Scalable Non-Volatile Chalcogenide Phase Change GeTe-Based Monolithically Integrated mmWave Crossbar Switch Matrix

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Abstract — This paper reports a novel millimeter-wave (mmWave) non-volatile chalcogenide phase change material (PCM) germanium telluride (GeTe) based scalable crossbar switch matrix. The proposed 2×2 crossbar switch matrix configuration is designed using PCM single-pole double-throw (SP2T) switches monolithically integrated with a scalable crossbar unit-cell. The presented switch matrix utilizes a maximum of only two series PCM switches in any possible signal route, minimizing the insertion loss. The non-volatile PCM switches consume no static dc power. The proposed switch matrix is fabricated in-house using an eight-layer custom micro-fabrication process. The 2×2 switch matrix is ultra-compact with the device area under 0.1 mm². Over dc to 40 GHz, the fully integrated 2×2 switch matrix exhibits a measured insertion loss less than 1.35 dB, a return loss better than 20 dB, and an isolation higher than 24 dB. The integrated PCM switches utilized in this matrix offer up to +35.5 dBm CW RF power handling and better than +41 dBm of linearity. The RF PCM switches are experimentally tested for more than 1 million reliable switch actuation cycles.

Keywords — Crossbar switch matrix, Germanium telluride (GeTe), mmWave circuits, Phase change material (PCM), Scalable PCM switch matrices, RF switch

I. INTRODUCTION

Radio frequency (RF) switches and switch matrices have tremendous applications in telecommunication, radar systems and instrumentation for providing efficient signal routing, effective bandwidth utilization and for enhancing system redundancy [1], [2]. Conventional switching networks use semiconductor or mechanical RF switches as the basic building blocks. The most commonly used coaxial mechanical switches despite of their excellent performance, are bulky and expensive [3]. While semiconductor-based switch technologies such as CMOS, GaAs, SiGe, and SOI offer devices with compact footprints and low-cost integration with other front-end modules, but they exhibit poor RF performance including very limited power handling and low linearity [4], [5]. In the last few years, microelectromechanical systems (MEMS)-based RF switches have demonstrated promising RF performance [6]–[8], but due to the mechanically moving micro-membranes, these devices suffer from contact degradation over time, require high operational voltage, and have reliability and packaging concerns [9]. More recently, RF MEMS switches with improved reliability have become commercially available by only up to 18 GHz.

The emerging chalcogenide phase change material (PCM) germanium telluride (GeTe)-based technology offers the flexibility to reduce the device area by dense integration of switching unit-cells. One of the key features of this technology is its non-volatile functionality, that does not require constant dc power to hold the switch state [10]–[18]. Recently, we have reported various reconfigurable phase change based mmWave components [19]–[24]. This paper presents the first demonstration of an ultra-compact PCM GeTe-based scalable non-volatile crossbar switch matrix. The presented mmWave switch matrix is developed in-house utilizing an optimized custom microfabrication process and monolithically integrated with multi-port RF switches and unit-cells as routing elements. A 2×2 crossbar switch matrix is presented exhibiting impeccable RF performance over dc to 40 GHz.

II. SCALABLE CROSSBAR SWITCH MATRIX

The scalable crossbar switch matrix architecture shown in Fig. 1, consists of an array of switch unit-cells labeled (SUx,y) and single-pole double-throw (SP2T) switches labeled (SDx,y). The switch units are arranged in a grid pattern to
achieve the designed signal routing states. The RF signal at any \( m \) input (RF\(_{i1}, \) RF\(_{i2}, \cdots, \) RF\(_{im}, \) RF\(_{in}\)) can be routed to any available \( n \) output port (RF\(_{o1}, \) RF\(_{o2}, \cdots, \) RF\(_{on1}, \) RF\(_{on}\)). Cross-over paths designed in switch unit-cells offer signal routing between two overlapping RF paths. With the scalable switch architecture shown in Fig. 1, crossbar switch matrix of size \( m \times n \) requires a total of \((mn−1)\) total cells, with \((m−1)\times(n−1)\) switch unit-cells and \((m−1)(n−1)\) SP2T switches. The switch unit-cell SU\(_{x,y}\) is designed using four single-pole single-throw (SPST) switches and the SD\(_{x,y}\) switch cell has two SPST switches monolithically integrated to satisfy the two operational state requirement as shown in Fig 2.

A. Crossbar Switch Matrix Unit-Cell

To attain the routing functionality of the RF signal at any input port to output port, unit-cells (SU\(_{x,y}\)) are designed to provide two operational states: ‘turn state’ and ‘thru state’. Switch unit-cell has four ports (RF\(_{1}, \) RF\(_{2}, \) RF\(_{3}, \) and RF\(_{4}\)), three RF paths (one ‘turn’ path RF\(_{1}–RF_{2}\) and two ‘thru’ paths RF\(_{1}–RF_{3}, \) and RF\(_{2}–RF_{4}\)). Two ‘thru’ paths can be connected simultaneously with the aid of the RF cross-over junction. Two PCM SPST series switches (b and c for RF\(_{1}–RF_{2}\) are required to route signal in ‘turn’ state and only one PCM SPST series switch is required for signal routing in ‘thru’ state (a for RF\(_{2}–RF_{4}\) and d for RF\(_{1}–RF_{3}\)) as shown in Fig. 1 and 2.

The crossbar unit-cells are arranged in a way such that, for a switch cell SD\(_{x,y}\), RF\(_{3}\) of the SD\(_{x,y}\) cell is connected to the RF\(_{1}\) port of the next cell SD\(_{x+1,y}\), while the RF\(_{2}\) port of the SD\(_{x,y}\) is connected to the RF\(_{4}\) port of the cell (SU\(_{x–1,y}\)). Switch unit-cells SU\(_{x,y}\) are also arranged in a similar manner.

III. Fabrication Process

A microfabrication process is developed and optimized for the RF PCM devices. The cross-section of the process is shown in Fig. 3, the devices are fabricated on an intrinsic high resistivity silicon substrate. The substrate is passivated with a thin silicon oxide (SiO\(_{2}\)) layer, followed by the deposition and reactive ion etching (RIE) of a refractory tungsten (W) layer. Silver (Ag) is sputtered and patterned using RIE for biasing. A thin-film of aluminum nitride (AlN) is RF sputtered and patterned using RIE as a barrier layer. A thin GeTe layer is sputtered and patterned using ion-milling followed by a gold (Au) layer as first metallization for RF signal flow with chromium (Cr) as a seed layer. A passivation layer of SiO\(_{2}\) is further deposited using PECVD and patterned using RIE. A second metallization layer of Au is deposited using titanium (Ti) as a seed layer. Further details on the microfabrication process are given in [23], [25]

IV. 2×2 Crossbar Switch Matrix

The PCM GeTe-based 2×2 switch matrix is implemented in a crossbar architecture. For \( m = 2 \) and \( n = 2 \) switch matrix, only one switch unit-cell (SU\(_{1,1}\)) and two SP2T switch cells (SD\(_{1,2}\) and SD\(_{2,1}\)) are required as shown in the routing configuration in Fig. 4. The RF signal can be routed from any input port RF\(_{i1}\) or RF\(_{i2}\) to any output port RF\(_{o1}\) or RF\(_{o2}\). The route configuration of respective signal paths and a total number of switches required are given in Table 1. Capacitive coupling from the bias network routed underneath is minimized by optimizing the CPW discontinuity. For a 2×2 configuration, in a switch unit-cell, switches \( a \) and \( d \) are not required, as the cells SD\(_{1,2}\) and SD\(_{2,1}\) are placed in a close proximity to the SU\(_{1,1}\) unit-cell. For higher order matrices, four switches are required in a unit-cell for better RF matching and isolation.

The optical micrograph of the 2×2 crossbar switch matrix is shown in Fig. 5(a). A close-up view of the PCM channel and the PCM switch junction is shown in the SEM micrographs in Fig. 5(b) and (c), respectively. The overall device area is under 0.1 mm\(^2\) including all ports and pads while the device core measures only 0.035 mm\(^2\) for integration.
The RF performance of the presented crossbar switch matrix is simulated in Ansys HFSS over dc to 40 GHz. Measured and simulated RF performance of an unit-cell SU\textsubscript{x,y} in ‘turn’ state is shown in Fig. 6. The measured and simulated insertion loss of a series PCM GeTe-based SPST switch is shown for comparison. The measured RF performance reports an insertion loss less than 0.8 dB, a return loss better than 21 dB, and an isolation higher than 26 dB up to 40 GHz.

The RF performance of a 2×2 crossbar switch matrix in all possible states is shown in Fig. 7. The measured insertion loss is less than 1.1 dB in route R1 and R2, and lower than 1.3 dB and 1.4 dB in routes R3 and R4, respectively. Route R4 is the worst case scenario in a 2×2 switch matrix as the signal passes through two SD\textsubscript{x,y} cells along with 90° bend with conductive lines crossing underneath, which contribute to a higher loss than that of the other routes. Simulated and measured return loss is better than 20 dB and isolation is higher than 24 dB in all possible routing scenarios. The integrated RF switches in the presented design have been experimentally tested for over 1 million reliable device switching cycles, with better than +35.5 dBm of RF power handling and higher than +41 dBm linearity. In-depth details on the power handling capability is given in [26]. To the best of our knowledge, this is the first ever demonstration of a miniaturized crossbar switch matrix utilizing phase change technology.

V. CONCLUSION

A scalable non-volatile PCM GeTe-based crossbar switch matrix is demonstrated for the first time. A 2×2 switch matrix with an ultra-compact device footprint is developed with exceptional RF performance over dc to 40 GHz bandwidth. The PCM multi-port switches and unit-cells are monolithically integrated utilizing an in-house optimized custom micro-fabrication process. An approach to easily scale the switch matrix to a much larger size is discussed. The reported switch matrix promises to be useful in a wide range of applications including satellite payloads and automated equipment testing applications.

REFERENCES


