Comparison and Analysis of GeTe-Based Phase Change RF Switch Structures and Modeling of Their Power Handling Capability

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Abstract: *This paper discusses the design, fabrication, and measurement results of germanium telluride (GeTe) based phase change RF switches with two different heating schemes: direct heating and indirect heating. Both switch types are fabricated in-house showing good RF performance and power handling capability. The measured insertion loss is below 0.6 dB and isolation above 13 dB from DC to 20 GHz for both switches. In order to better analyze the thermal properties and power handling performance of phase change switches, a thermoelectric model is developed utilizing Poole-Frenkel (PF) model, showing good agreement with the measurement results. Such accurate thermoelectric modeling method can be used to provide design guidelines for implementing phase change switches with improved performance.*

Keywords: chalcogenide; germanium telluride (GeTe); phase change switch; RF switch; thermoelectric model.

Introduction

RF ohmic switches using phase change (PC) materials have received increased attention during the last few years. Phase change materials refer to a class of chalcogenide compounds showing two distinct resistivity values in the amorphous and crystalline states [1]. Both states are stable at room temperature, a property that can be used to implement memories [2], [3], or latched ohmic switches [4], [5]. Compared to existing designs of RF switches using MEMS or solid state technologies, switches using phase change materials possess the advantage of simpler fabrication process, faster switching speed as well as smaller size. Germanium antimony telluride (GST), germanium antimonide (GeSb), and germanium telluride (GeTe) are some of the frequently used PC materials, with GeTe being a more popular material for RF ohmic switches because of its low ON-state resistivity value. RF ohmic switch designs using GeTe have already achieved cut-off frequencies in the THz range [4], [5].

Phase transition of PC materials between the low-resistance crystalline state and the high-resistance amorphous state is typically realized by thermal actuation. Accurate control of heating and cooling procedures with specific peak temperatures and cooling times is the key to switching the material in one direction or the other between the amorphous and crystalline states. In terms of the heating methods, depending on whether a bias current is drawn directly through the phase change material for heating or through a separate heater path, a switch can be directly or indirectly heated. Both heating methods have been used for state transitions of PC switches [4], [5]. Due to the differences in structures and heating mechanisms, the two types of switches exhibit different properties in terms of RF performance, power handling capability, non-linearity response, *etc*.

In this paper, we analyze and compare the two phase change RF switch designs with respect to these properties and demonstrate the limiting factors of the switch linearity and power handling capability, as well as provide guidelines on improving switch performance. Both types of switches using GeTe have been designed, fabricated, and measured for this purpose.

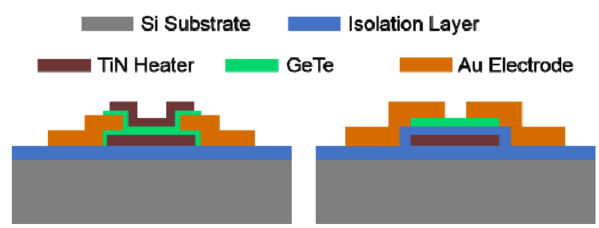

Figure 1. Cross-sectional views of (left) a directly and (right) an indirectly heated GeTe phase change switch.

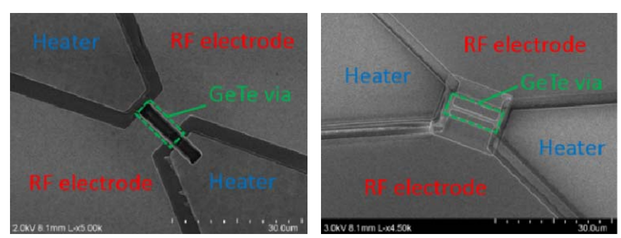

Figure 2. SEM images of the fabricated GeTe phase change switches. (Left) Directly heated phase change switch. (Right) Indirectly heated switch. For testing purposes, switches with different dimensions for the RF electrode connection have been fabricated. Specifically for the devices shown, both switches have an RF electrode separation of 1 μm, and an RF electrode width of 12 μm.

Structure and Fabrication

Structures of the directly and indirectly heated switch designs are shown in Figure 1. The directly heated switch employs two GeTe layers sandwiching the RF electrodes, forming a laterally connected RF signal path, and a top and a bottom heater, forming a vertically connected heater path [5]. The indirectly heated switch has a similar structure as those in [4], with a laterally connected RF signal path connected by the GeTe layer, and a separate heater layer that is electrically isolated from the RF path. Figure 2 shows the scanning electronic microscope (SEM) images of the two switch types.

RF Performance

RF measurements on both types of phase change switches were taken to compare and analyze their performance. Both switch types show promising insertion loss and isolation response as seen from the measurements results (Figure 3). Differences between the two switches are due to factors such as different parasitic elements seen in the switch structure and fabrication errors in defining small gaps.

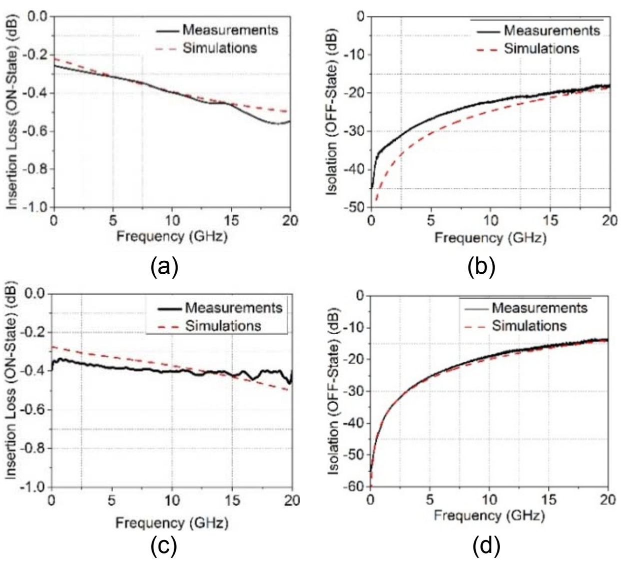

Figure 3. Measured switch responses. (a), (b) insertion loss and isolation of the directly heated switches; (c), (d) insertion loss and isolation of the indirectly heated switch.

In both types of switches, there are four terminals: two RF ports and two heater ports. The directly heated switch has the RF and heater ports electrically connected together through the PC material, while the indirectly heated switch has them electrically separated by an isolation layer. The RF performance of the directly heated switch with 200 nm of GeTe is measured and de-embedded, and the plots are shown in Figure 3(a), (b). As shown, the ON-state insertion loss is less than 0.6 dB, and the OFF-state isolation is above 18 dB from DC to 20 GHz. For the indirectly heated switch with 200 nm of GeTe, the RF measurements are shown in Figure 3(c), (d). From DC to 20 GHz, the ON-state insertion loss is better than 0.5 dB, and the OFF-state isolation is above 13 dB. For the directly heated switch, since the heater and RF paths are electrically coupled, the OFF/ON resistance ratio is potentially limited. For indirectly heated switches, the RF and heater paths are electrically separated so the OFF/ON resistance ratio is better, but the parasitic capacitance to the heater compromises the high-frequency isolation.

Thermoelectric Modeling

The thermoelectric modeling of PC switches is a method of analyzing the RF performance of the GeTe switches at different temperature and RF power levels. For the phase change switches, the power handling capability is dictated by the maximum RF power that can be applied without transitioning the switch into the other state. The non-linearity of the switch, however, is mostly limited by the resistance change with temperature (TCR) and RF voltage swings across the switch. A non-linear model for PC switches was reported in [6]. In this paper, we provide an improved modeling method (Figure 4) to predict the input third-order intercept point (IIP_3) and the 1-dB compression point (P_{1dB}) for the PC switches.

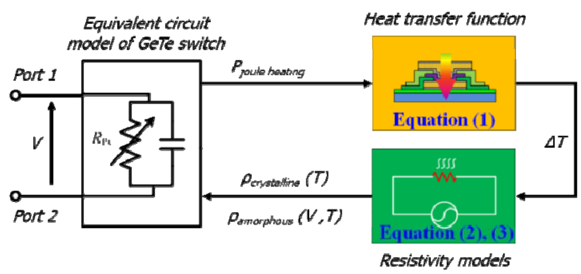

Figure 4. The thermoelectric model of the phase change switches. This model consists of a simplified equivalent circuit model of the PC switch, and the heat transfer function as well as the modeling of the changing electrical resistivity of GeTe with changing temperature and voltage across the PC layer.

To model the non-linear response, the Poole-Frenkel (PF) model is used in the amorphous state. In the crystalline state, we use a linear resistivity *vs*. temperature response since the voltage drop across the phase change layer in the crystalline state is a lot smaller compared to the amorphous state. The lumped-element equivalent circuit of the switch includes the PC series resistance, R_{PC}, and the parallel capacitance of the feed-line and the PC layer. The lumped element values are obtained by fitting to the measured *S*-parameter response. The temperature rise (ΔT) of the GeTe layer from the heating power (P) can be estimated using the heat transfer function (Eq. (1)) [7]. At the crystalline state, the resistivity exhibits metal-like temperature dependence (Eq. (2)) [8]. We measured the TCR (α) to be 2.3×10^{-3}/K in this state, which is close to the value reported in [8]. At the amorphous state, the resistivity change with temperature and RF voltage can be estimated using the PF model (Eq. (3)) [9]. The two main parameters in Eq. (3) are E_C-E_F (energy distance between the Fermi level and the conduction band) and N_T (trap concentration). Reducing E_C-E_F and increasing N_T make the amorphous resistivity vary less with temperature rise and high voltage swings, respectively, which results in improved P_{1dB} and IIP_3.

$$H(\omega)=\frac{\Delta T}{P}=\frac{1}{V_m}\cdot\frac{d_m\left[\left(d_f/k_f\right)\cdot\left(\tanh\beta_f/\beta_f\right)+R_B\right]}{1+j\omega C_m d_m\left[\left(d_f/k_f\right)\cdot\left(\tanh\beta_f/\beta_f\right)+R_B\right]},\ \beta_f=d_f\sqrt{j2\pi f_h\frac{C_f}{k_f}} \quad (1)$$

$$\rho_{\text{crystalline}}=\rho_0\left[1+\alpha\left(T-T_{\text{ref}}\right)\right] \quad (2)$$

$$\rho_{\text{amorphous}}=\frac{kT\tau_0}{(q\Delta z)^2 N_T}e^{-\frac{(E_C-E_F)}{kT}}\cosh^{-1}\left(\frac{qV_A}{kT}\frac{\Delta z}{2u_a}\right) \quad (3)$$

Based on Eq. (1), the simulated frequency response of a typical heat transfer function is predicted to show a low-pass characteristic. In general, the low frequency transfer function gain is much dependent on the RF electrode distance of the switch. A larger distance between the RF lines generally results in a smaller temperature rise at high RF power, which ensures a more linear response, but the insertion loss will be compromised. The two switch types in this case have similar RF spacing and GeTe volume. However, since in the directly heated switch the electrical resistance of the heater layer is in parallel with the GeTe resistance [5], the overall resistance varies less with temperature, resulting in a smaller temperature rise at high RF power and therefore a better linearity.

Based on the thermal modeling of the switches, the IIP_3 of the phase change switches is measured at different states to determine the accuracy of the modeling. The results are shown in Figures 5 and 6, for the directly and indirectly heated phase change switches, respectively. Simulated results are in good agreement with measurements in most cases. The discrepancy, especially in the modeling of IIP_3 with changing frequency offset, indicates that other possible factors, such as current crowding, and nucleation mechanisms, should be taken into account.

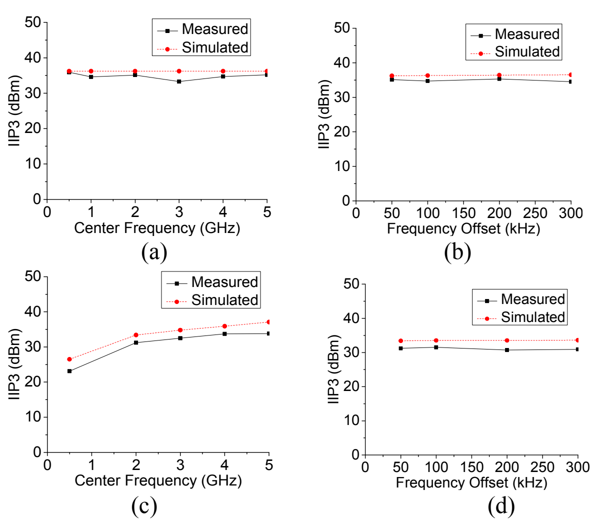

Figure 5. Simulated and measured IIP_3 of the directly heated switch with (a) changing center frequency and a constant 50 kHz frequency offset, (b) changing frequency offset and a constant 2 GHz center frequency at crystalline state. (c) and (d) show the corresponding responses at the amorphous state.

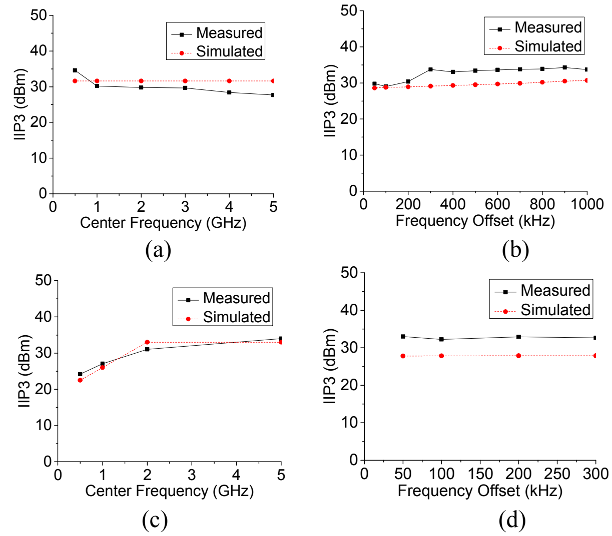

Figure 6. Simulated and measured IIP3 of the indirectly heated switch with (a) changing center frequency and a constant 50 kHz frequency offset, and (b) changing frequency offset and a constant 2 GHz center frequency at crystalline state. (c) and (d) show the corresponding responses at the amorphous state.

Conclusion

Phase change RF switches using a direct heating scheme and an indirect heating scheme have been designed, fabricated, and measured for comparison and analysis of their RF performance. For both types of switches, an insertion loss of less than 0.6 dB and an isolation above 13 dB at frequencies from DC to 20 GHz have been achieved, showing both types are promising candidates for reconfigurable RF applications. In addition, a detailed thermoelectric modeling method has been proposed to analyze the thermal properties of phase change switches with different structures. The directly heated phase change switch possesses the advantage of high power efficiency, better linearity, and potentially lower insertion loss, while the indirectly heated phase change switch offers better OFF/ON resistance ratio and potentially better reliability as the thermal path is not electrically coupled with the phase change layer.

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