Concept paper on novel radio frequency resistive switches

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ABSTRACT

For reconfigurable radios where the signals can be easily routed from one band to another band, new radio frequency switches (RF) are a fundament. The main factor driving the power consumption of the reconfigurable intelligent system (RIS) is the need for an intermediate device with static power consumption to maintain a certain surface configuration state. Since power usage scales quadratically with the RIS area, there is a relevant interest in mitigating this drawback so that this technology can be applied to everyday objects without needing such a high intrinsic power consumption. Current switch technologies such as PIN diodes, and field effect transistors (FETs) are volatile electronic devices, resulting in high static power. In addition, dynamic power dissipation related to switching event is also considerable. Regarding energy efficiency, non-volatile radio frequency resistive switch (RFRS) concept may be better alternative solution due to several advantages: smaller area, zero-hold voltage, lower actuation bias for operation, short switching time, scalability and capable to be fabricated in the backend-of-line of standard CMOS process.

CCS CONCEPTS

• **wireless communication, memristors, 6G network**;

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1 RADIO FREQUENCY RESISTIVE SWITCHING (RFRS) DEVICE CONCEPT

Memristors or resistive switching devices are recognized as non-linear resistors with intrinsic characteristics similar to biological memory. They represent the simplest form of a two-terminal hardware, wherein resistance is altered through electrical or thermal pulses serving as program/erase stimuli, allowing the resultant state to be stored. Due to this unique property, they have a variety of potential applications across different fields such as: Neuromorphic computing and bio-inspired systems enabling novel approaches to

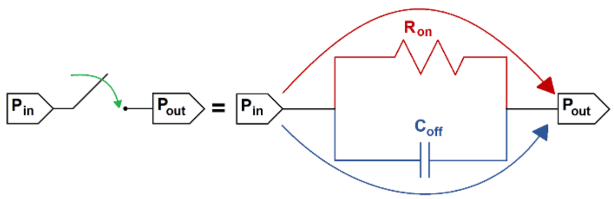

Figure 1: Equivalent circuit model of an RFRS switch. [1]

solve complex problems, sensor interfaces enabling direct conversion of analog sensor signals into digital data, reconfigurable circuits allowing the same hardware to be dynamically repurposed for different functions, programable analog circuits to emulate various passive electronic components for programmable analog circuits and filters, etc.

Based on the working principle, three main groups of non-volatile resistive switching devices can be realized as RFRS: 1. Oxide-based resistive switching devices as valence change memories (VCMs), 2. Electrochemical memories (ECMs) such as conductive bridge resistive switching devices (CBRAMs) and atomristors based on 2D material and 3. Phase change memories (PCM).

2 TECHNOLOGY CHALLENGES

To benchmark the figure of merit of RFRS using different technology, an equivalent circuit of parallel changeable resistor (R) and parasitic capacitor (C) is considered, see Figure 1. The low resistance state (LRS) of the RFRS is responsible for insertion loss (IL) and must be lower than 50Ω. The capacitance at the high resistance state (HRS) controls the isolation (IS) factor, namely the presence of parasitic and undesired leakage. Assuming the RC model, thus, the cutoff frequency is determined as of $1/2\pi R_{LRS}C_{HRS}$ [1].

Typically, the LRS of VCM devices measures around 1 kΩ, which is excessively high and results in significant insertion loss. CBRAMs might offer a better solution in this context, especially in cases where devices possess small nanogaps between electrodes, with one of them being composed of Ag (an electrochemically active electrode) [2]. As demonstrated in the literature, the 2D atomristor working principle falls under the same type of resistive switching nature: ECM resistive switching at the atomic scale. The exact mechanism of an atomristor can vary based on the specific electrode materials and design used but the memory cells can be programmed at low operating voltages and exhibit fast switching times similar to ECM and VCM counterparts, with a reasonable LRS lower than tens of ohms. Moreover, the capacitance in the HRS scales with the area (C_{HRS} of approximately 20 fF for a device feature size of 1 μm^2, [3]). Nonetheless, since both technologies are governed by filamentary mechanisms, there exists a trade-off between the C_{HRS} and R_{LRS}. When either the filament length or the nanogap is small, the LRS achieves lower values, leading to fast switching times and high energy efficiency. However, the negative consequence is larger capacitance at the HRS due to the reduced distance between electrodes, thereby compromising isolation. Moreover, the LRS is usually characterized by the introduction of compliance current (CC) series resistor. Increasing the CC yields a lower LRS, but this adversely affects device endurance and energy consumption.

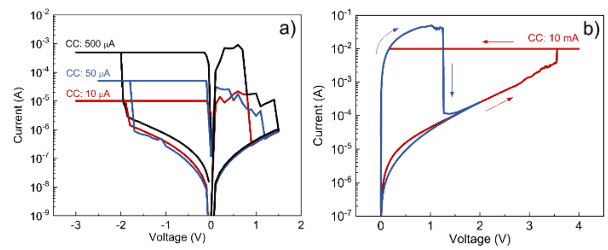

Figure 2: a) Typical bipolar quasistatic I-V characteristics of a CBRAM device, using Cu as electrochemical active electrode [4]. b) Unipolar resistive switching properties [5].

Regarding PCM cells, there are fundamental limitations such as the necessity for an integrated heater, relatively slower switching speeds, and challenges in reducing the area for higher frequencies. The limitations of PCMs stem from the mechanism relying on amorphous-crystalline transition through thermal force. In this concept paper, we focus on ECM-type devices. Figure 2 (a) shows typical bipolar quasistatic I-V characteristics of a CBRAM device, using Cu as an electrochemical active electrode [4]. It is notable that the replacement of silver electrodes with copper makes devices more compatible with CMOS technology. The device switches to low resistance state (LRS) at ~ -2 V and erases back to high resistance state (HRS) at 1.5 V. Formation of metallic filaments occurs at the negative polarity since the Cu electrode is the bottom contact, here. Multilevel cell (MLC) performance is also realized and can either be controlled by the application of different current compliance (CC) on the set side to control which is the final low resistance state or via reset-stop voltage on the side of reset [2]. Negative differential resistance (NDR) is a signature of partial filament ruptures, thus, any voltage pulse from the onset of NDR to full erase can be applied to reset the device to various HRSs. The MLC operation brings benefits to the beamforming precision, enabling finer phase quantification and minimizing spurious lobs in the radiation pattern. In addition to the mentioned characteristics, unipolar resistive switching concept can be also applied as RFRS, as shown in Figure 2 (b). Here the amplitude of current/voltage is responsible to set and reset the device rather than the polarity of the voltage bias [5]. The underlying reset mechanism is based on thermal rupture of the filament rather than electrochemical reaction.

Apart from the RFRS device concept, another technological consideration is integration. To the best of our knowledge, there have been no studies showcasing the integrated RFRS switch (see Figure 3).

To this end, surface roughness of some conventional substrates (Rogers 5880 ½ oz. rolled copper) is analyzed. As depicted in Figure 4, it becomes evident that it's not conducive to RFRS devices, especially when the thickness of device is only a few nanometers. Glass or silicon oxide substrates are the most common substrates that are used for resistive switching devices. These substrates, however, can present several challenges at gigahertz (GHz) and terahertz (THz) frequencies related to signal loss and dispersion, where different frequency components of the signal travel at varying speeds. For example, glass often has absorption bands at certain THz frequencies due to molecular vibrations. These absorption bands can cause

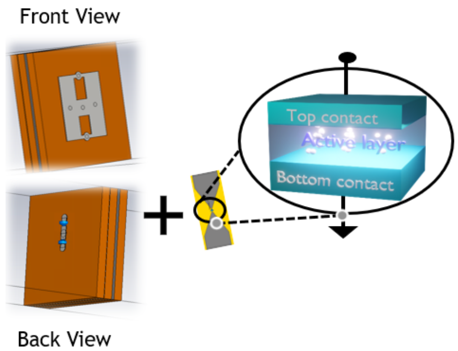

Figure 3: Adaption of RFRS switch design with wave guideline configuration.

selective signal loss and limit the available frequency bands for communication. In addition, designing effective THz waveguides within glass structures can be challenging due to the material's properties. In the case of silicon oxide, significant dielectric loss at GHz and higher frequencies results in energy absorption and signal attenuation as electromagnetic waves pass through the material. This can result in reduced signal strength and shorter communication distances.

3 PROSPECTS

Enhanced nanolithography techniques have the potential to decrease the area of RFRS devices, leading to enhanced isolation. Furthermore, similar to 2D monolayer atomristor, reducing the active layer thickness and employing material manipulation through localizing the filament formation by doping, it is possible to further decrease the LRS and lower the insertion loss through combined efforts. Interface engineering is also essential to stabilize the switching filaments, in order to increase endurance of the device [3]. Regarding substrates, low-loss dielectric materials with excellent transmission properties in the THz range and extremely low roughness are highly desirable. It is important to note that achieving very low roughness depends not only on the choice of substrate material but also on the quality of the manufacturing and polishing methodologies. Despite what substrate is chosen, careful attention to processing techniques is necessary to achieve the desired level of surface smoothness for a successful integration of memristors in THz antenna structures.

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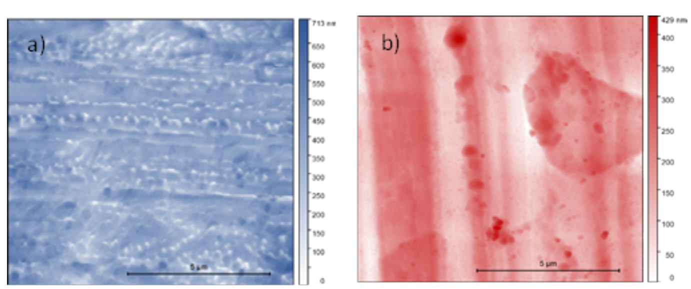

Figure 4: Atomic force microscopy (AFM) images of a) Roger substrate with an RMS roughness of 76.95 nm. b) ½ oz. rolled copper with an RMS roughness of 61.05 nm.