Low Energy Consumption GeTe Phase-Change Radio Frequency Switch With Direct Heating of Conductive Filament

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***Abstract*— The GeTe phase-change RF switch with Ag conductive filament (CF) as heater is fabricated. The Ag CF as heater can effectively reduce the energy consumption of the switch. In particular, the set energy consumption is as low as 19.2 nJ to set the switch. In durability test, the resistance ratio exceeds three orders of magnitude and remains almost constant over 1000 cycles. The insertion loss of the phase-change RF switch based on GeTe is less than 0.8 dB and the isolation is greater than 20 dB up to 67 GHz. The cut-off frequency of the switch is as high as 15 THz. This work demonstrates that the modulated CF can be used as the heater for phase change material (PCM), providing a new micro directly heated structure for low energy consumption phase-change RF switch.**

***Index Terms*— GeTe films, phase change material, RF switch, low energy consumption.**

I. Introduction

RADIO frequency (RF) switches are needed for signal control, which can be applied in reconfigurable systems, such as true delay, attenuators, and filters. [1], [2] Compared to RF switches in solid-state [3] or MEMS [4], RF switches based on phase change material (PCM) proposed recently [5], [6], [7] have the characteristics of low insertion loss, high cut-off frequency (F_{co}), and low energy consumption [8], [9].

PCM can be reversed between high resistance state (HRS) and low resistance state (LRS), where GeTe is considered to have the lowest resistivity [10]. The crystallization process of PCM includes two processes: ovonic threshold switching and ovonic memory switching [11], [12]. The amorphous process requires heating the PCM to the melting point and then quenching rapidly. Generally, a heater [13] is introduced into the phase-change switch to directly or indirectly heat the PCM by pulse voltage. While the indirectly heated switch has good RF transmission performance, but its energy consumption is high. The directly heated switch has low energy consumption, [14] but there are problems with electrode selection. In order to reduce the insertion loss, the resistance of the electrodes should be low enough. However, when the electrodes act as the heater, the metal material with higher resistance should be preferred.

Unlike horizontal operation and vertical actuation devices [15], [16], this work proposes a vertical operation and vertical actuation directly heated device, which uses Ag conductive filament (CF) as the heater for directly heated GeTe phase-change RF switch. Compared to a standard via-style PCM switch with a W-heater [17], [18], the Ag CF heater can fully crystallize CeTe due to the high density current generated, thereby reducing on-state resistance. This directly heated CF phase-change (CF-PC) RF switch can optimize both the heating and RF transmission paths, reducing switching energy consumption, especially set energy consumption. The insertion loss of the switch is below 0.8 dB (0-67 GHz) and the F_{co} is 15 THz. Compared to directly heated switches [15], [16], [19], [20], this work has lower insertion loss and higher F_{co}. Compared to indirectly heated switches [21], [22], [23], this work has lower energy consumption. This work provides a new idea for the design of low energy consumption phase-change RF switch.

II. Experimental

The CF-PC RF switch based on GeTe was fabricated from bottom to top on a Si-SiO_2 substrate and each layer of

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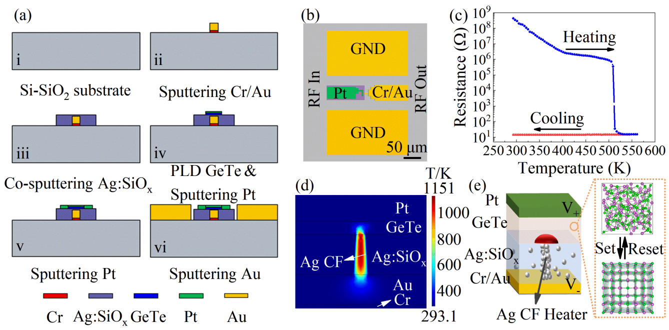

Fig. 1. (a) Cross section of the CF-PC RF switch and description of manufacturing process. (b) The top view of the CF-PC RF switch. (c) Temperature dependence of the resistance for an amorphous GeTe film. (d) The local temperature distribution of the CF-PC RF switch is simulated using COMSOL Multiphysics. (e) The operation mechanism of the CF-PC RF switch.

the switch was patterned with e-beam lithography (EBL). By sputtering deposition of a 100 nm thick Cr/Au as bottom electrode (BE). A 120 nm thick Ag doped SiO_x (Ag:SiO_x) layer was co-sputtered by Ag target and Si target. A 40 nm thick GeTe phase change layer was deposited by pulsed laser deposition (PLD) in the Ar atmosphere. Then deposited on the GeTe layer by magnetron sputtering a 80 nm thick Pt as the top electrode (TE). The widths of both BE and TE are 1 μm. A 120 nm thick Pt was deposited by sputtering as the remaining portion of the TE. Finally, a 200 nm thick Au was deposited by sputtering as the ground layer for RF testing. Fig. 1(a) and (b) present the main manufacturing process and the top view of the switch, respectively.

III. Results and Discussion

The resistance of the GeTe film was measured in-situ at a temperature change rate of 2 K/min. As shown in Fig. 1(c), when the temperature rises to 511 K, the resistance decreases sharply and the GeTe film crystallizes, which corresponds to the crystallization temperature. During subsequent heating and cooling processes, the resistance remains essentially unchanged. The resistance ratio of GeTe film before and after the crystallization phase transition is up to 10^7. To demonstrate the theoretical process of using Ag CF as a heater for GeTe, electrothermal simulation was carried out using COMSOL Multiphysics. Fig. 1(d) reveals the temperature distribution of the CF-PC RF switch with electrothermal boundary conditions. The Joule heat is concentrated at the Ag CF due to the current density. The temperature generated by Ag CF exceeds 1100 K, which is higher than the melting temperature of GeTe and can enable GeTe to complete amorphization. Since leakage current and heat dissipation within the device are not accounted for, the applied potential in the simulation result does not accurately match the actual experimental potential.

The operating mechanism of the CF-PC RF switch is schematically described in Fig. 1(e). It has been confirmed that the high current density associated with filamentous conduction can cause local Joule heat to cause rapid temperature rise [24]. When the pulse voltage is applied, the current density is highly concentrated on the top of the CF heater. Ag CF generates Joule heat, which is transferred to the GeTe layer, thus achieving the reversible phase transition of GeTe with low power consumption. When GeTe is converted to the crystalline state, the CF-PC RF switch is turned on. While GeTe returns to the amorphous state, the switch is turned off.

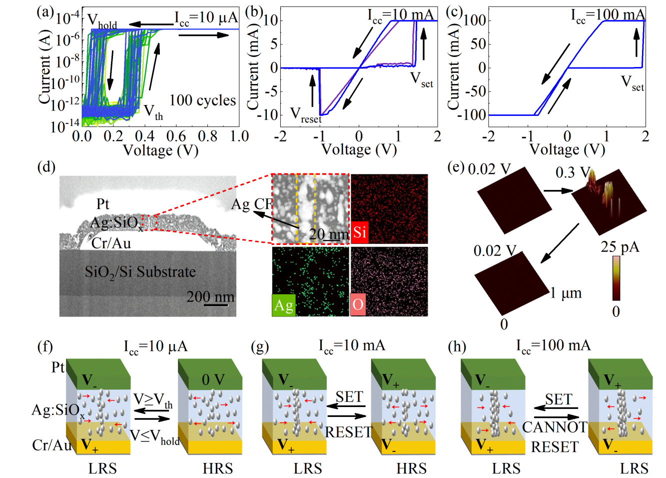

Fig. 2. The I-V characteristic curves of Cr/Au/Ag:SiO_x/Pt device when (a) $I_{cc} = 10\ \mu$A, (b) $I_{cc} = 10$ mA and (c) $I_{cc} = 100$ mA. (d) Cross-sectional TEM image and EDS elemental mapping for Cr/Au/Ag:SiO_x/Pt device after applying voltage ($I_{cc} = 100$mA). (e) Current mapping images of C-AFM for Cr/Au/Ag:SiO_x/Pt device. The switching mechanism diagram of Cr/Au/Ag:SiO_x/Pt device when (f) $I_{cc} = 10\ \mu$A, (g) $I_{cc} = 10$ mA and (h) $I_{cc} = 100$ mA.

The I-V characteristics of Cr/Au/Ag:SiO_x/Pt device was characterized and the device exhibits varying switching characteristics under different compliance currents (I_{cc}). As depicted in Fig. 2(a), while $I_{cc} = 10\ \mu$A, the device behaves as volatile threshold switch and can perform stable switching within 100 cycles. As illustrated in Fig. 2(b), the device exhibits nonvolatile bipolar resistive switch behavior when $I_{cc} = 10$ mA. The device completes the LRS and HRS transitions at positive and negative voltages respectively, and the resistance state is reversible. As demonstrated in Fig. 2(c), the device is converted from HRS to LRS at the positive voltage and the LRS remains unchanged regardless of the polarity of the applied voltage thereafter as $I_{cc} = 100$ mA. The low resistance of the device is about 8 Ω.

Since the CF with low resistance and can be maintained all the time is an ideal choice for phase-change RF switching microheater, the cross section of the device after applying voltage ($I_{cc} = 100$ mA) was characterized by TEM. As shown in Fig. 2(d), the width of approximately 15 nm for the CF is observed within the Ag:SiO_x layer. The EDS element mapping results further confirm the existence of Ag CF. The appearance of CF can be explained by the electric field inducing the formation of metal CF by silver clusters in the insulator matrix [25], [26], [27]. With the application of voltage, Ag clusters randomly distributed in the Ag:SiO_x layer migrate along the electric field direction to form chains of clusters until TE and BE are connected. Ag clusters forming CF is arranged along the electric field line, which is a direct manifestation of the influence of the electric field on the CF formation process. The internal conductivity mechanism of Ag:SiO_x film was studied by conducting atomic force microscopy (C-AFM). Due to the extremely small contact area of the AFM TE and the additional energy barrier between the

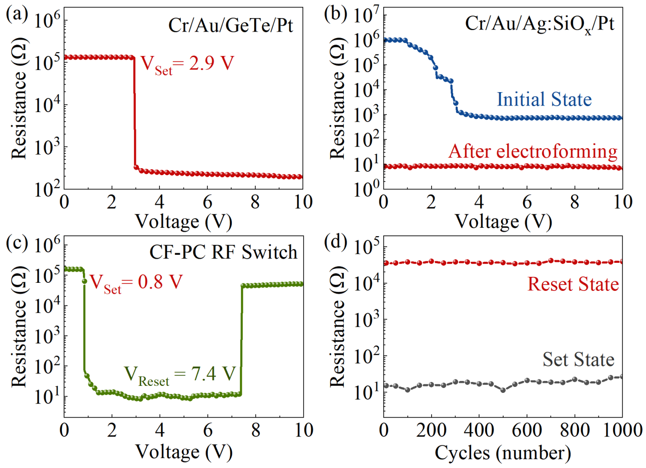

Fig. 3. Resistance-voltage characteristics of (a) Cr/Au/GeTe/Pt device, (b) Cr/Au/Ag:SiO_x/Pt device and (c) CF-PC RF switch based on GeTe. (d) Endurance characteristic of the CF-PC RF switch based on GeTe.

TABLE I
SUMMARY OF MEASUREMENT RESULTS

Insertion Loss (dB)	F_{co} (THz)	Set Enery Consumption	Total Consumption	Refs.
<0.3@40 GHz	7.3	750 nJ	870 nJ	[21]
<0.5@20 GHz	4	3.6 μJ	3.8 μJ	[34]
<1.0@25 GHz	-	3.6 μJ	12.8 μJ	[19]
<0.5@67 GHz	14.5	18.2 μJ	25.4 μJ	[8]
<0.8@67 GHz	15	19.2 nJ	1.6 μJ	This work

TE and the film [28], the current level measured by the C-AFM is relatively low. Fig. 2(e) shows that as the voltage increases, several conductive points appear in the 3D current mapping of Ag:SiO_x film, which means the formation of multiple CFs. The device has relatively high conductivity, which is the result of a local conductive effect rather than a uniformly distributed one. When the voltage decreases again, the conductive point disappears and Ag CFs rupture. The results indicate that the formation and rupture of Ag CF plays a crucial role in the switching behavior of the Ag:SiO_x film.

It is well known that as the device current reaches I_{cc}, the voltage drop across the device will decrease rapidly [29], [30], [31]. When the current of Cr/Au/Ag:SiO_x/Pt device reaches low compliance current (I_{cc} = 10 μA), the electric field weakens and limits the further migration and growth of Ag clusters. The unstable CF finally formed will have very limited size and strength. Once the electric field intensity decreases to a specific value, the thermal diffusion of Ag CF occurs due to the large surface energy and diffusion effect [32], [33]. The CF is damaged by Joule heat, and the device recovers HRS, as revealed in Fig. 2(f). When I_{cc} increases to 10 mA, the enhanced electric field will promote sufficient electromigration of Ag clusters, resulting in more stable CF compared to the previous situation. Joule heat is not enough to destroy CF, which requires a voltage of opposite polarity to rupture it, as shown in Fig. 2(g). As I_{cc} = 100 mA, more Ag clusters form locally high density and strong CF under the action of the strong electric field (15 kV/cm). Because CF is too stable to be destroyed by reverse electric fields or Joule heat (see Fig. 2(h)), CF will continue to exist.

The phase-change RF switch can be converted between on and off states by applying a pulse voltage. The applied pulse voltage is 0 to 10 V, with a pulse width of 300 ns. The resistance after each write operation is read using a 0.5 V pulse voltage. Fig. 3(a) illustrates that when the pulse voltage is applied to the Cr/Au/GeTe/Pt device, it can only complete the crystallization process. As shown in Fig. 3(b), the Cr/Au/Ag:SiO_x/Pt in the initial state eventually converts to LRS under the action of pulse voltage. For Cr/Au/Ag:SiO_x/Pt, the electroforming process is carried out at 15 kV/cm, and then a pulse voltage is applied. The resistance is almost unchanged, indicating that the pulse voltage will not destroy the formed Ag CF. For CF-PC RF switch, an electric field of 15 kV/cm (I_{cc} = 100 mA) is applied to it to form Ag CF firstly. Then a pulse voltage is applied to the CF-PC RF switch to make the GeTe phase transition. As illustrated in Fig. 3(c), the CF-PC RF switch is set and reset at 0.8 V and 7.4 V, respectively. The LRS of the switch is about 10 Ω. According to Fig. 3(d), the switch ratio of the CF-PC RF switch is over 3 orders of magnitude and remains almost unchanged for 1000 cycles of operation.

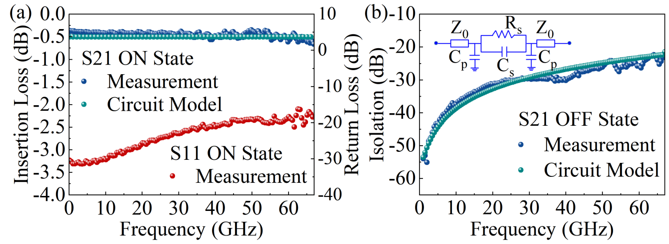

Fig. 4. Measured and simulated RF signal transmission from DC to 67 GHz for the CF-PC RF switch in (a) on state and in (b) off state.

RF transmission scattering parameters of the CF-PC RF switch were performed from DC to 67 GHz. Fig. 4(a) depicts the insertion loss is less than 0.8 dB at 67 GHz, and the return loss exceeds 18 dB. The isolation of the switch is higher than 20 dB, as shown in Fig. 4(b). The equivalent circuit model of the switch is shown in the inset image of Fig. 4(b). The R_{on} and C_{off} extracted using the Advanced Design System (ADS) are 5.9 Ω and 1.8 fF, respectively. Compared to the resistance extracted by ADS, the low resistance of the CF-PC switch is higher due to the use of transient current readout resistance in electrical measurement. The F_{co} is calculated as 15 THz. Table I shows a comparison of this work with some other directly heated phase change switches. The PC-RF switch has much smaller set energy consumption and lower total energy consumption, while offering competitive RF performance.

IV. CONCLUSION

In summary, the Ag CF formed could be used as a heater for the GeTe, which reduces the energy consumption of the switch. The set energy consumption can be as low as 19.2 nJ and the F_{co} is up to 15 THz. The insertion loss of the CF-PC RF switch is less than 0.8 dB and the isolation is higher than 20 dB up to 67 GHz. The current work provides a new microstructure for the design of phase-change RF switch heaters.

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