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Non-Linearity Analysis of RF Ohmic Switches Based on Phase Change Materials

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***Abstract*— We report on a thermoelectric model that can be used to analyze the nonlinearity and power handling capability of RF switches based on phase change (PC) materials. To analyze the nonlinear behavior of the PC switches, the Poole–Frenkel effect, the variation of thermal and electrical conductance with temperature, and the effect of Joule heating with increased RF signal power are all taken into account. The simulated input third-order intercept point and the 1-dB compression point (P_{1dB}) are compared with measured results of directly heated PC switches, showing a good agreement. Using this model, we provide insights into the effect of electrical resistance, and thermal properties, as well as the operation frequency on the switch nonlinearity and power handling capability.**

***Index Terms*— Phase change material, RF ohmic switch, GeTe, Poole–Frenkel effect, power handling capability, IIP_3, P_{1dB}.**

I. Introduction

PHASE change (PC) materials have recently attracted a lot of attention, not only in nonvolatile memories, but also as highly integrated RF switches [1], [2]. Larger resistance change ratio and lower ON-resistance is necessary in RF switches to achieve low loss at the crystalline state (ON) and good isolation at the amorphous state (OFF). Recently, germanium tellurium (GeTe), which provides the best switching property among various GST stoichiometric compositions, was utilized to implement switchable inductors [3]. In [4], we have developed the lumped-element model and characterized the basic RF properties of GeTe switches.

Phase transition of GeTe switches is achieved through Joule heating. Thus, high-power RF signals can derive undesired distortion or even complete phase transition. Additionally, at the OFF state, high voltage drop across PC layer results in a change in electrical resistivity due to the Poole-Frenkel (PF) effect [5], [6]. Since PC switches are sensitive to high-power RF signals, the linearity and power handling capability of PC switches needs systematic investigation before they can be utilized in RF systems. Better understanding of non-linear effects in PC switches also provides possible solutions to improve the switch properties.

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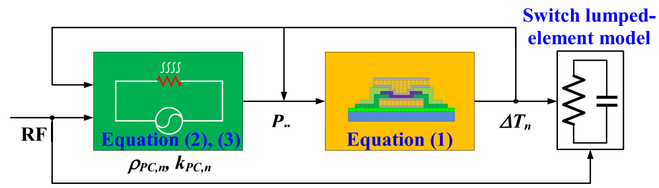

Fig. 1. Non-linear thermo-electric model of PC switch used in Agilent ADS.

In this letter, a thermo-electric model is proposed to analyze the non-linear response of RF PC switches, for the first time, taking into account the PF effect, the effect of Joule heating, and RF lumped element model of the switch. Utilizing this model, characteristics of the PC switch at both ON and OFF states are analyzed under different frequency and structural conditions. Measured results of a PC RF switch are also compared with simulations, verifying the accuracy of the presented non-linear thermo-electric model.

II. Non-Linear Model of PC Switch

Fig. 1 illustrates the proposed non-linear PC switch model. The switch is modeled using a lumped-element circuit as discussed in [4]. At the ON state, as RF signal passes through the PC switch, the local temperature (T) of the switch increases as a result of Joule heating, which in turn changes the PC material properties, such as the electrical resistivity (ρ_{PC}) and the thermal conductivity (k_{PC}). At the OFF state, in addition to the Joule heating effect, the resistivity of the switch changes upon application of a high-power RF signal due to PF effect. To model these effects, the material parameters of GeTe are updated depending on the input RF power.

To estimate the temperature rise (ΔT) from Joule heating, heat transfer equations can be utilized. As noted in [7], the frequency domain solution of the heat transfer function can be expressed as

$$H(\omega) = \frac{\Delta T}{P} = \frac{1}{V_E} \cdot \frac{t_E[(t_{PC}/k_{PC}) \cdot ((\tanh \beta_{PC})/\beta_{PC}) + R_B]}{1 + j\omega C_E t_E[(t_{PC}/k_{PC}) \cdot ((\tanh \beta_{PC})/\beta_{PC}) + R_B]}, \quad (1)$$

where V_E, C_E, and t_E are the volume, heat capacity, and thickness of the metal electrode, respectively. t_{PC} is the thickness of the PC via, R_B is thermal boundary resistance between the electrode and the PC via, and β_{PC} is the ratio of the film thickness to the thermal diffusion length. Fig. 2 shows the frequency response of the heat transfer function, $H(\omega)$, normalized to the amplitude value at the lowest sweeping frequency. As expected, the heat transfer function exhibits a low-pass filtering behavior [Fig. 2(a)]. The frequency of

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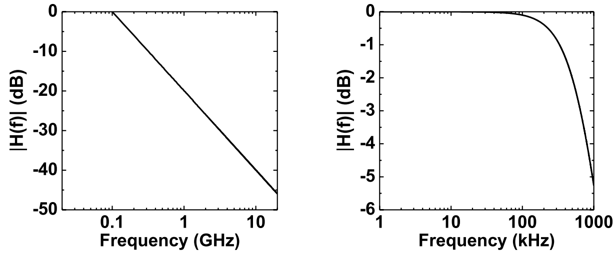


(a) (b)

Fig. 2. (a) and (b) Frequency response of heat transfer function.

the pole is influenced by both the thermal mass ($C_E t_E$) of the metal electrode and properties of GeTe such as t_{pc} and k_{pc} [7]. The 3 dB point is about 640 kHz, as shown in Fig. 2(b).

As noted earlier, the resistivity change with temperature and RF voltage at the OFF state can be estimated using the PF model. Although this effect is not as dominant at the ON state due to a smaller voltage drop across the PC layer, resistivity change of GeTe can also be described when crystallized using the same amorphous state model [5] with different trapping energy level (E_c) and effective level of charge carriers (N_T).

$$\rho_{PC} = \frac{kT \cdot \tau_0}{(q\Delta z)^2 \cdot N_T} \cdot e^{(E_C - E_F)/kT} \cdot \cosh^{-1}\left(\frac{qV}{kT} \cdot \frac{\Delta z}{2u_a}\right) + \rho_0, \tag{2}$$

where k, q, τ_0, E_F, V, Δz, u_a, and ρ_0 indicate Boltzmann constant, elementary charge, time constant for trapped electron, Fermi level, applied voltage, short trap distance, effective thickness of PC layer, and resistivity due to conventional drift, respectively.

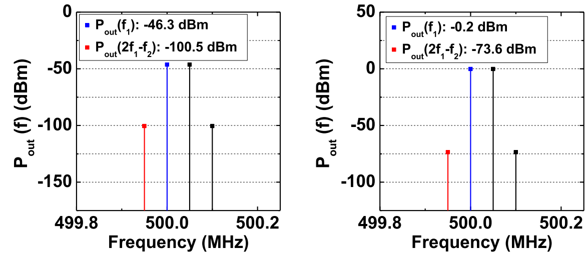
The measured temperature dependency of k_{PC} is previously shown in [8] and [9]. Referring to this result, temperature variations of k_{PC} is modeled as

$$k_{PC} = a \cdot \exp[-(T - T_0)/b] + c, \tag{3}$$

where $a, b,$ and c are constants that model temperature dependent thermal conductivity. For a given RF input, the solution at the equilibrium state is obtained using Agilent ADS software [10] by performing an iterative procedure on the model shown in Fig. 1 and using the parameters given in Section III until the solution was converged for the temperature change and the electrical and thermal conductivity values.

III. Linearity Analysis and Discussion

To gain better understanding of the non-linear effects in PC switches, a single directly heated PC via [4] is considered and its IIP_3 and P_{1dB} are simulated. Fig. 3 shows the simulated IIP_3 at the ON and OFF states of the PC switch. Because of the larger dependency of ρ_{PC} on the RF signal and temperature at OFF state, IIP_3 at the OFF state is lower than that at the ON state. Table I summarizes the IIP_3 simulation results at different frequencies for the two-tone RF input. IIP_3: model is simulated with the extracted constants from [4] and [9]. The common model parameters are set as $E_C = E_F + 0.37$ eV, $N_T = 1.0 \times 10^{16}\text{cm}^{-3}$, $\rho_0 = 1.9 \times 10^4 \Omega$.m, $\Delta z = 4$ nm, a $= -0.02$, b $= 16.27$, and c $= 0.25$ (OFF state), and $E_C = E_F +$ 0.04 eV, $N_T = 1.0 \times 10^{15}\text{cm}^{-3}$, $\rho_0 = 0.5\ \Omega$.m, $\Delta z = 20$ nm, a $= 0.27$, b $= 79.28$, and c $= 0.31$ (ON state). u_a =100 nm and τ_0 =*1* fs are set at the both states. Fig. 4 shows the temperature and voltage dependence of resistivity at OFF state. From our analysis, the contribution of thermal resistance is not as significant as the electrical resistivity. Nevertheless, thermal conductivity parameters are also scaled from values reported for a 900 nm film [8] to better reflect the behavior of the thinner GeTe layer and to be in the same order as the more recent data measured for GST compositions with similar thicknesses [9].



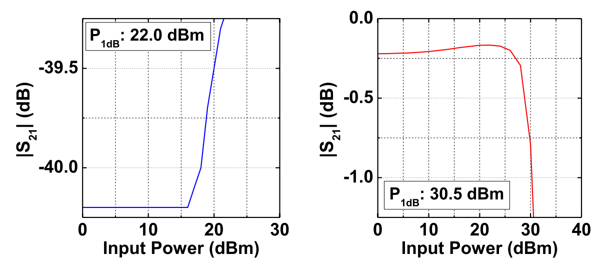
(a) (b)

Fig. 3. Simulated output power with fitted values at 500 MHz (P_{in} of 0 dBm; Δf of 50 kHz); (a) OFF state (IIP_3: 27.1 dBm); (b) ON state (IIP_3: 36.7 dBm).

TABLE I

IIP_3 Simulation Results for Different Frequencies (F_C and Offset Values (ΔF). Parameter δ Is the Percentage of PC Material Volume Affected by the RF Signal

#	State	f_c (GHz)	Δf (kHz)	δ	IIP_3:model (dBm)	IIP_3:measured (dBm)
1	OFF	0.5	50	1.0	27.1	27.0
2	OFF	0.5	1000	1.0	27.2	-
3	OFF	2.0	50	1.0	33.2	31.9
4	OFF	0.5	50	0.2	34.1	-
5	ON	0.5	50	1.0	36.7	35.9
6	ON	0.5	1000	1.0	39.1	-
7	ON	2.0	50	1.0	36.7	35.9
8	ON	0.5	50	0.2	50.7	-



(a) (b)

Fig. 4. Simulated P_{1dB} at 1 GHz; (a) at the OFF state; (b) at the ON state using the fitted parameters.

The first observation from Table I is that a smaller frequency offset (Δf) results in lower IIP_3 at both states (comparing #1 against #2, and #5 against #6). This is because of the low-pass thermal transfer function in Fig. 2. Non-linear response of the PC switch produces intermodulation products at different frequencies; the low-frequency term at Δf experiences a small loss and when further mixed with the original RF signal becomes the dominant third-order intermodulation signal (IM_3). Since the mixed term at Δf is suppressed more markedly at higher frequencies, it produces smaller IM_3 signals; thus two-tone signals with larger Δf (*i.e.*, Δf $>$ 640 kHz) show better IIP_3 at both states.

It is also noticeable that the dependence of IIP_3 on f_c is only observed at the amorphous state (comparing #1 against #3). The IM_3 products are not a function of center frequency because of the mixing effect and one may expect to see a

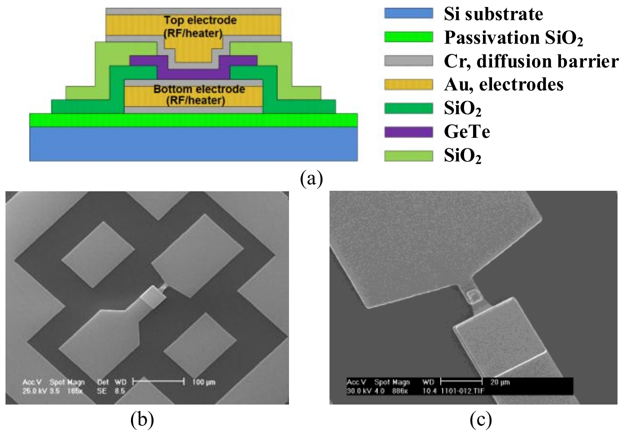


Fig. 5. (a) A schematic diagram showing the cross-section of the PC switch. SEM images of PC switch composed of 3 × 3 μm^2 GeTe via; (b) overall view; (c) enlarged view around the GeTe via area.

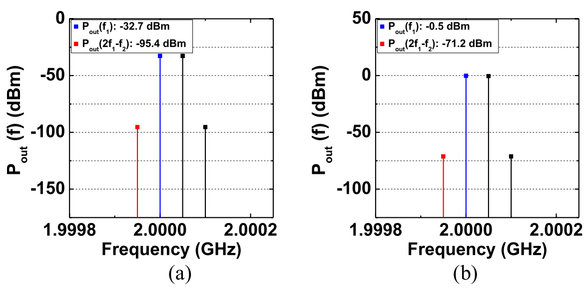


Fig. 6. Measured output power at 2 GHz (P_{in} of 0.52 dBm; Δf of 50 kHz); (a) OFF state (IIP_3: 31.9 dBm); (b) ON state (IIP_3: 35.9 dBm).

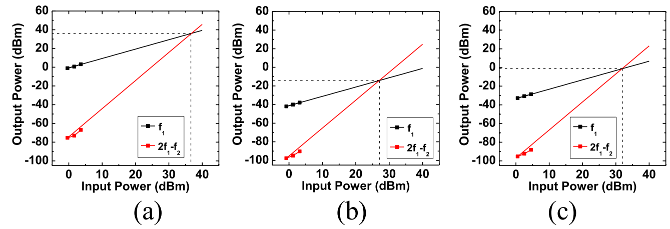


Fig. 7. (a) Measured IIP_3 at the ON state with f_1: 2 GHz, Δf: 50 kHz (IIP_3: 35.9 dBm). Measured IIP_3 at the OFF state (b) f_1: 500 MHz, Δf: 50 kHz (IIP_3: 27.0 dBm); (c) f_1: 2 GHz, Δf: 50 kHz (IIP_3: 31.9 dBm).

negligible change in IIP_3 as the frequency is varied. However, at the OFF state and at higher frequencies, the parallel parasitic capacitance starts to dominate [4], resulting in more pronounced variations in the total impedance of the switch with respect to frequency. Therefore, only at the OFF state, the IIP_3 is RF frequency dependent and degrades as the frequency (f_c) is decreased (*i.e.* when the electrical resistance dominates).

This model also provides a possible solution for linearity improvement of PC switches. If the input/output RF electrodes in the PC switch have larger contact area with the PC layer and a longer distance between them (translating to a larger volume of PC), a high-power RF signal is less capable of changing the state of the entire PC volume. If only 20% of the switch volume is affected by RF signal (*i.e.*, $\delta = 0.2$), the model predicts IIP_3 to be improved at both states (comparing #1 against #4 and #5 against #8). To realize such a high-performance RF switch, the heater path has to be separated from the RF path and the heater electrode design should be optimized to achieve efficient thermal transition in a larger volume of PC via.

Fig. 4 shows the P_{1dB} simulation results of the PC switch. Unlike IIP_3, P_{1dB} does not show any dependency on the RF signal frequency. This can be explained from the square term in the Joule heating equation, which forms a dominating DC signal and an insignificant high-frequency signal.

IV. Measurement Result

Analytical results are verified using one-port directly heated PC switches composed of a 100 nm thick 3 × 3 μm^2 GeTe via (Fig. 5). The device detail structure can be found in [4].

First, IIP_3 at both OFF and ON states is measured as shown in Fig. 6. As expected from the analysis, the ON state shows better IIP_3 than the OFF state as PC material property exhibits smaller temperature dependency at this state. Fig. 7 shows the extracted IIP_3 at different frequencies and states. Analysis showed better IIP_3 at the OFF state for higher f_c, which is confirmed by the results shown in Fig. 7. P_1dB results are previously shown in [4] where power distortion of ∼1 dB is observed at the OFF state with input RF power of 25 dBm. Note that the overall trends of P_1dB and IIP_3 are very similar to the analytical results using both fitted and nominal values.

V. Conclusion

The linearity of PC switches is analyzed using a new thermo-electric model and compared with measured results. More accurate estimation of IIP_3 and P_1dB should be achieved by considering other secondary effects such as current crowding, thermoelectric conduction, impact ionization, and phase change nucleation mechanisms. The analytical model can also be used to find optimal structures with improved power handling capability.

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