Directly Heated Four-Terminal Phase Change Switches

Muzhi Wang[1], *and Mina Rais-Zadeh*[1,2]

[1]*Electrical Engineering Department, University of Michigan, Ann Arbor, MI 48109, USA*
[2]*Mechanical Engineering Department, University of Michigan, Ann Arbor, MI 48109, USA*

Abstract — Measured results of a four-terminal directly heated RF phase change switch are presented. Germanium telluride (GeTe) is used as the main resistance change element, connecting the RF input/output lines. The resistivity of GeTe is switched between the high-resistance amorphous-state value of several kΩ and low-resistance crystallized value of less than 3.9 Ω in less than 404 μsec using current pulses passing though GeTe. The loss of this ohmic switch at ON state is less than 0.5 dB with isolation of more than 18 dB at frequencies up to 20 GHz, indicating a cutoff frequency of > 4 THz. The switch active area is less than 5 μm × 20 μm with GeTe volume of only 1.5 μm × 15 μm × 0.25 μm. The results presented in this paper prove phase change switches are competitive contenders as low-loss and fast RF power switches.

Index Terms — Chalcogenide, germanium telluride, insertion loss, phase change materials, RF switch.

I. INTRODUCTION

Phase change or resistance change materials, such as GeTe, exhibit two distinct resistivity values, different by several orders of magnitude, when they transition between the crystalline and amorphous states [1]. Advances in micro- and nano-fabrication technology have made it possible to integrate phase change materials into digital non-volatile memory cells [2], and more recently in RF switches [3]-[5]. Compared to switches using other solid-state or MEMS technologies, phase change switches (*a.k.a*. vias) offer smaller loss for a similar switch size with competitive linearity and power handling capability [3], [4]. Recent research also demonstrated phase change switches with incredibly high power handling capability and good linearity [4], making them a strong candidate for high-power RF applications.

The basic principle of operation for phase change switches is the thermal transition of the phase change layer between crystalline (low-resistance) and amorphous (high-resistance) states. When used as RF switches, the transition between these two states is typically achieved using either of the two Joule heating methods: direct or indirect heating, both with the application of current (or voltage) pulses. In the direct heating approach, the current is drawn through the phase change via itself, whereas in the indirect heating scheme, heater line is placed adjacent to the switch and is electrically isolated from the RF path but thermally coupled to the GeTe via. Using either of these methods, the linearity and power handling of the switch is dictated by the variation in the electrical and thermal properties of GeTe with temperature change, induced by high-power RF signals [6]. In other words, high-power RF signals can derive undesired distortion or even complete phase transition by Joule heating the phase change layer. Additionally, high voltage drop across the phase change layer can result in a change in its electrical resistivity because of the Poole-Frenkel effect, further reducing the switch linearity [6].

The main challenge with designing phase change switches is to achieve good power handling and low power consumption at the same time. For example, the switch in [4] requires several watts of power to achieve state transition in each switching cycle but has good power handling capability. Directly heated switches in which current pulses are applied through the RF path can be low power but may suffer from low power handling and early non-linearity [6]. Recently, we presented a new directly heated four-terminal switch architecture consisting of two RF ports (input and output) and a separate path for the heater, allowing the bias current to go through the GeTe layer to obtain the desired temperature [7]. This design offers higher power handling capability with significantly lower power consumption compared to indirectly heated switches [4], [7]. Since our work presented in [7], we have made a number of modifications to the switch layout aiming for lower loss at the ON state, while maintaining low power consumption and good power handling performance. Here, we present our latest results on these directly heated four-terminal GeTe switches.

II. DEVICE STRUCTURE & FABRICATION

A. Device Structure

Fig. 1 shows a 3D view of the switch structure. It consists of a GeTe layer, connecting the four terminals of the switch: two RF electrodes and two heater electrodes, forming two perpendicular electrical paths. More specifically, on the bottom and top are the two titanium nitride (TiN) heater electrodes, vertically connected through a 250 nm thick GeTe layer in the center. The two RF electrodes, separated by 0.6

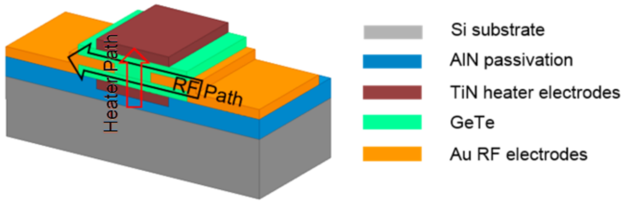


Fig. 1. 3D view of the four-terminal directly heated GeTe switch.

µm, are laterally connected through the GeTe layer. From this figure, it can be directly inferred that the RF power required to transition the via is high as the separation between the two RF electrodes is relatively large.

B. *Fabrication Process*

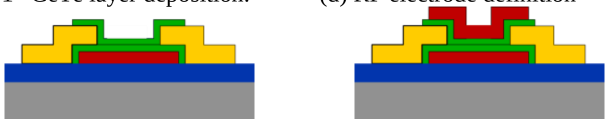
The fabrication process starts with the deposition of a 1 µm thick aluminum nitride (AlN) passivation layer on a silicon substrate (Fig. 2). AlN is chosen because of its high thermal conductivity and low loss tangent at GHz frequencies. The TiN bottom heater layer is then deposited and patterned. Next, the first GeTe layer with a thickness of 125 nm is sputtered and patterned. A 0.5 µm thick gold (Au) layer is deposited with thin Ti layers on both sides as diffusion barriers. The Au layer defines the RF electrodes and is also deposited on the DC heater feed-line. Then, the second 125 nm thick GeTe layer is deposited and patterned. After each GeTe deposition, a brief oven baking at 250 °C is performed to crystallize GeTe. Finally, the top heater layer is deposited and patterned.

(a) Deposit 1 µm thick AlN layer on a silicon substrate.

(b) Deposit & pattern the bottom heater layer.

(c) 1^{st} GeTe layer deposition.

(d) RF electrode definition

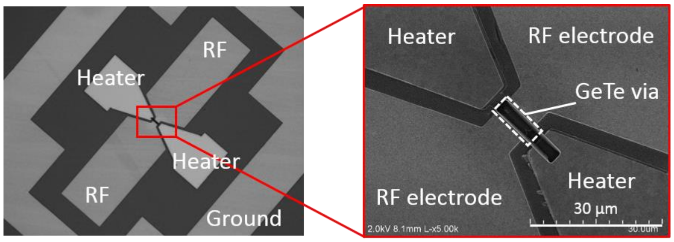


(e) 2^{nd} GeTe layer deposition.

(f) Top heater layer definition.

Fig. 2. Fabrication process flow of phase change RF switches.

Fig. 3 shows scanning electron microscope (SEM) images of a fabricated phase change switch. In different designs, the width of the RF electrodes varies from 4 µm to 12 µm, and the spacing between the electrodes varies from 0.6 µm to 1 µm.



(a)

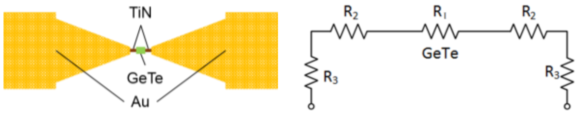
(b)

Fig. 3. Top view SEM images of a fabricated phase change switch. (a) The complete device, including the core GeTe via, the four terminals, and the ground ring; (b) the zoomed-in view of the center active area.

The specific device shown in Fig. 3 has an RF connection width of 12 µm and a spacing of 0.6 µm. The heater layers are vertically connected through the GeTe via and the overlap between the top and bottom heater layers is approximately 13 µm × 5 µm, with a slight variation among different designs. The two RF signal pads together with the ground ring form two co-planar transmission lines with a characteristic impedance of 50 Ω, matching the termination impedance. The central part of the heater path is made out of TiN, but the heater feed-lines are covered with gold to ensure that the resistance along the heater path concentrates in the center GeTe area to effectively heat GeTe volume and obtain reliable phase transition with minimum power consumption.

C. *Heater Design*

Fig. 4 shows the layout and equivalent DC circuit model of the heater layer path. In Fig. 4(b), resistor R_I represents the vertical resistance of GeTe, which varies between the crystalline (ON) and amorphous (OFF) states. Resistors R_2 represent the TiN sections of the heater path, and R_3 is the resistance of each DC pad covered with Au. From modeling and simulation, the value of R_I (GeTe resistance) is smaller than 5 Ω at the crystalline state and is above 5 kΩ at amorphous state. R_3 is within 5 Ω as gold is a good conductor. R_2 is > 0.5 kΩ. Therefore, when GeTe is at crystalline state, the resistance along the heater path is concentrated at the TiN sections, ensuring that the generated heat is only used to phase transition GeTe. When GeTe is at the amorphous state, R_I becomes the dominant resistance, and the resistance of TiN (R_2) serves as protection for GeTe, so that once GeTe is back to the crystalline state, most power is dissipated in the TiN sections and GeTe is not instantly heated back to the amorphous state.



(a)

(b)

Fig. 4. (a) Layout of the heater path and materials in different sections. (b) Modeled equivalent circuit for the heater path.

To verify the required bias for Joule heating of GeTe, thermal simulations are performed using COMSOL multi-physics simulation tool. To convert GeTe from crystalline to amorphous state, the Joule heating temperature should rise above the GeTe melting point. Heat dissipation to the substrate need to be rapid enough to freeze the atoms in the amorphous state for the transition to be successful; thus, GeTe should have good thermal coupling to the substrate. In order to transition the phase change via from the amorphous state back to the crystalline state, lower power needs to be applied. The temperature must rise above the crystallization temperature of approximately 190 °C, while remaining below the melting temperature. The switch should cool down gradually by slow removal of the voltage to convert the via back to the crystalline state. In COMSOL simulations, a voltage pulse with an amplitude of 7 V is applied to the heater path. After 2 µs, the temperature response is shown in Fig. 5. It can be seen that the amorphization temperature is reached.

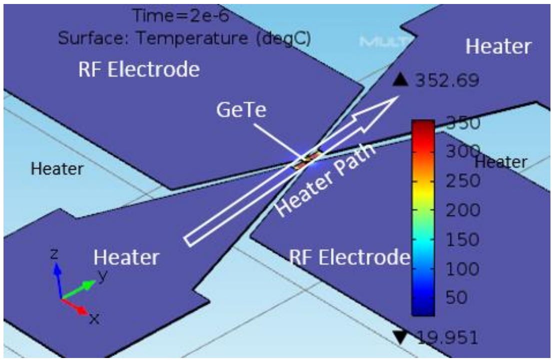
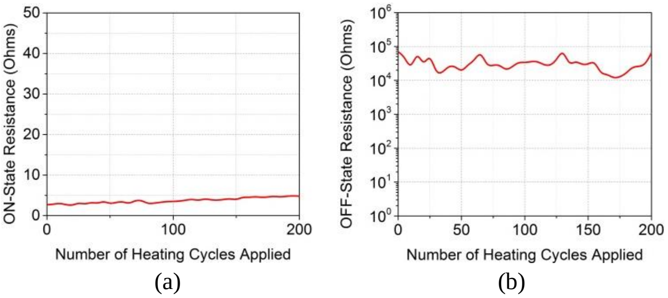


Fig. 5. COMSOL simulation for Joule heating condition. In the simulation, a voltage pulse with an amplitude of 7 V is applied for a duration of 2 μs, the maximum temperature at the GeTe volume reaches 310 °C, which meets the heating requirements.

III. MEASUREMENT RESULTS

A. DC Measurements

DC measurements to verify the biasing condition of the heater are performed using DC probes and Agilent 34410A Digital Multi-Meter. Joule heating currents are generated using a voltage function generator. The initial (ON state) DC resistance of GeTe along the RF path, after de-embedding the resistance of the probes and feed-lines, is about 3.9 Ω. After applying a heating voltage pulse through the heater layer path with an amplitude of ~8.5 V and pulse width of 2 μs, GeTe is transitioned to amorphous state with resistance value ranging from 8 kΩ to 100 kΩ. By applying a heating voltage pulse with an amplitude of about 9 V and with a longer falling edge of ~ 400 μs, GeTe is transitioned back to the crystalline state (ON state). The required heating power for amorphization and crystallization is ~ 73 mW and 9 mW, respectively. Transitions between the two states have been performed repeatedly. The ON-state and OFF-state resistance values of a GeTe switch are shown in Fig. 6.



(a) (b)

Fig. 6. DC resistance values versus the number of heating cycles at (a) the crystalline state and (b) the amorphous state.

B. RF Modeling and Measurements

Fig. 7 shows the equivalent circuit model of the phase change switch [7]. Along the heater path, the core GeTe layer is modeled as a capacitance C_I in parallel with the resistance R_I. Along the RF path, several parallel paths exist: Path 1 connects the two RF lines through GeTe laterally (R_{I3}); Paths 2 and 3 are due to the overlap of RF signal line with the heater line through vertical GeTe resistance (R_{I2}). Here R_H models the lateral resistance of the heater line. The parallel resistance of these three paths switches between R_{ON} at crystalline state to R_{OFF} at amorphous state. Along the RF path from Port 1 to Port 2, there is also a feed-through capacitance, modeling the lateral capacitance of GeTe (C_{I2}). Lumped elements R_S, L_S, and C_P model the parasitics of the contact pads and RF transmission lines [7].

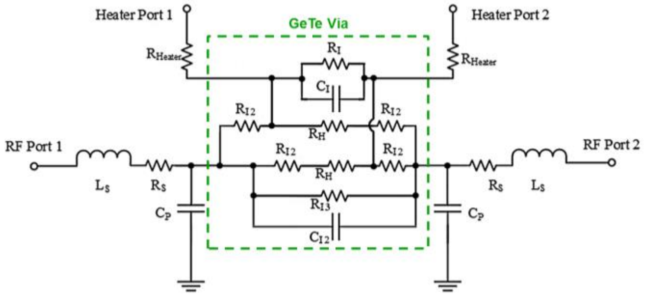
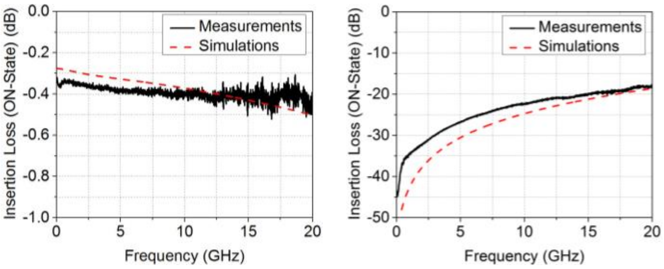


Fig. 7. Electrical model of the directly heated phase change switch with separate heater path (note the model is modified from [7]).

RF measurements are performed using Cascade ACP Ground-Signal-Ground (GSG) probes and an Agilent N5242A PNA-X. The on-wafer measurement and the ANSYS HFSS electromagnetics simulation results are shown in Fig. 8. The ohmic loss of probes and signal lines are de-embedded from measured data. In simulations, the conductivity of GeTe in the crystalline state is taken as 5×10^4 S/m, while its amorphous state conductivity is taken as 1 S/m. The discrepancy between measurements and simulations are mostly due to a lower OFF/ON resistance ratio achieved in this fabrication run.



(a) (b)

Fig. 8. Measured and simulated results of the phase change switch at the (a) ON state (insertion loss) and (b) OFF state (isolation).

C. Isolation Between Heater and RF Paths

The transmission between the heater port and RF port at the ON state has been measured to verify that the two paths are reasonably isolated from each other (R_{I2} + R_{Heater} in Fig. 7). Fig. 9 shows that the isolation from one RF port to a heater port is above 18 dB at frequencies up to 20 GHz as the heater path has a high DC resistance in the kΩ range. To improve the isolation, a choke could be placed along the heater path. Simulation results showing the effect a 1 μH in improving the heater/RF isolation is also shown in Fig. 9.

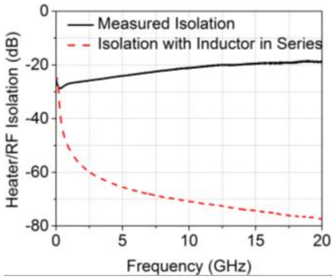
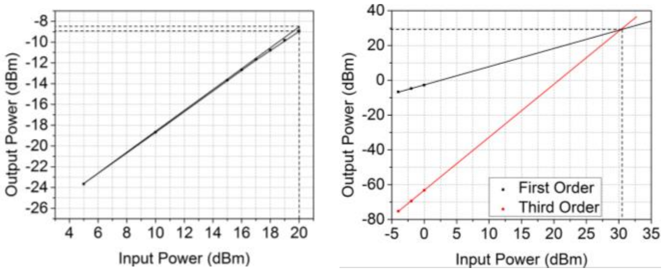


Fig. 9. Solid line shows measured isolation between one RF electrode and one heater electrode of the GeTe switch at the ON state. Dashed line shows the isolation if a 1 µH choke is used along the heater path.

D. *Power Handling Measurements*

It was analyzed in [6] that the power handling of phase change switches with a structure in which the heater affects a larger portion of the GeTe volume is higher than switches where the RF path completely sandwiches the phase change layer. From this analysis, it is expected that the power handling, 1dB compression point (P_{1dB}), and third-order input intercept point (IIP_3) performance of the presented switches outperform the performance of conventional directly heated vias, such as those in [3]. The P_{1dB} and IIP_3 of the switch are measured at both states to verify the power handling. The worst case P_{1dB} is verified to be above 20 dBm (the maximum input power is tool limited). The ON-state IIP_3 is measured to be 30.5 dBm at 2 GHz with frequency offset of 50 kHz. OFF-state IIP_3 value is also > 30 dBm. Fig. 10 shows the results of P_{1dB} and IIP_3 measurements. As expected, the IIP_3 of this switch is in fact higher than conventional directly heated switches in which the RF input/output sandwich the phase change layer [3].



(a) (b)

Fig. 10. (a) P_{1dB} measured at OFF-state at 2 GHz; (b) IIP_3 measured at ON-state at 2 GHz with a frequency offset of 50 kHz.

A summary of the measurement results is listed in Table I. As shown, the presented phase change switch offers low loss, high isolation, and lower power for phase transition compared to other reported phase change switches [4], [7].

IV. CONCLUSION

A directly heated four-terminal RF switch using GeTe phase change chalcogenide material has been designed, fabricated, and measured. The ON-state insertion loss of the switch is measured to be less than 0.5 dB and the off-state isolation is above 18 dB at frequencies up to 20 GHz, indicating a switch cutoff frequency of > 4 THz. The total power consumption in one switching cycle is about 82 mW, dominated by the power required for amorphization and is impressively smaller than indirectly heated switches by more than an order of magnitude [4]. The P_{1dB} is measured to be much more than 20 dBm, and the IIP_3 is higher than 30 dBm. Future work will be focused on optimization of the fabrication process to achieve better OFF/ON resistance ratio and switch repeatability.

TABLE I
SUMMARY OF MEASUREMENT RESULTS

	[4]	[7]	This work
ON-state DC resistance	1.2 Ω	5 Ω	3.9 Ω
OFF/ON resistance ratio	9.2×10^4	0.96×10^4	$> 0.2\times10^4$
Insertion loss at 20 GHz	< 0.3 dB	< 0.6 dB	< 0.5 dB
Isolation at 20 GHz	12 dB	20 dB	> 18 dB
Cut-off Frequency	7.3 THz	3.7 THz	~ 4 THz
Switching time per 1 cycle	–	600.5 µs	404 µs
Power consumption per cycle	4.5 W	92 mW	82 mW
P_{1dB}	> 35 dBm	>20 dBm	> 20 dBm
IIP_3	–	33 dBm	> 30 dBm

V. ACKNOWLEDGMENT

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