A Low-Loss Directly Heated Two-Port RF Phase Change Switch

Muzhi Wang, Yonghyun Shim, and Mina Rais-Zadeh

Abstract—In this letter, we report on the design, fabrication, and measured results of a directly heated phase change RF switch (or via) using germanium telluride in a four-terminal configuration. The switch is heated using a separate heater path combining the advantages of directly heated vias, such as low power dissipation for phase transition, and indirectly heated vias, such as high power handling capability. The phase change switch shows an insertion loss of less than 0.6 dB and an isolation of higher than 20 dB at frequencies up to 20 GHz, indicating a cutoff frequency of more than 3.7 THz. The switch area is only $4 \mu m \times 6 \mu m$, which is smaller than RF MEMS switches with similar insertion loss performance. To the best of our knowledge, this is the first report on a four-terminal, directly heated, RF phase change switch.

Index Terms—Germanium telluride, input third-order intercept, insertion loss, phase change, RF switch.

I. INTRODUCTION

PHASE change (PC) materials refer to a class of resistive materials capable of transitioning between crystalline and amorphous states showing a significant resistivity change. The properties of phase change materials have been studied for decades [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 [6], PC switches (a.k.a. vias) offer smaller loss for a similar switch size with competitive linearity and power handling capability [3], [4].

The PC layer can be thermally transitioned between crystalline (low resistance) and amorphous (high resistance) states. The transition between these two states can be achieved using different heating methods: direct and indirect heating, both with the application of current (or voltage) pulses. In the direct heating approach, the current is drawn through the PC via itself. The challenge with existing direct heating structures, specifically for RF applications, is that the DC and RF thermal path are not isolated and therefore, the heater cannot be designed independently. For the heater, high electrical resistance is needed, whereas for the RF path the electrical and contact resistance should be as low as possible. In the indirect heating scheme, a separate conductive path is used for the heater. The heater line is placed adjacent to the switch [4]. Indirect heating schemes have several issues: 1) higher power is required to phase transition the PC layer; 2) the RF connection to the PC layer is a local cold spot, resulting in an increased ON resistance. Running higher current through the heater to increase the temperature at the RF/PC layer contact increases the power consumption and may reduce reliability.

To address these issues, we present a new two-port switch architecture: a multilayer switching element which has a separate path for the heater but is directly heated, allowing the bias current to go through the PC layer to get the desired temperature (Fig. 1). This design offers higher power handling capability with low ON resistance but requires fine lithography and alignment between layers. Among phase change materials, germanium telluride (Ge$_{50}$Te$_{50}$ or GeTe) has the advantages of fast switching time and high OFF/ON resistivity ratio and is the PC material used in this letter. This configuration of the PC switch is the first reported design of its kind using direct heating method.

II. DEVICE STRUCTURE AND FABRICATION

A. Device Structure

Fig. 1 shows a cross-sectional view of the structure. The switch consists of a GeTe connection via, connecting four terminals, 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 100 nm thick GeTe layer in the center. The two gold (Au) RF electrodes, covered with titanium (Ti) top and bottom diffusion barriers, are laterally connected through a few microns wide GeTe layer. From this figure, it can be directly inferred that the RF power required to transition the via is high due to the large separation between the two RF electrodes, resulting in
The fabrication process of the PC switch starts with the deposition of an aluminum nitride (AlN) passivation layer on a silicon substrate. A TiN layer is sputtered as the bottom heater layer. Next, the first GeTe layer of 50 nm thickness is sputtered. The gold RF electrodes are then deposited with a thin Ti layer on both sides as the diffusion barriers. Then the second 50 nm thick GeTe layer is deposited. After each GeTe deposition, an oven baking at 220 °C is performed for 15 minutes to initially crystallize the GeTe. Finally, the TiN top heater layer is deposited and patterned. Fig. 2 shows scanning electron microscope (SEM) images of a fabricated device.

III. SIMULATIONS AND MEASUREMENTS

A. Heating Simulations

Thermal simulations are performed using COMSOL finite element tool to analyze the joule heating profile. The thermal profile of directly heated PC switches is compared to that using indirect heating method. The size of the indirectly heated switch is the same as the directly heated one shown in Fig. 3. However, for the indirectly heated switch, the heater path is electrically isolated (but thermally coupled) to the GeTe layer by a thin (300 nm) layer of AlN. As shown in Fig. 3, using the indirect heating method, most heat generated by the heater is dissipated isotropically and the contact between the RF and GeTe layers is at a much lower temperature than the heater temperature (local cold spot). This results in low power efficiency as well as incomplete state transitions for the GeTe via. The direct heating method, on the other hand, allows current to flow through the via, uniformly heating the entire PC volume. Not only will this improve the power efficiency, but also complete phase transition of GeTe is ensured, resulting in lower ON resistance. For this reason, direct heating scheme is chosen in this letter.

B. Measurement Result

The equivalent circuit model of the directly heated two-port GeTe switches is shown in Fig. 4. Along the heater path (the vertical direction), the core GeTe layer is modeled as a capacitance CΙ in parallel with the resistance RΙ, which has an ON-state and an OFF-state resistance value (RONH and ROFFH). Meanwhile, along the RF path (the lateral direction), the GeTe resistance is modeled as a series connection of RΙ with resistances R12, giving the total RF switch resistance of R1 + 2 × R12. This total resistance switches between RON at crystalline state to ROFF at amorphous state. Along the RF path from Port 1 to Port 2, there are also series lumped elements R5 and L5 and parallel capacitors C5, modeling the parasitics of the contact pads and RF transmission lines.

The heating condition is verified by measuring the DC resistance of the switch between the RF probes upon application of DC pulses to the heater electrodes. The initial resistance of the switch is low as the GeTe is in the crystalline state post-fabrication. After applying a heating current-pulse with an amplitude of 5.5 mA, rise and fall time of 20 ns, and a pulse width of 0.5 μs, GeTe is transitioned to the amorphous state (OFF-state). By applying heating current with an amplitude of 200 μA, rise time of 0.5 μs, duration of 200 μs, and a longer falling edge of 400 μsec, the GeTe is transitioned back to the crystalline state (ON-state). The required heating power for amorphization and crystallization is 90 mW and 2 mW, respectively.

RF measurements are performed using Cascade ACP Ground-Signal-Ground (GSG) probes and an Agilent N5242 PNA-X at high frequency (10 MHz–20 GHz). The RF performance of the switch from on-wafer measurements along with the HFSS simulation and the modeling results are shown in Fig. 5.

The ohmic loss of probes and signal lines are de-embedded from S21 transmission at ON-state. The value of the parameters in the equivalent electrical model are fitted to be ROFF = R1 + 2 × R12 = 48.2 kΩ and COFF ≈ C12 = 8.5 fF at the off state and RON = 5.0 Ω at the ON-state. RHEATER is approximately 1 kΩ. R5, L5 and C5 are 0.12 Ω, 53 pH and 20 fF.
Fig. 5. Measured and simulated results of the phase change switch at the (a) ON-state (insertion loss) and (b) OFF-state (isolation).

Fig. 6. (a) $P_{1\text{dB}}$ measured at OFF-state at 2 GHz; (b) $I\text{IP}_3$ measured at ON-state at 2 GHz with a frequency offset of 50 kHz.

TABLE I
SUMMARY OF MEASUREMENT RESULTS

<table>
<thead>
<tr>
<th>Performance Aspect</th>
<th>Direct Heating This work</th>
<th>Indirect Heating [4]</th>
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<tbody>
<tr>
<td>Area of PC via</td>
<td>24 $\mu$m$^2$</td>
<td>27 $\mu$m$^2$</td>
</tr>
<tr>
<td>ON-State Resistance ($R_{\text{ON}}$)</td>
<td>5.9 $\Omega$</td>
<td>1.2 $\Omega$</td>
</tr>
<tr>
<td>OFF-State Resistance ($R_{\text{OFF}}$)</td>
<td>48.2 $k\Omega$</td>
<td>110 $k\Omega$</td>
</tr>
<tr>
<td>OFF/ON Resistance Ratio</td>
<td>9.96 $\times$10$^6$</td>
<td>9.2 $\times$10$^6$</td>
</tr>
<tr>
<td>ON-State Insertion Loss (@20 GHz)</td>
<td>&lt;0.6 dB</td>
<td>&lt;0.3 dB</td>
</tr>
<tr>
<td>OFF-State Isolation (@20 GHz)</td>
<td>20 dB</td>
<td>12 dB</td>
</tr>
<tr>
<td>Via Capacitance ($C_{\text{via}}$)</td>
<td>8.5 fF</td>
<td>18.1 fF</td>
</tr>
<tr>
<td>Cutoff Frequency ($f_{\text{CO}}$)</td>
<td>3.7 THz</td>
<td>7.3 THz</td>
</tr>
<tr>
<td>$I\text{IP}_3$ (@ 2 GHz, 50 kHz freq. offset)</td>
<td>33 dBm</td>
<td>NA</td>
</tr>
<tr>
<td>Max heater power</td>
<td>92 mW</td>
<td>4.5 W</td>
</tr>
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</table>

respectively. Therefore, the cutoff frequency ($f_{\text{CO}}$) defined as $1/(2\pi \times R_{\text{ON}} \times C_{\text{OFF}})$ is approximately 3.7 THz. The discrepancy between HFSS results and measured data is mainly due to higher ON-conductivity of $4.7 \times 10^4$ S/m assumed in simulations compared to conductivity of $3.3 \times 10^5$ S/m extracted for GeTe in this fabrication run.

The $P_{1\text{dB}}$ and $I\text{IP}_3$ of the switch are measured at both states to verify its linearity and power handling capability. The $P_{1\text{dB}}$ is verified to be above 20 dBm (the maximum input power is tool limited). The ON-state $I\text{IP}_3$ is measured to be 33 dBm at 2 GHz with frequency offset of 50 kHz. OFF-state $I\text{IP}_3$ value is also >30 dBm. Fig. 6 shows the $P_{1\text{dB}}$ and $I\text{IP}_3$ measurement results. The switch $I\text{IP}_3$ is much higher at larger frequency offsets [7]. The performance of the presented PC switch with direct heating scheme is comparable to the best reported indirectly heated two-port GeTe switch [4]. A summary of the performance comparison is listed in Table I. As evident from Table I, directly heated PC switches consume much smaller power in each switching cycle, while offering competitive RF performance.

IV. CONCLUSION

A directly heated two-port RF switch using GeTe phase change material has been designed, fabricated, and measured. This phase change switch design with an RF signal path and a separate direct heater path enables separate handling of heater bias condition and RF signal transmission. A new equivalent circuit model is proposed for such directly heated switches. The ON-state insertion loss of the switch is measured to be less than 0.6 dB and the off-state isolation is above 20 $\text{dB}$ at frequencies up to 20 GHz, indicating a switch cutoff frequency of more than 3.7 THz. The total power consumption in one switching cycle of $\sim 600.5 \mu$s is about 92 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 $P_{1\text{dB}}$ is measured to be much more than 20 dBm, and the $I\text{IP}_3$ is higher than 30 dBm. This is a novel implementation of the directly heated phase change switch and is proved to have a competitive performance [3], [4]. Future research will be focused on improving the OFF/ON resistance ratio by optimizing the fabrication process and material selection in the stack. The switch cutoff frequency can be improved by substrate micromachining techniques, such as those demonstrated in [8].

REFERENCES