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

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Introduction: 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 (F_{co}) 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 nonvolatile RF switch. To the best of our knowledge, this is the first reported implementation of an RF phase change switch in a four-terminal, inline configuration.

Problem: Unlike digital applications where the dominant requirement is a large dc OFF/ON ratio, radio-frequency (RF) applications require switches with a low ON-resistance and 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. 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 nonvolatile switches.

Digital Approach: 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]-[8]. 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 [5]). 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.

New RF Approach: 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) [14]. 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 resistor terminals, creating a short but intense heat pulse. The heat profile is designed to increase the temperature of the PCM above its melting point (725°C [10]), while allowing the heat to be removed sufficiently fast to quench it in the amorphous state. To convert the amorphous PCM back to the crystalline state, a longer pulse with lower voltage is applied to the heater which sustains a temperature between the recrystallization temperature and the melting temperature.

Results: 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. Switching between the two states was achieved with electrical pulse powers ranging from 0.5W to 4W, and pulse widths ranging from 30ns to 1.5µs. 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 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 coplanar waveguide (CPW) 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 CPW 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 (Fco): 1/(2π•Ron•Coff). The featured GeTe IPCS switch had an Fco 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, or 104.7 W/mm when normalized for periphery. 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 size of the device. Table I shows measured data on 3 different switch layouts. Fig. 6 shows measured SPDT switch with a microstrip design in comparison to other switch technologies from 0-18 GHz. Insertion loss less than 0.3dB and Isolation better than 35dB is seen across the band.

Conclusion: 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.

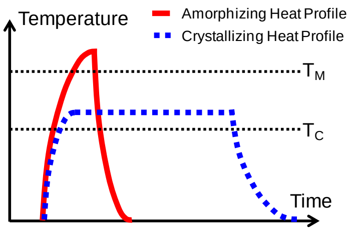


Fig. 1. Diagram showing the heat profiles used to transition to each state. Amorphizing heat profile (red solid line) is used to melt/quench the PCM and set it in the amorphous (OFF) state, whereas the crystallizing heat profile (dashed blue line) is used to crystallize the PCM and set it to the ON-state.

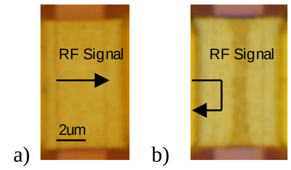


Fig. 3. Optical pictures showing a GeTe switch in the a) crystalline state and b) in the amorphous state. It is worth noting that the entire patch of GeTe did not amorphize from the pulse, only a limited area in the center. This particular switch has a PCS length of 7um and TFR width of 3um

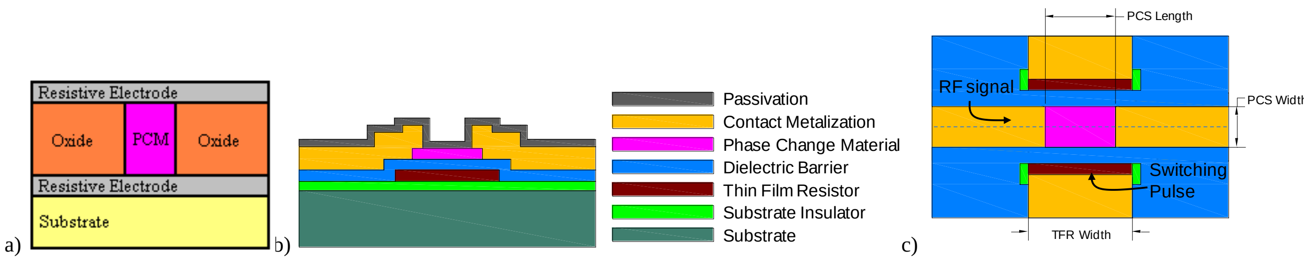
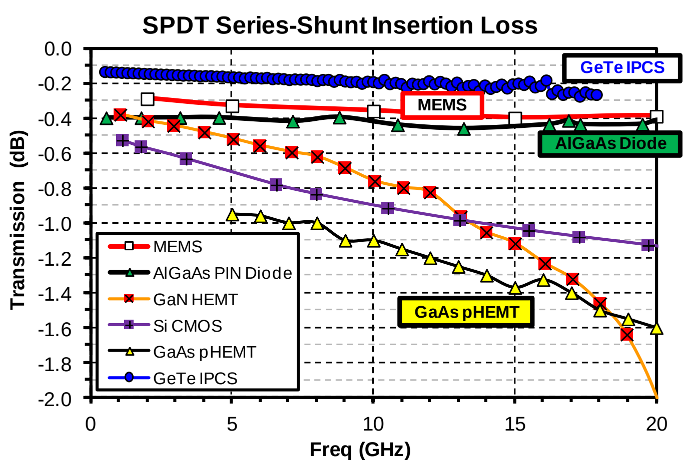
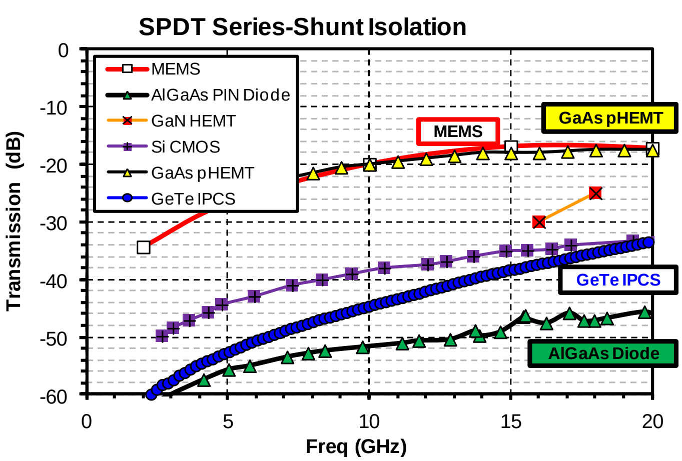


Fig. 2. (a) Cross section of the conventional vertical PCS architecture where the control current flows directly through the PCM producing one of the two heating profiles shown in Fig. 1, resulting in phase transformation. (b) Cross-sectional schematic diagram of the IPCS and its constituent layers.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





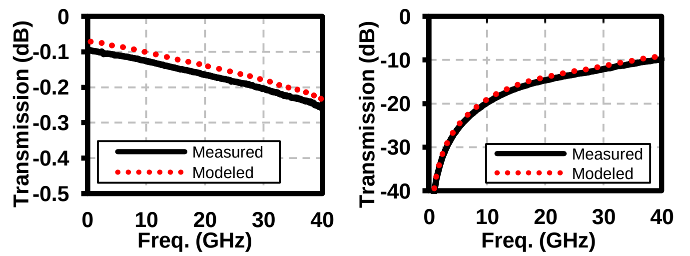
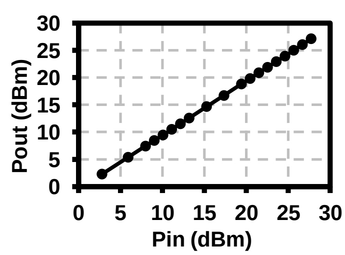


Fig. 4. Measured and modeled a) insertion loss (on-state transmission) and b) isolation (off-state transmission) for a single pole, single throw switch with 0.9um PCS length and 30um PCS width.



a)

b)

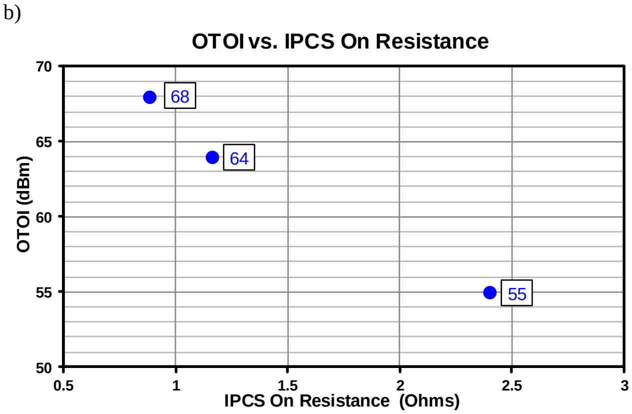


Fig. 5. a) Measured Pin vs. Pout for the 1.0 THz Fco switch at 10 GHz, showing 104.7W/mm of CW power handling. b) Measured OTOI showing better than 68 dBm.