In-depth caracterisation of the structural phase change of Germanium Telluride for RF switches

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Abstract— This paper presents the phase change characterization of Germanium Telluride GeTe used for RF switches when a direct heating is performed. The study describes the method to activate the transition between crystalline and amorphous states, allowing to reach a resistance ratio of $1.8.10^4$ between both states. RF measurements were performed up to 40 GHz on fabricated switches, showing an ON-state resistance of 1.7 Ω. An OFF-state capacitance of 5.4 fF was extracted from simulation, resulting in an estimated cutoff frequency of 17 THz. The study also shows the importance of the GeTe thickness to optimize the performance of the device.

Keywords—RF switches, phase-change material, GeTe, direct heating

I. INTRODUCTION

With the evolution of communication means in our societies, it is necessary to develop components that can answer the future trends for the new mobile telephony networks. Within those networks, and more precisely at the front-end modules (FEM) level, switches play a fundamental role for reconfigurability. This role is even strengthened with the incoming of the massive multiple input multiple output (MIMO) systems and the principle of aggregation linked to 4G and next 5G. Phase change material (PCM) based switch is a recent and much reliable approach to challenge MEMS, MOS transistors or PIN diodes. Several publications already have showed that their electrical performance can overcome the current state-of-the-art of conventional devices. Several PCM as Germanium Telluride GeTe [1], Germanium Antimony Telluride GeSbTe [2], and Germanium Antimonide GeSb [3] have already been used. Electrical switching is ensured by a change in the structural phase of the material submitted to a temperature gradient. On the basis of the structure represented in Fig. 1.a, heating may be induced by direct contact as in [4]. The signal line disrupted by the presence of the PCM conveys an electrical signal that generates the temperature gradient in the material [4]. Heating may also be indirect. In that case, electrical signal heats an intermediate highly resistive material that transfers its calorific energy to PCM via Joule effect [1]. Phase change induces an important resistive transition in the material. Its electric conductivity increases from less than 10 S/m, in its amorphous phase (high resistivity phase), to more than 100 kS/m in its crystalline phase (low resistivity phase).

From a technological point-of-view, indirect heating is more complicated as an intermediate material (heater) and an extra metallic layer to convey electrical excitation are needed. As well, an early eldering of the heater is observed, due to the high temperature necessary for changing PCM from one phase to another. As a consequence, reliability still has to be proved. Direct heating seems much simpler. However, it has to be pointed out that very few studies focus on this technique, since direct heating phase change is more complicated to manage in terms of technological stack.

In this paper, a DC study is first presented, enabling to characterize the phase change of GeTe when a direct heating is performed. The ratio R_{OFF}/R_{ON} is extracted as an indicator of the potential RF performance in terms of switching. Then, RF results are shown for both crystalline phase (simulation and measurement) and amorphous phase (simulation). Finally, results are compared with the state-of-the-art.

II. GERMANIUM TELLURIDE BASED SWITCH

A. Technology description

Understanding the phase change mechanisms in GeTe technology is one of the most challenging part of this work. This is the reason why simple structures were realized (Fig 1.a). Aluminum feeding lines (440-nm thick) were patterned over 500 nm thick thermal oxide on a high resistivity substrate (resistivity above 1 000 Ω.cm). GeTe is deposited on a preliminary planarized surface and patterned by dry etching (RIE). Such process allows to define uniform patterns lwith minimum width of 250nm. To protect the PCM and passivate the surface, a 100-nm PECVD SiN dielectric is deposited. The test pads are opened by standard RIE etching. The technological stack was developed with CMOS back-end-of-line (BEOL) compatible materials: aluminum was chosen instead of gold or platinum, and a silicon substrate was preferred.

To manage the experimental floorplan, two parameters were introduced in Fig 1.b, the length (L) and the width (W)

of the device. Length of GeTe is defined as the distance between the two metallic electrodes.

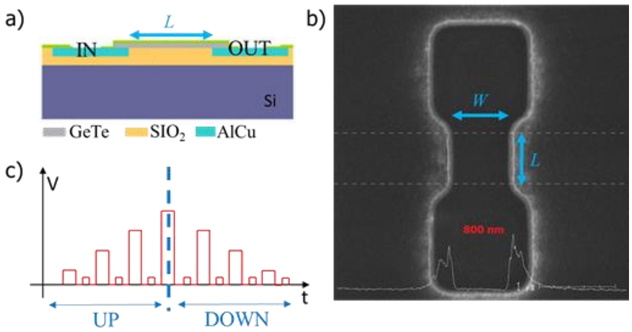

Fig. 1. a) The PCM swicth technological stack. b) SEM view of a switch. c) Pulse excitation for phase change.

B. *Electrical characterization*

As already mentioned, direct heating was performed. A current excitation based on pulses was applied via the feeding line, leading to a progressive heating of the device in the PCM material.

Amorphization and crystallization phases need different current waveforms, which are detailed hereafter. Fig. 1.c gives the two different pulse streams that may be used for crystallization and amorphization phases. The very small pulses between the larger ones are necessary for reading the resistance value of the device (the small voltage induces a low current that is too small to program the cell, but is sufficient to calculate the resistance). They are called “reading pulses”.

After wafer manufacturing, GeTe shows a crystalline phase with low resistivity (*ON-state*). The first part of the signal aims at amorphizing it. A stair case stream is thus generated to reach the minimum pulse magnitude enabling the transition towards the amorphous state with high resistivity (*OFF-state*). Signal intensity depends on the device geometry. In Fig. 2, the current set point of 9 mA stands for a device of length L=800 nm and width W=500 nm. Reading pulses have not been represented in Fig. 2. The current waveform shows a rise time of 5 ns with a high-level during 300 ns followed by a fall time of 5 ns. Such signal enables to quench the material towards an amorphous state obtained thanks to a rapid freezing after melting during high-level. Once the material is melted, the quick fall time of only 5 ns is thus the most important part of the waveform.

On the contrary, to crystallize the material (turn *ON* the switch) two different approaches can be used. First one consists in melting it and then to slowly cool it towards its crystalline phase. This could be obtained thanks to a current pulse of the same order of magnitude as for amorphization (9 mA) but with a much longer fall time (100 µs). Second way that was implemented during this study, represented on the right part in Fig. 2, consists in applying a decreasing stair case to the feeding line to reach the targeted state of crystallization. Practically, rise or fall times are not of first priority here, we applied the same ones as for amorphization (rise and fall time of about 5 ns). On the contrary, to overpass the breakdown voltage for which the material turns towards its low resistivity state (*ON-state*), it is necessary to apply a voltage of 3.5 V holding out during 500 ns, which is sufficient to enable a whole crystallization of the active zone of the device.

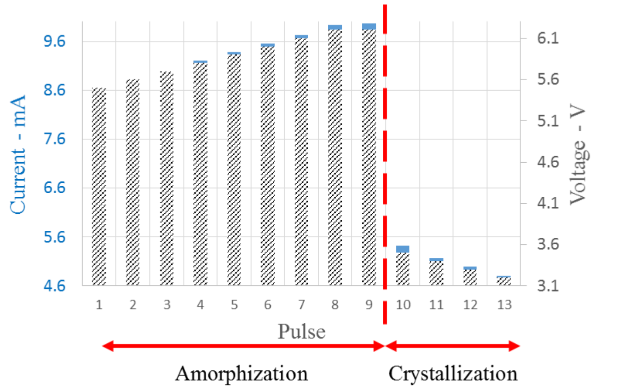

Fig. 2. Current and voltage of the device of Fig. 1.b for both amorphization and crystallization stages. L=800 nm and W=500 nm.

Fig. 3 shows the variation of the switch resistance for a complete amorphization-crystallization cycle as described in Fig. 2. The device shows a resistance of 160 Ω at the beginning, in total agreement with the dimensions of the studied piece of PCM, reaching 3 MΩ at *OFF-state* before falling back to 170 Ω after new crystallization. The R_{OFF}/R_{ON} ratio reaches 1.8×10^4. Such performance is compared to the state-of-the-art in Table 1, with the two kinds of heating.

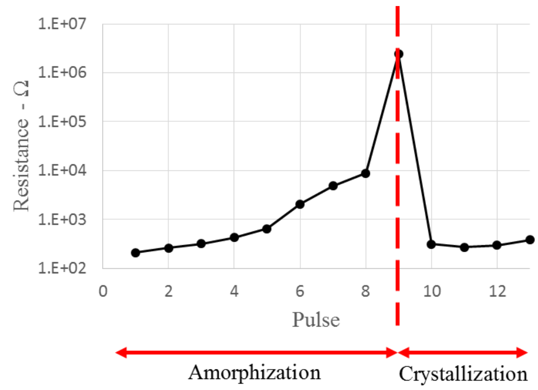

Fig. 3. The resistance variation of the device during amorphisation and crystallization stages.

Several simulations were carried out to optimize the device in terms of Figure of Merit ($FoM = R_{ON} \cdot C_{OFF}$), switch dimension that must be the smallest as possible and R_{OFF}/R_{ON} ratio that must be maximized. Optimization is carried out by varying the GeTe dimensions, i.e. length, width and thickness. Length of GeTe is defined as the distance between the two metallic electrodes. Thickness is defined by the technological stack and is of 300 nm here.

TABLE I. STATE-OF-THE-ART FOR R_{OFF}/R_{ON} RATIO.

Technology	**Ratio R_{OFF}/R_{ON}**	**Heating**
GeTe – this work	1.8×10^4	Direct
GeTe [1]	10^5	Indirect
GeSbTe [2]	9.3×10^3	Indirect
GeSb [3]	1.4×10^3	Indirect

GeTe [4]	$9.6x10^3$	Direct

III. RF Measurement Results

Wide band S-parameters measurements were realized from 40 MHz up to 40 GHz using RF-probes (Z-probes) with 150-µm pitch. The measurement set-up is composed of a semi-automatic probe station, linked to a Vector Network Analyzer (VNA – Anritsu 37369). SOLT (Short, Open, Load, Thru) calibration was performed.

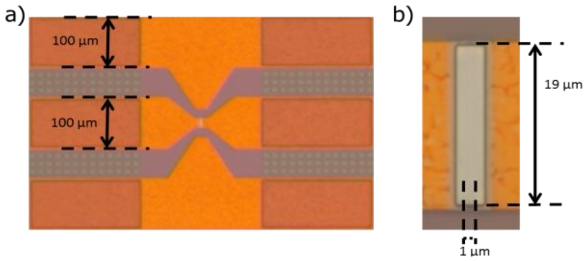

Fig. 4. a). Optical view of a CPW switch. b). Close-up of the PCM area.

Fig 4. presents the layout of the RF switch in a Coplanar Waveguide (CPW) topology. The width of the central strip is 100 µm for the feeding lines in both sides, and 20 µm in the GeTe area. The device was matched to 50 Ω. A close-up micrograph of the switch in the "ON" state shows the light color of GeTe in its crystalline state (Fig 4 b).

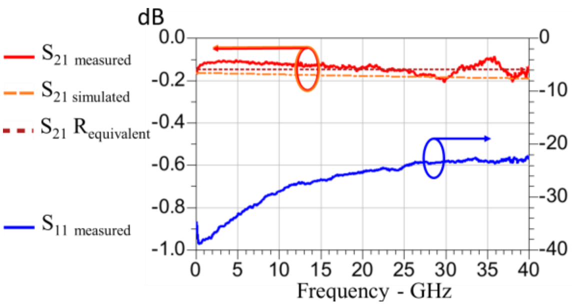

Fig. 5. Measured de-embedded switch performance in transmission (red), and comparison with ANSYS HFSS simulations (orange) and equivalent resistance model (1.7 Ω, dotted red) for a 300-nm thick GeTe film. Measured de-embedded return loss (blue).

Measurements are in agreement with ANSYS HFSS simulation results carried out with a conductivity equal to 100 kS/m for the crystalline GeTe as measured on-wafer by the Van Der Pauw method. Fig 5 show the results carried out for a 300-nm thick GeTe film. High microwave performance is reached over the whole frequency band, with insertion loss lower than 0.2 dB up to 40 GHz. The fit with a simple model of R_{ON} is obtained for a value of 1.7 Ω.

S-parameters for the OFF state was also simulated, as shown in Fig. 6. From the extracted R_{ON} in ON state and measured R_{OFF}/R_{ON} ratio equal to $1.8 \cdot 10^4$ (Fig. 3), an electric conductivity of 5.5 S/m can be estimated for the *OFF-state*. This value was used to carry out simulations for the *OFF-state*, with ANSYS HFSS. The fit with an equivalent RC circuit model is also shown in Fig. 6.

Simulation results give an *OFF-state* resistance of 20 kΩ for the 300-nm thick GeTe, and an *OFF-state* capacitance of 5.4 fF, resulting in an isolation better than 18 dB up to 40 GHz. The resulting cutoff frequency $f_{CO} = 1/(2\pi \cdot R_{ON} \cdot C_{OFF})$ reaches 17 THz. This results to comparable performance with the best published results in the-state-of-the-art (TABLE II.), thus showing the great potential of the proposed technology.

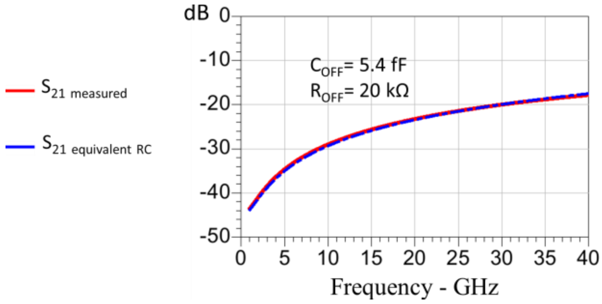

Fig. 6. S_{21} parameters of simulated de-embedded switch (red) and its RC equivalent circuit (blue) for 300 nm thick film of GeTe.

TABLE II. State-of-the-art for RF PCM Switches.

Technology	**FoM - fs**	**R_{ON} - Ω**
GeTe – this work	9.18	1.7
GeSbTe [2]	38	10
GeSb [3]	-	49
GeTe [1]	15.5	1.1
GeTe [5]	15	2.4
SOI [6]	250	-

IV. Conclusion

A study of GeTe phase change material with direct heating used to realize RF switches was presented. Dedicated design was developed to characterize the switch in DC. A R_{OFF}/R_{ON} ratio of $1.8 \cdot 10^4$ was obtained, i.e. better that the state-of-the-art for direct heating. Wide band devices were realized and measured from 40 MHz up to 40 GHz on the ON state. The measurements confirm the small resistance due to the GeTe thickness (300 nm), with a R_{ON} equal to 1.7 Ω. To go further a microwave simulation was carried out, predicting the device behavior at the *OFF-state*. These results permit to show that the proposed device could reach a 17 THz cutoff frequency corresponding to a 9.18 fs FoM.

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