Improvements in GeTe-Based Inline Phase-Change Switch Technology for RF Switching Applications

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Abstract

An inline chalcogenide phase-change radiofrequency (RF) switch using germanium telluride and driven by an integrated, electrically isolated thin-film heater for thermal actuation has been fabricated. A voltage pulse applied to the heater terminals was used to transition the phase-change material between the crystalline and amorphous states. An ON-state resistance of 0.9Ω (0.027 Ω-mm) with an OFF-state capacitance and resistance of 14.1 fF and 0.5 MΩ, respectively, were measured resulting in an RF switch cutoff frequency (Fco) of 12.5 THz and an OFF/ON resistance ratio of 10^5. The output third-order intercept point measured 68 dBm, with zero power consumption during steady-state operation, making it a non-volatile RF switch.

INTRODUCTION

Chalcogenide phase-change (PC) materials (PCMs) have been exploited for their unique optical characteristics since their discovery in the late 1960s [1]. Recently, the digital memory industry also began exploiting PCMs for their distinct phase-dependent electrical properties [2]-[4]. PCM devices are based on a vertical architecture, which offers increased memory density and improved switching speed over flash memory.

Unlike digital applications where the dominant requirement is a large DC OFF/ON ratio, RF applications require switches with a low on-resistance and a low off-capacitance. In solid-state switching devices, off-state capacitance can be improved by changing the device geometry, but only at the expense of degraded on-state resistance, and vice versa. The ultimate performance is limited by the sheet resistance of the switchable channel.

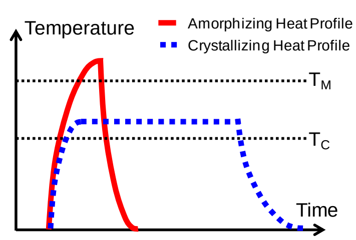

Fig. 1. Diagram showing the heat profiles used to transition to each state. Amorphizing heat profile (red solid line) is used to melt/quench the PCM and set it in the amorphous (OFF) state, whereas the crystallizing heat profile (dashed blue line) is used to crystallize the PCM and set it to the ON-state.

The sheet resistance of switchable PCM films such as germanium telluride (GeTe) can be more than an order of magnitude lower than that of state of the art FETs, allowing for a lower switch on-resistance for the same or similar device geometry. In addition to improved performance, PCM switches also possess the unique characteristic of zero prime power consumption during steady state operation, making them non-volatile switches

CHALCOGENIDE PHASE TRANSITIONS

Transitioning between the amorphous (insulating) and the crystalline (conductive) states is accomplished by heating and cooling the PCM. When the PCM is in the crystalline state, the transition to the amorphous state is achieved by heating it beyond is melting temperature (T_M), and quenching it to solidify the atoms in the amorphous state (red solid line in Fig. 1). When the PCM is in the amorphous state, the transition to the crystalline state is achieved by heating the material above its recrystallization temperature (T_C), which is the temperature at which nucleation and growth of crystalline grains is enabled (blue dashed line in Fig. 1) [3].

Digital applications accomplish phase transitions by flowing current directly through the PCM. In these switches, the PCM is sandwiched or capped with resistive metal electrodes (Fig. 2a), and a short (~ns) DC pulse is applied [2]-[4]. Joule heating from the electrical current raises the temperature of the PCM (Fig. 1). The resistance of each individual bit is relatively high (~10^3Ω in the on-state, ~10^7 Ω in the off-state [4]). This resistance is too high for an RF switch, where the large on-state resistance translates to unacceptably high insertion loss. Paralleling more phase change switches can decrease on-state resistance, but would prohibitively increase the current needed for Joule heating to the point where it becomes unsuitable for RF system applications.

An alternative approach would be to independently heat the PCM from an external source (not in the same path as the RF signal), much like the gate on a FET supplies an electric field between the source and drain, creating a 4-terminal, inline phase change switch (IPCS) [5], [6]. A cross-sectional schematic of the fabricated device is shown in Fig. 2. In order to convert the PCM to the amorphous state, a short voltage pulse was applied across the thin film

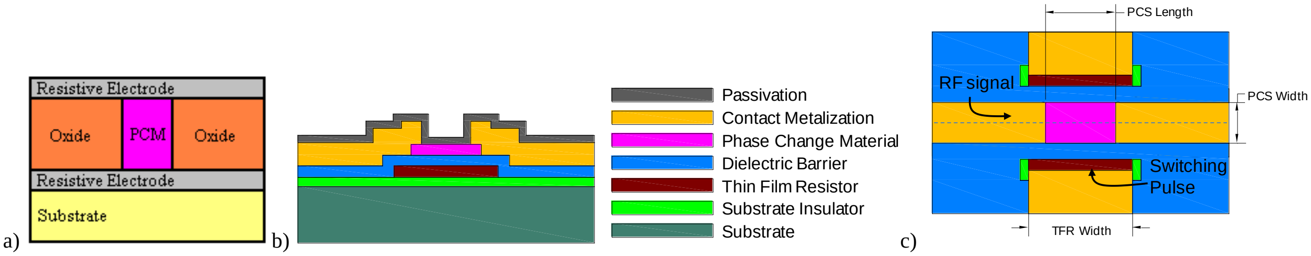

Fig. 2. (a) Cross section of the conventional vertical PCS architecture where the control current flows directly through the PCM producing one of the two heating profiles shown in Fig. 1, resulting in phase transformation. (b) Cross-sectional schematic diagram of the IPCS and its constituent layers. (c) Top-side view of the switch showing the control signal path and the RF signal trace, not showing the passivation.

resistor (TFR) terminals, causing an increase in the TFR temperature due to Joule heating. The heat from this pulse conducts from the TFR through the dielectric barrier to the proximal PCM above it, raising the temperature of the PCM above its melting point of 725°C [7] by the end of the pulse. The natural cooling that takes place at the end of the pulse (with heat being conducted into the underlying substrate and surrounding contact metallization) is rapid enough to freeze the atoms of the PCM in the amorphous state. The length of the cooling cycle is a function of the material configuration around the PCM and TFR, and was optimized prior to device fabrication using finite element thermal modeling software. In order to convert the amorphous PCM back to the crystalline state, a lower intensity pulse was applied across the heater, causing the temperature of the PCM to rise above the recrystallization temperature (~190°C) but remain below the melting temperature through the duration of the pulse.

Fabrication & Results

A cross-sectional schematic of the fabricated device is shown in Fig. 2. Fabrication began with a dielectric material (substrate insulator) being CVD or thermally grown on the surface of the substrate. In this work, both Si and SiC substrates were used, with SiO_2 as the substrate insulator. Next, a NiCrSi thin film resistor metal was patterned through lift-off techniques. A PECVD Si_3N_4 dielectric barrier material was then deposited. Contact openings in the dielectric barrier were dry etched, followed by a lift-off of the sputtered GeTe. Ti/Au ohmic contact and interconnect metallization was patterned via lift-off, followed by an additional PECVD Si_3N_4 dielectric passivation with dry etched openings for electrical probing of the device.

Using the fabrication process described above, different layouts of the IPCS switch were fabricated, with lengths ranging from 0.9µm to 2.5µm, widths ranging from 10µm to 30µm, and TFR widths ranging from 0.5um to 2.5um (Fig. 2c). Fig. 3 shows magnified views of the fabricated switch in the ON and OFF states, demonstrating the optical difference between the crystalline and amorphous states of GeTe film. Fig. 3b shows the switch in the OFF state, with a clearly defined darkened stripe down the center of the GeTe, which is orthogonal to the RF signal trace. This darkened stripe is the amorphous GeTe that prevents horizontal current flow. Once set in the amorphous (OFF) or crystalline (ON) state, the switch consumed no power, making it a non-volatile switch. The GeTe IPCS switches in this work were successfully cycled 10,000 times between the ON and OFF states before the test was terminated due to time constraints. Fig. 4 shows the measured and modeled insertion loss and isolation for the fabricated 2-port, microstrip, single-pole, single-throw switch. For a switch with PCS width of 30um, insertion loss measured better than 0.25dB up to 40 GHz. The measured isolation of 15dB at 18 GHz is attributed to the coupling of the RF signal through the heater and to the coupling through the gap capacitance. The figure of merit commonly used for RF switches is the ratio of off-impedance to on-impedance, referred to as cut-off frequency (F_{co}): $1/(2\pi \bullet R_{on} \bullet C_{off})$. The featured GeTe IPCS switch had an F_{co} of 12.5 THz, limited by the width of the heater and dielectric barrier thickness between the GeTe and heater. Fig. 5 shows power handling data for the GeTe IPCS switches. The power handling capability of the 12.5 THz switch was measured at 3.1W continuous wave RF power at 10 GHz. OFF-state breakdown voltage or threshold switching voltage of these devices has not yet been measured. These IPCS devices had a measured third-order intercept data between 55 and 68 dBm, dependent on the

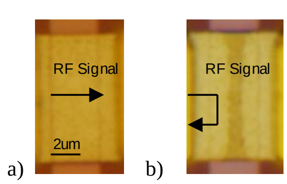

Fig. 3. Optical pictures showing a GeTe switch in the a) crystalline state and b) in the amorphous state. It is worth noting that the entire patch of GeTe did not amorphize from the pulse, only a limited area in the center. This particular switch has a PCS length of 7um and TFR width of 3um

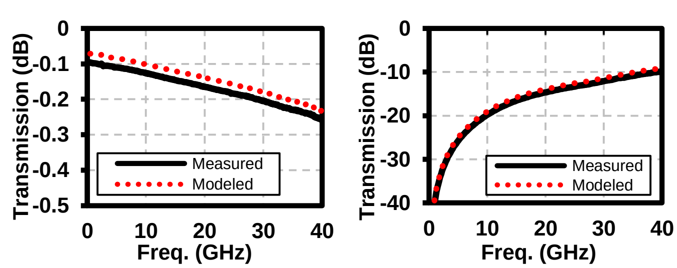

Fig. 4. Measured and modeled a) insertion loss (on-state transmission) and b) isolation (off-state transmission) for a 12.5 Thz single pole, single throw switch with 0.9um PCS length and 30um PCS width.

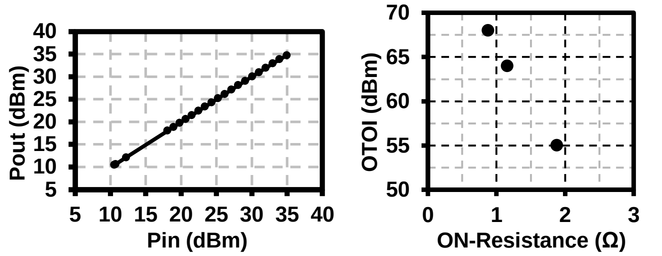

Fig. 5. a) Measured Pin vs. Pout for the 7.3 THz switch b) Measured TOI for the 3 lowest resistance switches

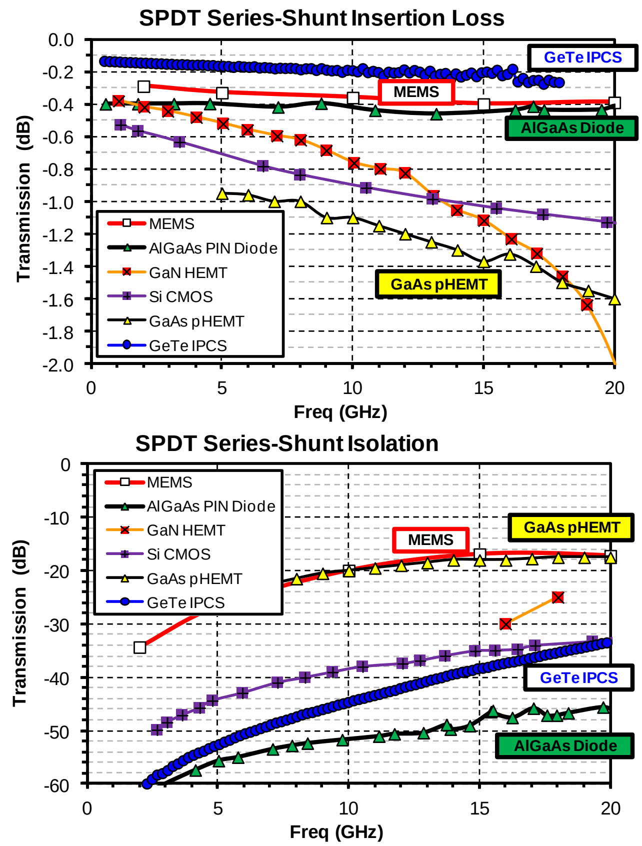

Fig. 6. Measured a) insertion loss (on-state transmission) and b) isolation (off-state transmission) for a single pole, double throw with a series-shunt configuration, with comparisons to other switch technologies

size of the device. Table I shows measured data on 4 different switch layouts. Fig. 6 shows a measured SPDT switch with a microstrip design in comparison to other switch technologies from 0-18 GHz [8]-[12]. Insertion loss less than 0.3dB and isolation better than 35dB is seen across the band.

TABLE I
RF PERFORMANCE OF GETE IPCS SWITCHES

PCS Length	PCS Width	TFR Width	R_{ON} (Ω)	C_{OFF} (fF)	F_{CO} (THz)
0.9um	10um	1.7um	3.7	7.7	5.7
0.9um	20um	1.7um	1.8	13	6.8
0.9um	30um	1.7um	1.2	18.1	7.3
0.9um	30um	0.9um	0.9	14.1	12.5

CONCLUSIONS

A 4 terminal in-line GeTe RF switch has been fabricated with an integrated, independent resistive heater. To the authors' knowledge, this is the first time a switch of this architecture has been fabricated, tested, and successfully demonstrated. Future work, already in progress, focuses on dimensional scaling, improved fabrication techniques, and alternate geometries to improve cut-off frequency beyond 30 THz.

ACKNOWLEDGEMENTS

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ACRONYMS

PC: Phase Change
PCM: Phase Change Material
GeTe: Germanium Telluride
TOI: Third Order Intercept
SPDT: Single Pole, Double Throw
IPCS: Inline Phase-Change Switch