High Performance and Low Energy Consumption in Phase Change Material RF Switches

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***Abstract* — This paper presents a RF to mm-wave switch based on Germanium Telluride phase change material. An integration process compatible with a standard CMOS back end of line is proposed to realize directly heated switches. RF measurements, performed up to 65 GHz, show an *ON*-state resistance of 1 Ω with an *OFF*-state capacitance of 7 fF corresponding to a 22 THz cut-off frequency which constitutes a state-of-the-art Figure-of-Merit. Switching time of only 60 ns in both phase changes allow energy consumption one decade lower than the state-of-the-art for crystallization. A geometrical variation of GeTe dimensions shows a linear evolution of RF performance in terms of *ON*-state resistance and an almost unchanged performance in the *OFF*-state.**

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

I. Introduction

Switching is a key function in many RF and mm-wave circuits. In particular, mm-wave applications such as 5G, back-hauling, automotive radars, RF imaging, etc, will require high-performance switches, which are not available yet. From a circuit point of view, performing switches need low insertion loss (*IL*), outlined by a low *ON*-state resistance R_{on}, and high isolation, outlined by a low *OFF*-state capacitance C_{off}. As a trade-off, the cut-off frequency $(1/2\pi R_{on}C_{off})$ is the major Figure-of-Merit (FoM) for switches; but the switching time, the power consumption, the DC bias voltage, the reliability, and the cost also play a significant role. To address all these requirements, many technologies have been studied during the last decades, such as CMOS and BiCMOS, MEMS, and more recently Conductive-Bridge (CB) or Phase Change Materials (PCM).

CMOS and BiCMOS technologies are limited by their *ON*-state resistance R_{on}, which leads to pretty high insertion loss. A switch achieving a cut-off frequency of 1.4 THz ($R_{on} = 0.5\,\Omega$) was presented in SOI technology, [1]. Low R_{on} performance was achieved at the expense of the surface on the die, with a width equal to 1 mm. MEMS switches are very good candidates for low insertion loss with 0.25 dB at 40 GHz in [2] and *OFF*-state capacitance lower than 10 fF but their reliability and packaging still remain an issue to overcome. CB technology, inspired from CBRAM, constitutes a promising technology, essentially for cost reasons as very simple processes were demonstrated on PCB, for example in [3]. However, integrated CB switches for mm-waves still have to be proven.

Meanwhile, PCMs show outstanding performance in terms of both insertion loss and FoM, with cut-off frequencies over tens of THz, but also extremely low R_{on}/R_{off} ratios, especially with GeTe material, where each resistance state is clearly identified and corresponds to a stable material phase: amorphous and crystalline [4]-[7]. Competitors may be GeSbTe [8], but with a lower R_{on}/R_{off} ratio and a lower *ON*-state conductivity. Finally, VO_2 presents the advantage of requiring low energy as the phase change occurs at 68°C only but is unfortunately not bi-stable (crystalline state needs voltage to be maintained), thus reducing the field of applications [9].

When focusing on GeTe based switches, attention has to be paid on their integration, with technological stacks and processes that are CMOS compatible. Both direct [5] and indirect [4] heating can be envisaged. Indirect heating through a heater has proven good performance but may be quite energy consuming, also suffering from a degradation of the heater over the time, thus leading to reliability issues.

In this paper, it is proposed to evaluate the potentialities of a simple technological stack enabling direct heating and high thicknesses of GeTe, which permits to lower the R_{on} resistance, leading to a high FoM, while drastically reducing the energy consumption for switching.

In part II, the switches fabrication technique and design are described. Emphasis is put on the geometrical parameters that influence the performance. The interest for direct electrical actuation to reduce energy consumption is shown in part III. In part IV, 40 MHz to 65 GHz measurement results are shown. They prove low insertion loss and high Figure-of-Merit.

II. Fabrication & Design Description

The process stack is described in Fig. 1. The flow developed so far fulfills two requirements: standard CMOS process compatibility and switching performance. First, compatibility of the materials and techniques with a standard CMOS back-end-of-line (BEOL) must be considered for further integration. For instance, neither platinum, nor gold were used, but only aluminum and standard RF silicon materials. Second, different technological stacks were tested to enhance the PCM switch performance. As shown in Fig. 1.b, the PCM is contacted backside using metallic strip lines that optimize electrical contact. Following a strict process flow, aluminum feeding strip lines for backside contact are first patterned on a HR-silicon wafer, after thermal oxidation. Next, GeTe is deposited in a co-pulverization step and patterned thanks to dry etching (RIE). This process allows defining uniform patterns, with width as low as 250 nm. Then a 100-nm thick PECVD SiN dielectric covers and protects GeTe. By the end, a second level of metallic strip lines, etched with a standard RIE, is contacting the first one.

Finally, SiO_2 is sputtered for passivation and test pads are opened by RIE.

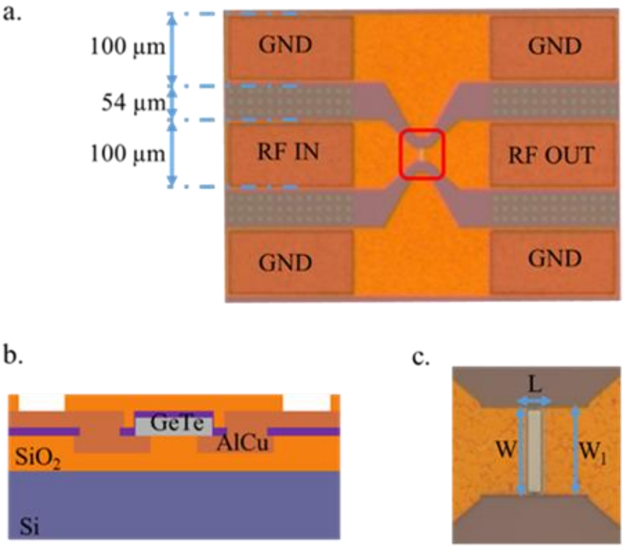

Fig. 1. a) Optical view of a CPW GeTe switch. b) Technological Stack. c) Close-up on the PCM area with W the width of GeTe and W_l the width of CPW line.

CPWs were used as feeding lines. They were designed for 125 or 150 µm pitch probes. The width W_l of the central strip is 100 µm. It reduces to 5 or 20 µm in the GeTe area as emphasized in Fig. 1.c (20 µm case). All devices are matched to 50 Ω. As illustrated in Fig.1.c, the influence of two parameters of the active PCM part were studied in practice, length (L) and width (W).

III. Electrical Actuation

After manufacturing, GeTe shows a crystalline phase – low resistivity – due to thermal budget of the technology, so that the first step consists in amorphizing the material.

As mentioned in the introduction, and thanks to the chosen technological stack, direct heating can be performed. A current excitation based on pulses is simply applied via the feeding line to change the phase of the PCM.

Usually, amorphization and crystallization need different excitations shapes, enabling freezing or stabilization of the atomic arrangement, respectively, [4]. In this study, we used the same waveforms for both transitions: a rise time of 5 ns followed with 50-ns duration time at high-voltage and a fall time of 5 ns. The only difference is the voltage value as the amorphization step needs higher energy. Two conditions must be considered to amorphize the device: i) melting temperature must be reached and, ii) thermal tempering must occur to freeze the material into a messy state. The latter is obtained with the short 5-ns fall time. Meanwhile crystallization step theoretically needs lower energy with a mid-temperature higher than the material crystallization one, but lower than the melting temperature to avoid parasitic amorphization. However, a second phenomenon occurs with direct actuation, i.e. a conductive filament is created if the crystallization voltage is sufficient. To comfort the operation, and after a deep optimization floorplan, it was found that two pulses must be sent to amorphize the device, and three pulses to crystallize it, respectively.

As explained above, several devices with various widths W and lengths L were designed and tested. Also, two thicknesses t of GeTe were compared, 100 nm and 300 nm, respectively. As seen in Fig. 2, for $L = 1$ µm, the necessary programming current to amorphize or crystallize the PCM evolves linearly versus W, from 300 nm to 19 µm. The electrical current evolution is also proportional to the GeTe thickness.

TABLE I
Energy Balance in Literature

Paper	Length [µm]	Width [µm]	Thickness [nm]	Area [µm²]	Volume [mm³]	Amorphization Energy [J]	Amorphization Volumic Energy [J/mm³]	Crystallization Energy [J]	Crystallization Volumic Energy [J/mm³]
El-Hinnawy *et al.* [4]	0.9	30	150		$4.0.10^{-9}$	$1.2.10^{-7}$	30	$6.0.10^{-7}$	150
Wang *et al.* [5]			100	24	$2.4.10^{-9}$	$4.5.10^{-8}$	19	$8.0.10^{-7}$	330
King *et al.* [6]	1.3	30	75		$2.9.10^{-9}$	$9.0.10^{-8}$	31	$6.0.10^{-7}$	210
This work	1	4.5	300		$1.4.10^{-9}$	$2.95.10^{-8}$	22	$2.36.10^{-8}$	17.5

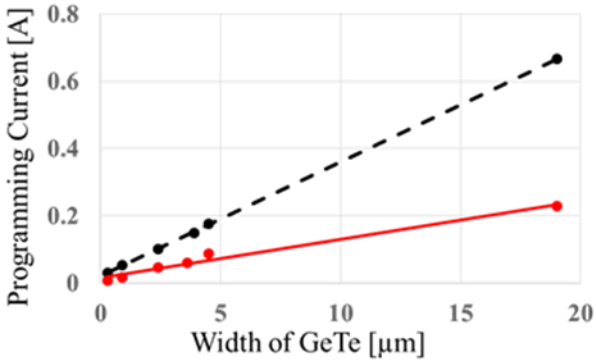

Fig. 2. Programming current for amorphization versus GeTe width *W*. GeTe thickness *t* = 100 nm (red solid line), and *t* = 300 nm (black dashed line). *L* = 1 µm.

The study of the energy consumption during switching was carried out and results compared to the state-of-the-art in table I. The switching energy was calculated as follows: power consumption (activation voltage times current of activation) multiplied by the time duration of the pulse. The comparison with the state-of-the-art is not straightforward, since sizes are somewhat different, that is why a volumic energy was considered, since the current magnitude increases linearly versus dimensions. For amorphization, the volumic energy is similar for all the devices. For crystallization, the consumption of the proposed devices is a decade lower. This very promising consumption is made possible thanks to a performing direct control.

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IV. Results

S-parameters measurements were carried out from 40 MHz to 65 GHz using RF-probes with 150-µm pitch. The measurement setup is composed of a semi-automatic probe station, and a Vector Network Analyzer ANRITSU ME7808C. A SOLT (Short, Open, Load, Thru) calibration was performed.

Fig. 3a shows the S-parameters at *ON*- and *OFF*-states when the device in Fig. 1 is crystallized, and amorphized, respectively, for different widths W and thicknesses t of GeTe. Devices could not be de-embedded, leading to a significant influence of pads and feeding lines at high frequencies above 60 GHz.

The insertion loss is constant with frequency in the *ON*-state. It ranges from -0.1 dB at 40 MHz to -0.12 dB at 65 GHz for $W = 19$ µm, $L = 1$ µm and $t = 300$ nm, and from -3.5 dB at 40 MHz to -3.6 dB at 65 GHz for $W =$ 300 nm, $L = 1$ µm and $t = 300$ nm, respectively. It is noticeable that the same *IL* is obtained for the *ON*-state whatever the couple $W = 300$ nm and $t = 300$ nm or $W = 900$ nm and $t = 100$ nm. Depending on the surface defined by W times t, *IL* varies between -0.1 dB and -3.5 dB.

Two groups of curves are obtained for the *OFF*-state, with C_{off} capacitors of 5 fF and 7 fF, respectively. The value of C_{off} is mostly given by metallic feeding lines with an important role played by the fringing electrical field, and corresponds to the two considered widths W_l , i.e. 5 and 20 µm, respectively.

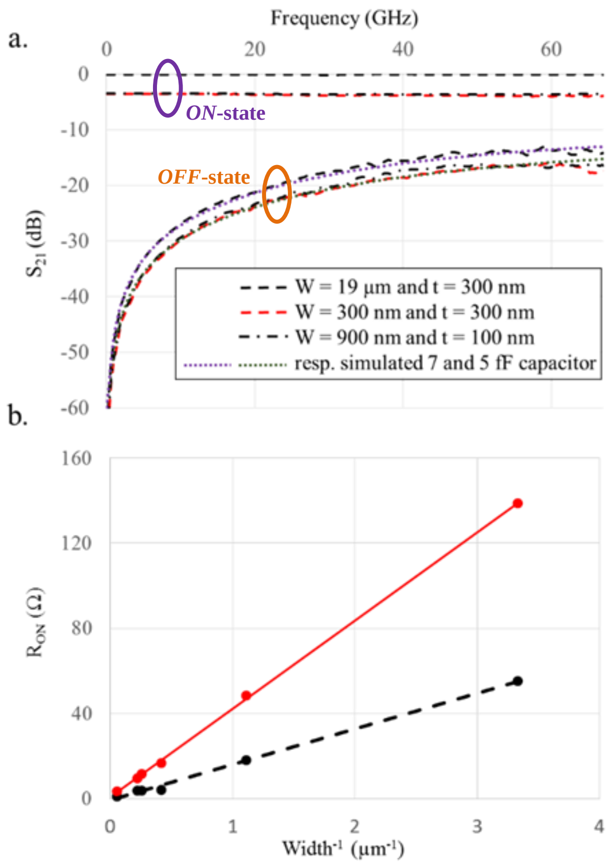

Fig 3. a) Measured S_{21} parameter for various geometries for both *ON*- and *OFF*-states. b) Evolution of R_{on} relatively to the inverse of GeTe width (red solid line for t = 100 nm and black dashed line for t=300 nm). L = 1 µm.

The R_{on} resistance is given in Fig. 3b. All the devices present a pure linear resistive behavior versus thickness and width. As direct heating is used, there is no loss added by metallic heating strip line, contrarily to indirect heating. For a 300-nm thick GeTe and a width of 19 µm, R_{on} is equal to 1 Ω (corresponding to *IL* lower than 0.1 dB up to 65 GHz, as shown above).

The cut-off frequency (F_{co}) reaches 22 THz for the best geometry ($W = 19$ µm, $L = 1$ µm and $t = 300$ nm), with $R_{on} = 1$ Ω and $C_{off} = 7$ fF.

V. Conclusion

PCM switches based on GeTe were designed, realized and tested up to 65 GHz. A geometrical study was performed to evaluate the potentialities of direct heating actuation. The stack simplicity enables to propose thicknesses as high as

300 nm, leading to state-of-the-art *ON*-state resistance, leading to a cut-off frequency as high as 22 THz. Meanwhile, direct actuation enables to reduce power consumption, with a measured volumic energy for crystallization 10 to 20 times smaller than the usual energy needed by indirect heating. It is interesting to note that with direct actuation, volumic energy for crystallization becomes similar to the one needed for amorphization. Energy consumption is not driven anymore by the long time needed for stabilizing the atomic arrangement as in the indirect heating case. Direct crystallization is assumed to be performed thanks to an efficient creation of a conductive filament.

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