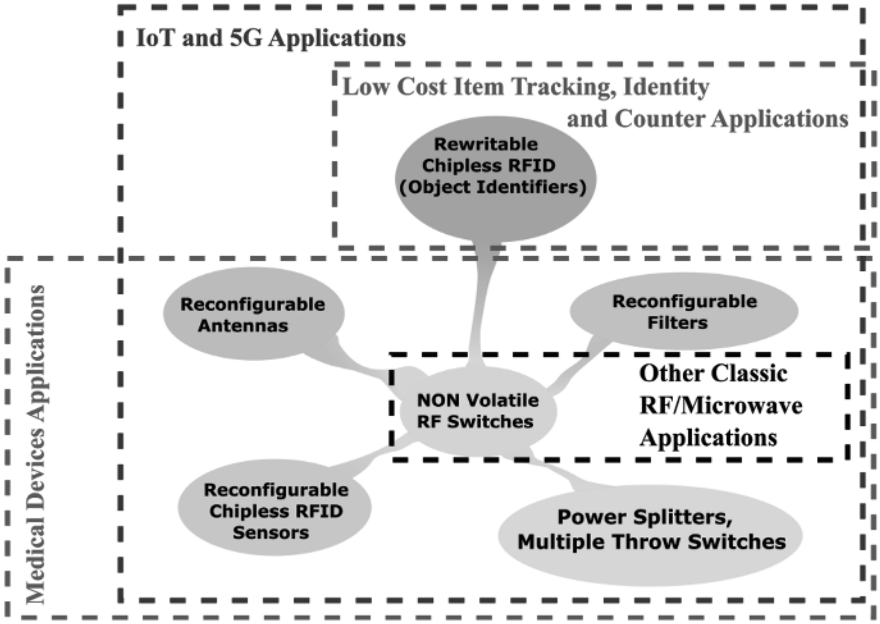

Figure 1.15. *Core areas of application of a non-volatile RF switch. For a color version of this figure, see www.iste.co.uk/jayakrishnan/technology.zip*

In this book, importance is given to investigation and optimization of a low-cost non-volatile RF switch, which could be directly integrated into an RF/microwave device or circuit, using simple processes compatible for mass production. Such an approach has never been produced up to now (to the best of our knowledge), despite the research for revealing best performance and potential theories related to any particular switching technology. Here we ask ourselves and try to answer the following questions: is it possible to print a switch with a simple off-the-shelf printer? Or at least is it possible to realize a low-cost non-volatile RF switch (integrated into RF devices) using simple and rapid industrial technology used for printed electronics? Both classic electronic substrates and flexible substrates like PET are expanded as Polyethylene terephthalate or paper to call these devices the smart labels of future.

To answer these challenges, we choose the CBRAM/MIM switch technology for the following reasons. Out of the two main available solutions for non-volatile RF switching technology, PCM and CBRAM/MIM, it appeared to us that CBRAM/MIM is a simpler technology, compatible with mass production in an industrial setup. The proof of concept of this simplicity of CBRAM/MIM technology is our primary goal through this research. Thus in contrary to previous studies in this domain, we try to show that simple materials (that exist not only in clean room technologies), through uncomplicated processes, could be utilized for establishing a low-cost switching solution based on CBRAM/MIM technology.

As of now, PCM technologies necessarily require clean room microfabrication technologies, high temperature processes and even joule heating simulations setups, which span a great deal of tedious requirements all the way from their design procedure to manufacture, which imply a great spectrum of multidomain challenges for practical industrial processes. It is worth comparing CBRAM/MIM technology to PCM at this point, which could meet these challenges exquisitely in a much adroit approach.

Recent developments introduced at the LCIS laboratory of the University of Grenoble Alpes, in association with the IES laboratory of the University of Montpellier and CNRS, on CBRAM/MIM switch technology, bring hope and a new horizon for low-cost and passive reconfigurable electronics compatible with mass production in industrial setups (Vena *et al.* 2012a;

Perret *et al.* 2015; Jian *et al.* 2017) and for an inventive development of electronically reconfigurable passive RF devices.

Now, to continue the comparison of CBRAM/MIM and PCM, an Achilles heel in the design of PCM switches is the requirement of a heater for the phase change process of the switching material from amorphous to crystalline and back. About the complexity of the realization technique, we can note that the control part requires the use of transducers to apply the heating pulse, which greatly complicates the realization. This heater path is different from the RF signal path in the case of indirect heating. In such indirect heating, a DC electrical signal heats an intermediate highly resistive material that transfers its calorific energy to PCM via the Joule effect, which requires a complicated multilayer structure. Conversely, we can consider the techniques of direct heating, in which the heat pulses are applied directly through the RF path. A smart material for the heating process must be found that could simultaneously maintain a low resistance path for the RF signal and a high resistance path for resistive heating, which again complicates the system (Mahanta *et al*. 2018).

However, it is true that after a lot of work done by different teams from all around the world, PCM technology is now more mature, and is still advancing at a good rate. Still, from the authors' point of view, the weightage of simplicity in fabrication is more on the side of CBRAM/MIM technology due to the following reasons.

PCM switches are based on the use of some very specific materials (GeTe for example). This type of material requires a series of sophisticated process steps for layer formation; and also needs a passivation layer to protect it from the environment; if not, the material is not stable in an ambient atmosphere. Up to now, it seems very difficult (even impossible) to print this material. At the same time, several studies (Vena *et al.* 2012a; Perret *et al.* 2015; Jian *et al.* 2017) indicate a ray of hope for printing a CBRAM/MIM switch layer by layer using an inkjet printer, utilizing metallic inks, and polymer ion-conductor solutions, such as poly methyl methacrylate (PMMA).

Such a breakthrough would be a great advantage for printed passive stand-alone RF and microwave devices such as rewritable chipless RFID-based identifiers and sensors. This would also be a great step in the integration of these switches without any techniques like soldering, in directly printed RF and microwave circuits, realized with the help of inkjet or 3D printing technologies (Cook *et al.* 2013), even on low-cost and flexible substrates like paper (Vena *et al.* 2013a; Borgese *et al.* 2017; Vena *et al.* 2018) or PET (Ali *et al.* 2019).

Such a non-volatile RF switch could find applications in the following domains:

– providing electronic rewriteablity to chipless RFID tags for identification and sensing, and manufacture of such tags (smart labels) on flexible substrates like paper;

– providing electronic reconfigurability to filters and antennas, which include systems such as frequency reconfigurable and tunable filters, pattern steerable antenna systems, frequency agile smart antennas and so on. Mechanically complicated designs like reflect and transmit arrays and MIMO systems could be printed directly along with integrated switches on flexible substrates, which could then be reconfigured electronically, and mechanically oriented, utilizing the flexible nature of substrates;

– realizations of electronically reconfigurable multiple throw switches and power splitters;

– low-cost smart wireless sensors: these devices are an intelligent combination of all three above-mentioned applications, and would find great demand in IoT applications. Such passive transponders handling sensing and communication require electronically reconfigurable and non-volatile switches for antenna, filter and identifier (chipless RFID) requirements.

In this book, we present a summary of our efforts and affirmative outcomes of an investigation of the possibilities of design and fabrication of integrated non-volatile CBRAM/MIM RF switches for passive and low-power applications through simple processes compatible with mass production in an industrial setup on classic and flexible substrates. Table 1.3 summarizes desired improvements addressed in this book in switching performance and fabrication technologies for CBRAM-based RF switches in comparison to limitations faced by reported state of the art devices in this field.

Limitations faced by present state of the art technology for CBRAM RF switches	**Targeted and desired improvements for CBRAM RF switching technology**
Low switching cycle repeatability achieved (<1,000 cycles).	Improved switching repeatability suitable for target application.
Fabrication techniques are mainly "clean room"-based processes.	CBRAM RF switches compatible with low cost industrial mass productions in ambient environment.
Inorganic materials that require sophisticated high temperature processes are used as ion-conductors.	Fabrication of CBRAM RF switches using (easily) moldable polymer-based ion conductors that do not require a high-temperature process.
No commercial products (RF switches) to date.	Low-cost techniques and materials compatible with mass commercial production.

Table 1.3. *Targeted and desired improvements for CBRAM RF switching technology addressed in this book*

We believe that we have answered some parts of the above-mentioned issues successfully through the work and outcomes presented here: is it possible to print a switch with a simple off-the-shelf printer, or at least to realize a low-cost non-volatile RF switch using simple and rapid industrial technology used for printed electronics on rigid and flexible substrates like paper?

The answer here is yes! We have affirmatively proved the feasibility of realizing low-cost non-volatile RF switches and passive RF devices integrated with these non-volatile switches. The CBRAM/MIM switching technology is utilized in simple and rapid process steps compatible with mass production, on rigid as well as flexible substrates like paper. The presented switch technology and chosen materials are potentially printable, and the optimization for this is progressing quickly.

1.6. Conclusion

In this chapter, we discussed the motivation for and background to the need for a low-cost non-volatile RF switch technology. We presented in brief an idea about the requirements and expected performance factors of a switch at RF and microwave frequencies. Then we gave an overview of the concepts and advances of prominent RF switching technologies available at present. The state of the art in CBRAM/MIM switch technology was also presented. After that, we discussed in detail the requirement of a low-cost and non-volatile RF switch and reasons for the choice of CBRAM/MIM switch technology for applications addressed in this book.

We have also discussed in detail the versatile applications of CBRAM/MIM RF switches, using the proposed fabrication processes in this book, in the domain of IoT and 5G applications. CBRAM/MIM switching technology is a simple approach for a new generation of low-cost RF switching solutions. The simplicity in realization and potential printability of this technology provides a good contrast from other similar counterparts such as PCM. Physical functioning of CBRAM/MIM switches are straightforward to understand and easy to analyze, and so is the control over electrical parameters such as ON/OFF state impedance and OFF state capacitances, which play a critical role in RF performance.

The layer architecture of CBRAM/MIM cells makes it easy to integrate it among a standard RF circuit to achieve electronic reconfigurability, without much perturbation to the natural working of the circuit. Moreover, the optimization of such devices could be done directly in electromagnetic simulation platforms, without the direct requirements of multiphysical parameter simulation support.

The ion-conducting performance observed in moldable polymers like PMMA is a crucial factor in simplifying the realization of RF devices with integrated CBRAM/MIM switches, as explained in this book. Here, we introduce the use of a much more efficient and innovative ion-conducting polymer called nafion for CBRAM-based RF switching applications. The most endorsed specialty of these polymer ion-conductors over classic compounds like chalcogenides is their availability in form of resin solutions. This helps in growth/formation of layers of desired thickness through simple processes like spin coating. These polymers do not require any high-temperature processes for curing and are stable in ambient environments. In the following chapters, we present the integration of CBRAM/MIM switches, using such polymers (Nafion), into passive microwave devices such as chipless RFID tags, antennas, filters and SPDT switches, making them non-volatile electronically reconfigurable devices. The reasons for the choice of nafion and its advantages are explained in detail in Chapter 2.

With the confidence gained from the outcomes of experimental results obtained in this study, and the considerable RF performance quality of presented devices, we optimistically predict the development of fully printed electronically reconfigurable passive RF devices, realized using common off-the-shelf printers, commercially as well as for domestic use, in the near future. This would be done on flexible substrates such as paper, utilizing metallic and ion conductor inks.

In the next chapter, we present the real-world implementation challenges of a low-cost non-volatile RF switch, and the proposed techniques to efficiently overcome them. In Chapter 2 we propose simple realizations of CBRAM/MIM RF switches that could be undertaken in an ambient environment using processes compatible with mass production. These are validated through the realization of CPW RF switches on rigid and flexible substrates and extension of the application to an SPDT switch.