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Nafion Based Fully Passive Solid State Conductive Bridging RF Switch

M.P. Jayakrishnan, Arnaud Vena, Afaf Meghit, Brice Sorli, and Etienne Perret, *Senior Member, IEEE*

Abstract—This letter reports the design and development of a Conductive Bridging RF-Switch with simple fabrication steps without the use of any clean room technologies. The reported device is a fully passive shunt mode RF-Switch on a Co-Planar Waveguide (CPW) transmission line, which operates in the DC to 3GHz range. This particular topology is chosen in contemplation to limitations imposed by the chosen realization process. The device is based on a Metal-Insulator (electrolyte)-Metal (MIM) structure, with Copper-Nafion®-Aluminum switching layers. S21 switching between -1dB (RF- On) and -16dB (RF- Off) is demonstrated till 3GHz by the device. DC pulses in the range 18V/0.5mA and -20V/0.1A are used respectively to SET and RESET the switch, and the instantaneous power consumed for SET and RESET is respectively 1.7μW and 3mW. The SET and RESET state DC resistance of the switch are observed as 2Ω and 2MΩ subsequently. The model is initially simulated using commercial FEM based Electromagnetic modeling tool and validated experimentally.

Keywords: CBRAM, Memristor, RF-Switch

I. INTRODUCTION

SWITCHES are inevitable parts of any electronic system, and so it is for passive reconfigurable devices. Passive and electronically controllable switches have been a topic of keen interest among the scientific community since the last decade.

The RF engineering field is in need of high speed electronically controllable switches over the past years. Some of the popular available solution to these requirements are the semi-conductor based solid-state switches like PIN diodes, MEMS RF-Switches [1] etc., which cater this need beautifully, even up to THz, but with an added budget of requiring a constant power supply, to maintain the state. This drawback limits the use of PIN and MEMS switches for low power and passive reconfigurable devices.

The yearning for a low cost and printable RF-Switch, which could increase the functionality and lower the power consumption of passive/semi-passive RF devices, is avid in

the industry [2]. An alternative to this problem, at least up to a few GHz are the RF switches based on the Programmable Metallization Cell (PMC) theory [3], introduced in 1996 by Michael Kozicki. PMC switches consume power only to establish their states and do not require any power supply to maintain them. Switching topologies like the Conductive Bridging Random Access Memory (CBRAM), Phase Change Memory (PCM) etc., are evolved from the PMC theory. A few Memristive RF-switching devices based on PCM [4], CBRAM [5] etc., are reported in the recent years.

In this letter, we present a simple design of an RF-Switch based on the CBRAM technology, using Nafion as the electrolyte (Nafion is a registered trademark of the E. I. du Pont de Nemours & Co. [6]). Yet very simple, this topology has the potential to be used as a fully printable switching technology in the near future. Thanks to Nafion, the reliability has been significantly improved. Also, there are no publications till date which use Nafion for CBRAM RF-switching devices, to the best of our knowledge.

The device is fabricated using simple in house and basic lab facilities, close to a basic realization setup, and could not be applied for the manufacture of PCM or MEMS devices [1, 4]. This experiment is an attempt to democratize the realization/printing of RF-switches on classic PCB/circuits. Comparison of the presented design with state of the art devices is given in Table 1.

TABLE I
COMPARISON WITH STATE-OF-THE-ART

Features	Our Design	Nanoionics E.g. [5]	MEMS E.g. [1]
Min. Fabrication size Requirement	100μm	10μm	<1μm
Frequency Range	DC - 3GHz	DC - 6GHz	DC - 35GHz
Isolation (avg.)	-16dB to -34dB	-35dB	-35dB
Insertion Loss (avg.)	0.5dB	0.5dB	0.25dB
Actuation Voltage	~10V/-20V*	~1V	30-50V
Power Consumption	μW/mW*	μW	μW
Energy Consumption to Maintain State	0	0	μJ
SET - Resistance (avg.)	2-5Ω	10Ω	0.35Ω
Switching Speed	#	1 - 10μs	~5μs
Alignment Accuracy required for fabrication	Low	Very High	Very High
Fabrication Environment	Ambient room	Clean room	Clean room
Fabrication Cost (Laboratory Perspective)	Low	High	High
Fabrication Cost (Industrial Perspective)	Low	Moderate	High

* For SET/RESET respectively

#At present, we do not have enough information for calculating the switching time of the presented device. In order to ensure a smooth and stable switching, a slow sweep is used to SET/RESET the Switch (as shown in the Fig. 4) and this limits in determining the switching time. However, from experiments, it is clear that the switch can be SET/RESET using instantaneous voltage pulses,

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and such short pulses could be used to operate the switch after a detailed study of the DC dynamics, after which one could accurately determine the switching time.

II. MOTIVATION AND OVERVIEW

A Metal-Insulator-Metal structure as shown in Fig. 1 is the fundamental switching element of the CBRAM switching technology. The Insulator layer is a solid electrolyte, like common synthetic resin [7], [8] and one of the electrodes is an electrochemically active metal like copper or silver and the other is a relatively inert metal like aluminum or gold.

The switch is SET by sufficiently high electric field applied among the electrodes, which makes the active metal-ions migrate through the electrolyte, to form a metallic link between the electrodes to establish the SET state. An electric field of opposite polarity could be used to dissolve the link to attain the RESET state as shown in the Fig. 1. The switch consumes power only to form or dissolve the link, and not to maintain state, making it an interesting passive device. The electrical equivalent circuit of the MIM switch could be approximated to a RC parallel circuit as shown in the Fig. 1(d). R_{SET}/R_{RESET} is the equivalent DC resistance of the filament in SET/RESET state and C is the equivalent capacitance due to geometry of electrodes of the switch.

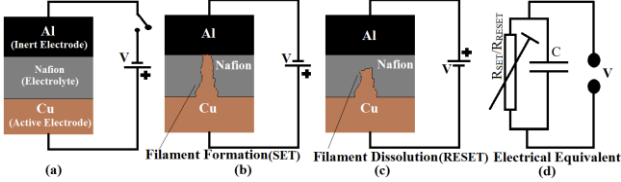


Fig. 1. (a) The Conductive Bridging MIM switch, (b) SET, (c) RESET, (d) electrical equivalent circuit.

III. DESIGN AND FABRICATION

The RF Switch is designed in shunt mode on a 50Ω CPW line. Fig. 2 shows the topology of the device. This particular design is chosen over two simple transmission line segments sandwiching the electrolyte. This is due to the limitations imposed by the high capacitance at higher frequencies. In order to achieve the same performances with a Microstrip line, one has to taper the switch area to very small dimensions, than what is presented herewith using a CPW. The MIM switching element is formed between the $100\mu\text{m}$ wide shunt line (which is a part of the Ground plane) and the $300\mu\text{m}$ wide aluminum metallization (which forms the signal line), with a 600nm thick Nafion electrolyte layer sandwiched among them. The Nafion is basically a sulfonated tetrafluoroethylene based fluoropolymer-copolymer, well known for its fast ion conducting properties and use in proton-exchange-membrane fuel cells [6]. This particular polymer has the specific advantage over the inorganic materials used classically [5], in terms of the ease of fabrication, that this material could be just spin coated and air dried, even though the long term stability and reliability are a question to be studied in depth. When the switch is SET, the power from Port1 is short circuited to the ground, isolating it from the Port2, establishing the OFF state of the RF-Switch. The switch is RESET to resume the connection between the Port1 and Port2 establishing the ON state. The switch is fabricated on low cost FR4 substrate using the following procedures.

The copper trace pattern is first engraved on the substrate using classical UV lithography. The copper trace thus formed is $35\mu\text{m}$ thick. This step-discontinuity is filled using a synthetic epoxy resin and then polished to reveal the copper surface. This filling makes a smooth surface which helps to achieve even thickness for the electrolyte and metal layers. The substrate is heated at 100°C for 4 min to have a thin layer of copper oxide, which is found to enhance the efficiency of the SET-RESET cycles, based on the first hypothesis drawn after long exhaustive experimental realizations. The 600nm Nafion layer is deposited by spin coating the 'Nafion perfluorinated resin solution' (supplied by Sigma Aldrich), at 500rpm for 30s. The layer is then heat cured at 100°C for 60s to enhance the adhesion with copper. Then the aluminum layer, which connects the two segments of the transmission lines, is deposited by thermal evaporation technique. Thickness of the deposited aluminum layer is measured to be $1.6\mu\text{m}$, using the Dektak-150 mechanical Profilometer. Fig. 3 shows the photographs of the fabricated device.

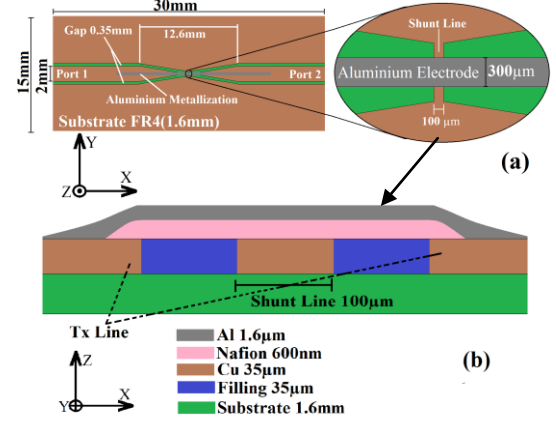


Fig. 2. (a) The shunt mode RF switch, (b) cross section of the shunt line showing the MIM structure.

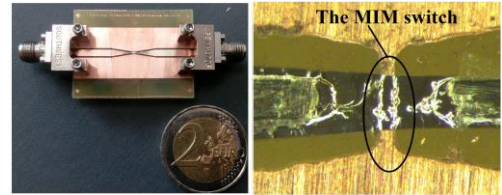


Fig. 3. Photograph of the fabricated switch (left) micro-photograph of the MIM switch structure (right).

The DC pulses for switching are generated using the Keithley-2400 source meter. DC pulses in the range $18\text{V}/0.5\text{mA}$ and $-20\text{V}/0.1\text{A}$ are used respectively to SET and RESET the switch, as illustrated in the Fig. 4. In this case the switch is SET at 10V , and RESET instantaneously at -20V , and the instantaneous power consumed for SET and RESET is respectively $1.7\mu\text{W}$ and 3mW (calculated from the instantaneous value of SET/RESET voltage and current from the pulse plots). A sudden fall in voltage and rise in current of the SET pulse indicate the formation of a conductive filament in the MIM structure. In reverse there is an abrupt rise in voltage and fall in current across the switch when the filament is dissolved, Re-Setting the Switch as shown in the Fig. 4. If the switch is not SET by the applied field, the DC voltage pulse follows the path marked by the dotted-blue trace. The voltage/current is present in the DC-path only during a SET/RESET process.

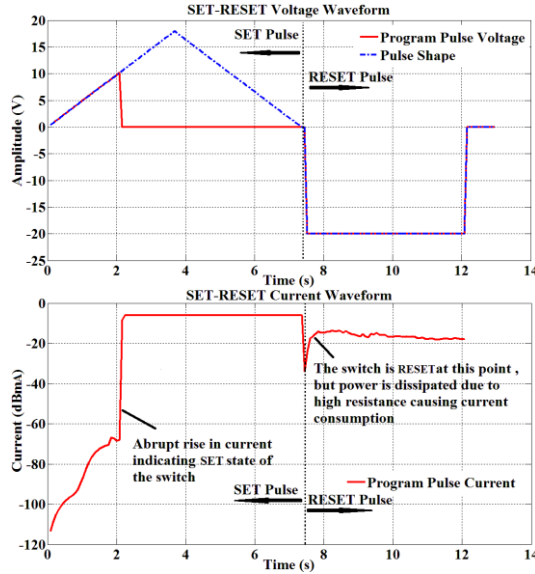


Fig. 4. The DC Voltage (top) and Current (bottom) waveforms used for operating the switch.

IV. RESULTS AND DISCUSSION

The RF measurements of the Switch are done using the Agilent ENA E5061B (3GHz) Network Analyzer, using ordinary SOLT calibration and signal power level of 0dBm, and are depicted in Fig. 5, along with simulation results for reference. The fabricated RF switch shows acceptable results from DC to 3GHz. The ON (RESET) state insertion loss of the full structure is 0.5dB at 1GHz and less than 1.1dB up to 3GHz. The OFF (SET) state isolation is greater than 16dB up to 3GHz. The DC resistance of the switch is measured to be in the range of 2Ω to few hundreds of Ω , and hundreds of $k\Omega$ to $M\Omega$ in the SET (R_{SET}) and RESET (R_{RESET}) states respectively, for different switching cycles. For the first few cycles the observed maximum R_{SET} is 5Ω and minimum R_{RESET} is $1M\Omega$, which is a good R_{RESET}/R_{SET} ratio. An approximate lumped circuit model using an RC parallel circuit, fitted using simulation with the measurement results, in place of the ‘bridge filament’, attached to the CPW line is shown in the inset of Fig. 5. This RC circuit is placed after removing the shunt line which forms the active electrode of the switch. This is similar to adding a discrete MIM switch (Fig. 1) to a CPW line tapered at the center. The values of the resistance that fit the experiment are 2.5Ω and $2M\Omega$, for the SET (RF-Off) and RESET (RF-On) respectively and that for C is $1pF$. The measured parameters stated above are inclusive of the effects of the connectors and the CPW feed lines. More accurate calibration schemes like the TRL could be applied to resolve the independent response of the switch, which would be more superior to what is presented herewith, and could be used to determine the accurate lumped circuit model of the switch.

V. CONCLUSION

We have presented the design and development of a fully passive conductive bridging RF-Switch, which uses simple fabrication steps and shows good performance till 3GHz. Low resistance values of around 3Ω have been obtained for the SET. The simulated lumped circuit model is also in agreement

with the measured DC resistance values and shows good comparison with the RF results. One of the prime concerns regarding the switch is its switching-reliability: at this stage we could operate it at least for 50 cycles, despite of the fabrication tolerances, and the step discontinuity due to the thickness of the copper trace. But, we were able to achieve switching as stable as 2000 cycles with a comparable MIM cell [8]. This adds to the confidence that the number of switching cycles could be improved by careful modeling of the device. Further, the study of the maximum switching cycles would be carried out in the future.

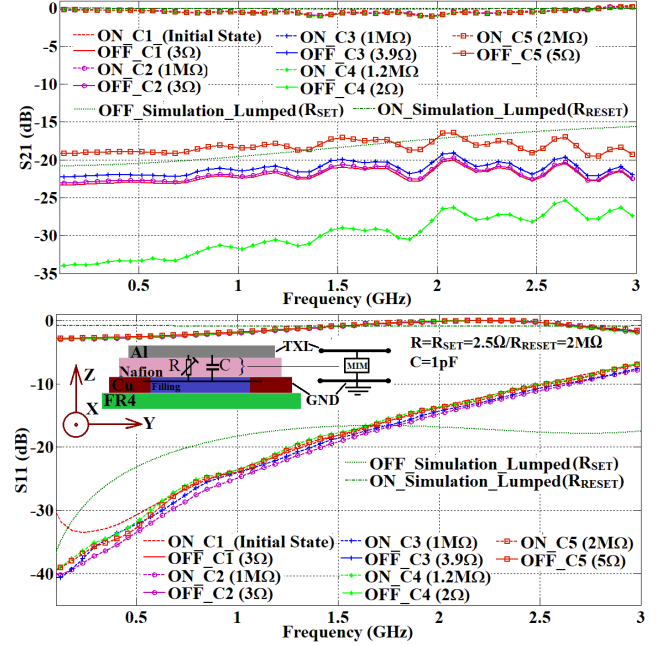


Fig. 5. The S-Parameters of the switch, S21 (top) and S11 (bottom). The DC-resistance of each state is given in brackets. The inset of bottom figure shows the lumped model equivalent of the MIM - Switch.

Focus is also given on increasing the frequency of operation. Development of a fully printed RF switch on flexible RF substrate for application in low power and/or passive reconfigurable devices like, antennas, filters, RFID, phase shifters etc. is in progress.

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