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Optimization of the melt and quench behavior of phase-change RF switch to improve power handling

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Abstract — This paper presents two methods to improve the reliability and the melting/quench behavior of phase change materials (PCM) used in radiofrequency (RF) switches. Results show benefits of the addition of an aluminum nitride heat spreading layer and the reduction of the distance between the substrate and the PCM. The reduction of the PCM cooling time shown in simulations and the power handling improvement observed in measurements on series structures support our proposed designs of GeTe based switches with RF gaps lengths over 4 μ m, allowing the power handling going to reach 31dBm in both ON and OFF states.

Keywords — RF switches, PCM, GeTe, Power handling, Quench

I. INTRODUCTION

To keep up with the newest requirements in the signals transmission domain and most specifically in 5G communications, phase-change material based radiofrequency switches appear as a new solution. The use of PCM, already deployed in memories [1], [2], allows low signals insertion losses. Moreover, this technology can be easily integrated in the back end of the line (BEOL) of CMOS components and, unlike SOI based devices [4], it possesses a bi-stable behavior.

In the switch domain, PCM are used to link two RF transmission lines together. By changing their own structures between crystalline and amorphous states, they can act directly on the ON/OFF state of a device.

One of the keys to achieve great performances with this technology is the quality of the transmission. Losses have to be avoided in the ON state and isolation must be maximized in the OFF state. Therefore, the values of the resistance in the ON state (R_{on}) and the capacitance in the OFF state (C_{off}) must be minimized. The figure-of-merit $FOM=R_{ON} \cdot C_{OFF}$ allows a comparison between different kinds of switches. It needs to be lowered to improve performance.

Another important parameter is the quench duration of the PCM when, after having being melted, it quickly cools down so to keep a disorganized structure, blocking the signal transmission and setting the switch in the OFF state. Thus, the effective management of the temperature in the device is a key issue regarding both its RF performance and its reliability. In particular, for switches requiring high power-handling, an in-depth study of switches with significant RF channels lengths and widths is needed [5].

This work proposes two methods to improve thermal management. The use of an aluminum nitride (AlN) heat spreading layer in the upper part of the switch helps dissipate heat and reduces the hot spots in the device. Finite element electro-thermal simulations made with Comsol Multiphysics[®] software show improvements in quenching time and reliability.

The second idea is to build the PCM layer closer to the substrate. A variation performed on the thicknesses of the dielectric layers and the RF contacts separating the substrate from the PCM shows the impact of this distance on quenching speed and energy consumption.

Finally, measurements performed on series switches demonstrate the effectiveness of these solutions, with power handling reaching 31dB in both ON and OFF states and with a greater number of devices successfully tested without failure.

II. TECHNICAL DESCRIPTION OF THE PCM DEVICE

Following the technological steps described in [6], the switch stack contains a PCM, here made with GeTe, linking two RF electrodes. A tungsten element, called heater, is used as a heating resistance (Fig. 1). A voltage pulse is applied on it and the heat resulting from the joule effect is transferred to the PCM. Based on the amount of heat received and the pulse duration, the structure of the GeTe can end in two states.

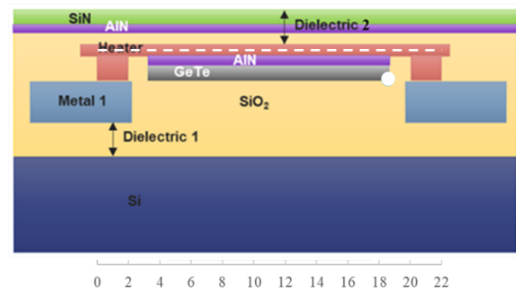


Fig. 1. Schematic technological stack of the switch seen along heater length as used in simulations. The white line and white point are the observation spots used in the graphs. The scale under the figure is the one used in Fig. 2.

A moderate voltage applied during 1 μ s crystallizes the PCM, lowering the resistivity and allowing the current to flow. On the contrary, a higher voltage applied in a shorter time helps the PCM to reach its melting temperature. Its structure disorganizes and the short duration of the pulse causes the

material to quench, resulting in an amorphous phase going together with a high resistive state and blocking the current. Thanks to these mechanisms, the switch requires energy only for the phase change of the material, making it bistable.

All dielectric layers used in the technological stack are carefully selected to control the heat flux. The dielectric layers with low thermal conductivity confine the heat to help the PCM to reach the targeted temperatures and those with high thermal conductivity allow to heat and cool the device faster.

Electro-thermal behavior of devices is studied for the switches with geometrical dimensions given in Table 1.

Table 1. Dimensions of studied switches. The width of the PCM (W_{PCM}), the length of the space separating the RF contacts (L_{RFGap}) and the width of the heater (W_{heater}) are the varying parameters.

Reference	W_{PCM}	L_{RFGap}	W_{heater}
Device A	20 μm	1 μm	1 μm
Device B	20 μm	1.5 μm	1 μm
Device C	20 μm	4 μm	3 μm

The simulations conditions are as follow: the actuation voltage is determined so that the melting temperature (998K) is reached in a central part of the PCM covering at least 66% of the RF gap length. As for measurement, the applied voltage V_{app} is the voltage applied by a pulse generator, with a source impedance of 50 Ω , to a charge of 50 Ω . The voltage actually applied to the heater terminal, V_H , is therefore calculated using (1), where R_H is the resistance of the heater. V_H varies as the resistance of the heater varies with temperature. Changes in thermal properties of the GeTe and boundaries thermal resistances are not taken into consideration. The quenching time is the time for temperature to decrease from the melting temperature down to 500 K.

$$V_H = \frac{2V_{app}R_H}{50+R_H} \quad (1)$$

III. SIMULATIONS

A. Effect of the AlN diffusion layer on the heater reliability

Temperatures are observed for device B along a line crossing the length of the heater, with and without an AlN heat diffusion layer for comparison. The observation is made at the end of a 400 ns amorphization pulse, when the heater reaches its maximum temperature (Fig. 2).

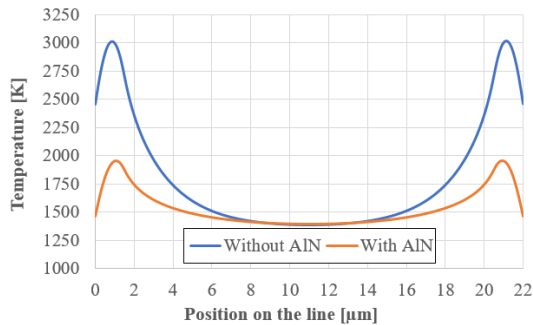


Fig. 2. Temperature in the heater for device B observed along the white line defined in Fig. 1.

In devices with shorter RF gaps, the RF contacts are close to the PCM. As the heat evacuates faster, the voltage applied on the heater has to be increased enough in order to reach the melting temperature. By doing so, the heater extremities, which are surrounded by dielectrics with low thermal conductivity, see their temperature rise to dangerous levels. Adding the AlN layer homogenizes and lowers the temperature inside the heater, reducing the breaking risk. In devices with longer gaps, there aren't hot spots in the heater but the AlN layer still helps homogenizing the heat.

B. Effect of the AlN diffusion layer on the PCM quench

The temperature variation along the duration of the pulse is observed, on the white point location shown in Fig. 1, for devices A and C, with and without the AlN diffusion layer. The exact position of the point is at the end of the PCM width, in the middle of its length and at the bottom of its thickness. The pulse duration is 150 ns.

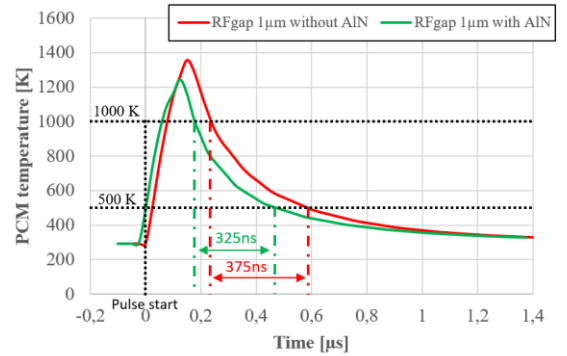


Fig. 3. Temperature observed in the PCM of device A, on the white point defined in Fig. 1.

The temperature evolution in device A is shown in Fig. 3. When comparing the time required for the PCM to cool down from 1000K to 500K, the addition of AlN in dielectric 2 reduces it thanks to better heat dissipation. For devices, with longer RF gap, the quenching time is also reduced (Table 2). However, as the heat still mainly evacuate through the metal RF contacts, it remains longer to cool down the center part of the PCM for long RF gaps.

Table 2. Switches performances for combinations of capping and RFgap length which have been studied

	Without AlN		With AlN	
	A	C	A	C
Device reference	A	C	A	C
RFgap length (μm)	1	4	1	4
Applied Voltage V_{app} (V)	10.9	9	12.2	10.2
Consumed Energy (nJ)	215	147	269	187
Heater max temperature (K)	2464	1977	2182	2029
Quench time (ns)	375	725	325	650

Table 2 displays, for both devices, the voltages applied to reach 1000K in the active zone of the PCM, the energy consumed during the pulse, the quenching time and the maximal temperature observed in the heater.

Due to improved thermal dissipation induced by the AlN layer, more energy and higher voltage are required to heat and change the phase of the PCM. But since the quenching time is shorter with the AlN, that will result in less recrystallization of the material and, finally, to a longer length of amorphous material.

C. Reduction of the distance between substrate and PCM

The silicon substrate being an excellent thermal conductor, bringing it closer to the PCM is another solution to evacuate the heat faster from the PCM. To evaluate the benefits, the quench time has been simulated in different configurations. Here the thicknesses of the dielectric 1 and the RF contacts vary from 500 nm to 50 nm and 600 nm to 100 nm respectively. The pulse is 400 ns long, the RF gap length is 4 μm and the observation is made at a point placed in the center of the RF gap, in the middle of the PCM length and at the bottom of the latter (Fig. 4).

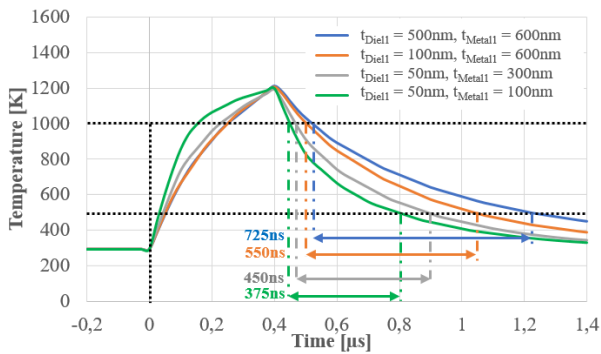


Fig. 4. Temperature observed in the PCM of device C.

According to results of Fig. 4, reducing the distance between the PCM and the substrate is an effective way to accelerate quenching, allowing to bring it from 725 ns down to 375 ns. However, this technique is limited by its impact on the other performances of the devices. Table 3 gives an insight on those limitations.

Table 3. Switches performances for different dielectric 1 and metal 1 thicknesses

Dielectric 1 thickness (nm)	500	100	50	50
RF contacts thickness (nm)	600	600	300	100
Voltage used (V)	7.2	7.2	7.8	10.1
Consumed energy (nJ)	207	208	246	411
Heater max temperature (K)	1510	1530	1652	2110
Quench time (ns)	725	550	450	375

As the substrate gets closer to the PCM, the heat evacuates more easily. It is an advantage for the quenching phase, but penalizes the temperature rise. As a result, the required voltage, the consumed energy and the maximum temperature reached in the heater increase exponentially. In order to limit these increases, a good compromise is to keep a 50 nm thick dielectric 1 and 300 nm thick RF contacts. This reduces the quenching time down to 450 ns while limiting the impact on the other performance.

IV. POWER HANDLING AND FOM CHARACTERIZATION

A. Measurements setup and method

A setup based on the schematic shown in Fig. 5 has been used to measure the power handling of devices with various geometries. A 915 MHz continuous-wave is applied to the switches while the input power is discretely ramped-up from 0 dBm to 40 dBm with a step of 0.2 dBm. The output power is measured at each step, at the fundamental frequency $f_0 = 915\text{MHz}$, at $2f_0$ and at $3f_0$. Meanwhile, the resistance of the switches is also measured in order to check the integrity of the switch.

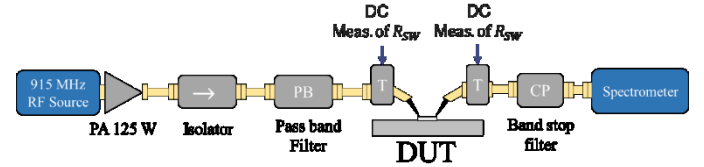


Fig. 5. Test setup used for power handling measurement

Prior to the characterizations, all devices have been switched 5 times between OFF-state - with pulses of 400 ns duration - and ON-state - with pulses of 2 μs duration.

B. Results

The power handling has been measured for two fabrication lots, on devices mounted in series configuration (Fig. 6). The generation 1 lot has no AlN dissipation layer, a dielectric 1 thickness of 500 nm and a RF contact thickness of 600 nm. For generation 2, the lot has been optimized with the addition of the AlN in the dielectric 2 and a reduction of the dielectric 1 thickness down to 100 nm. The RF gap is either 3 μm or 4 μm long and the heater width is either 2 μm or 3 μm .

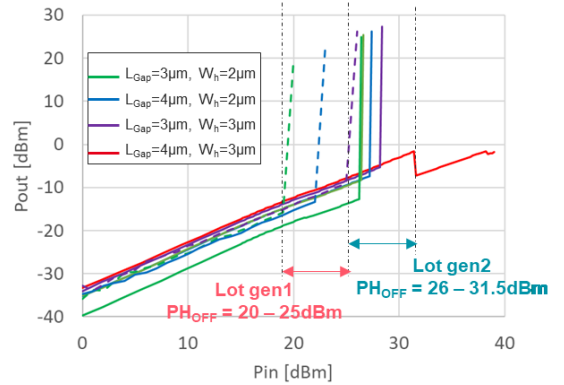


Fig. 6. Comparison of OFF-state power handling capability before (lot gen1) and after (lot gen2) the addition of the AlN heat spreading layer and reduction of the dielectric 1 thickness.

Fig. 6 clearly shows an improvement for gen2 devices with the OFF-state power handling going up to 31.5 dBm for the device with the longer RF gap and the largest heater width. This device is the only one which gets destroyed when failing, as opposed to the other switches which turn to the ON-state. An explanation can be found when looking at Fig. 7, where its power handling in both ON-state and OFF-state are represented. The switch handles a power of 31 dBm in the ON-state. Thus,

when failing at 31.5 dBm in OFF-state, it can't crystallize because the power is not supported in the ON-state.

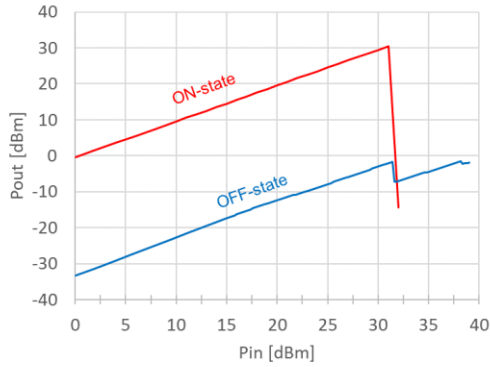


Fig. 7. OFF and ON states power handling for a switch with $L_{RFgap}=4 \mu\text{m}$, and $W_{heater}=3 \mu\text{m}$ and $W_{GeTe}=50 \mu\text{m}$.

For this device, the insertion loss is lower than 0.4 dB and isolation is higher than 16 dB up to 10 GHz (Fig. 8). Corresponding R_{ON} and C_{OFF} values are 4.5Ω and 25 fF respectively, resulting in a FOM of 112 fs.

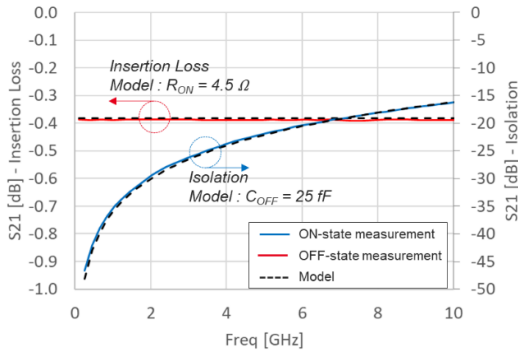


Fig. 8: S-parameters after de-embedding for a switch with $L_{RFgap}=4 \mu\text{m}$, $W_{heater}=3 \mu\text{m}$ and $W_{GeTe}=50 \mu\text{m}$.

The R_{ON} is in agreement with the expectations while the C_{OFF} was expected to achieve 14 fF, which would have resulted in a 61 fs FOM. As the expected power handling performance for an amorphous material length of $2.7 \mu\text{m}$, corresponding to 2/3 of the $4 \mu\text{m}$ RF gap length, was 36 dBm, those results show that improvements still have to be done in order to reach the targeted performance.

Yet, when comparing to the state of the art, reaching 31 dBm of power handling in both ON and OFF state is the highest value reported up to now for a single PCM RF switch measured in series configuration (Table 4).

Table 4. RF performances comparison between state of the art and AlN spreader equipped device with highest heater width and RFgap length.

Ref.	RF gap length (μm)	GeTe width (μm)	PH ON-state (dBm)	PH OFF-state (dBm)	FOM (fs)
[7]	1	10	27	23	10
[7] (stack of 4 switches)	1	10	27	34.5	50
[8]	3	10	39	26	35
[6]	4	90	37	29	93
This work	4	50	31	31.5	112

V. CONCLUSION

Two strategies for optimizing the thermal management in the PCM-based RF switch technological stack were presented: the first is the use of an AlN heat diffusion layer deposited above the heater, and the second is the optimization of the distance between the silicon substrate and the phase-change material. As example, simulations have shown a noticeable reduction of the quenching time without major impact on the other performances. We integrated such technological improvements for devices with $4 \mu\text{m}$ long RF gaps for targeting the amorphization of a portion of the PCM sufficient enough to reach 36 dBm of power handling. Measurements established that adding an AlN spreading layer improves the power-handling by 6 dB in OFF-state over the previous lots.

Others PCM based switches designs are currently under study to push the quench reduction further and reach the 36 dBm power handling objective in both ON and OFF-state for switches in series configurations.

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