Effect of scaling on thermal properties and switching operation of phase change memory devices

Jie Zhu¹, Changcheng Ma¹, Jing He¹, Jingjing Lu¹, Zuoqi Hu¹,*

¹School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, 430070, China

Abstract. Phase change memory (PCM) is one of the most promising emerging non-volatile memory technologies. This paper simulates phase change memory devices (PCMDs) with careful attention to the scaling and its resulting impact on programming current during the switching operation, while Thomson heating within the phase change material and Peltier heating at the electrode interface are considered. The simulation results show that the device scaling has an influence on temperature distribution, volume of the molten region, heat diffusion and switching operation of PCMDs. The programming current decreases with smaller electrode size, greater thickness of phase change material and deeper isotropic scaling. The heat diffusion becomes more serious when the thickness of phase change materials decreases and the size of PCMD is isotropically scaled down. The scaling arguments also indicate that the impact of thermoelectric phenomena weakens with smaller dimensions due to the influence of programming current, heat diffusion and action area. This simulation provides useful insights to understand the switching operation of the PCMDs under the impact of thermoelectric effects. The process is instrumental for a complete understanding of device operation and hence provides valuable feedback for fine-tuning the device design so as to enhance its efficiency.

1 Introduction

To date, phase change memory (PCM) is one of the most promising emerging non-volatile memory technologies due to its fast programming speed, exceptional endurance and capability of scaling [1-3]. In terms of a phase change memory device (PCMD), with the application of bias voltage the information can be programmed by a non-volatile phase transition of phase change materials, especially some chalcogenide materials like GST [2,4]. In a set operation, the phase change material can be switched from a low-resistance crystalline state, set state as well, to a high-resistance amorphous state, namely reset state, because of the Joule heating [5]. On the other hand, during a reset operation, the reset state

* Corresponding author: hu_zuoqi@hust.edu.cn
turns back to the set state when the current is extremely high that the temperature of phase change material is above the melting point [6].

However, the reset operation is considered as a Gordian knot for research of PCM, owing to the requirement of a relatively high current, which is limited by the minimal size of devices and the possibility of parallel programming in an array. Therefore, recently great efforts have been made to analyze the relationship between programming current and scaling [3-4, 6-11]. In addition, with the size of PCMD scaled down, the thermoelectric effects in phase change material becomes more predominated [12-14]. Hence, it is essential that thermoelectric heating should be considered in studying the switching operation in PCM devices. This paper simulates PCMD aiming at studying the relationship between the scaling and its resulting impact on programming current during the switching operation, while thermoelectric effects are considered.

2 Model

In our study, the PCMD is designed as a mushroom-shaped structure, a widely utilized structure in PCMDs, containing a TiN top electrode, a 200 nm thick GST phase change layer and a 200 nm thick TiN pillar-type bottom electrode with a diameter of 250 nm, while top and bottom electrodes are respectively contacted with W electrode contacts, and the whole structure is surrounded by SiO2 electrical passivation. During the switching operation, the top electrode is biased while the bottom electrode is grounded.

In our simulation, based on the finite difference method [15-16], the model contains electrical, thermal, phase-change and percolation sub-models for a total demonstration of PCM switching operation. When the size of PCMDs scaled down, the thermoelectric effects cannot be omitted. To calculate the spatial electrical potential distribution, we not only iteratively solve the Laplace equation for each mesh element, but also consider additional generated current by Seebeck effects [13,16]. The current continuity equation is shown as

$$\nabla \cdot J = \nabla \cdot \left\{ \sigma (\nabla V + S \nabla T) \right\} = 0$$

where $J$ is the current density, $\sigma$ is the electrical conductivity, $V$ is the electric potential, $S$ is Seebeck coefficient. In addition, we calculate the temperature distribution by solving the heating conduction equation, while we consider Joule heating induced by each mesh element, as well as Thomson heat within the GST and Peltier heat near the GST–TiN interface [12,17]. And the heat conduction equation is shown as

$$C \left( \frac{dT}{dt} \right) - \nabla \cdot (\kappa \nabla T) = Q + Q_{th}$$

where $C$ is the volumetric heat capacity, $T$ is temperature, $t$ is time, $\kappa$ is the thermal conductivity, $Q$ is the Joule heat and $Q_{th}$ is the contribution of thermoelectric effect. Then, according to the resulting temperature distribution, we model the phase-change process by the class theory of nucleation, and we adopt the Bruggeman effective medium approximation to discuss the percolation effect of a phase change material [16].

Table 1 shows the parameters used in our model at zero electric field and 300K room temperature, while experimental curves of detailed parameters utilized in our model is shown in Figure 1 [12-14,16].
Fig. 1. (a) Electrical conductivity of crystalline and amorphous GST. (b) Constructed thermal conductivity of GST with phonon and electronic contributions shown. (c) Heat capacity for GST with a plateau at melting to include latent heat of fusion. (d) Seebeck coefficients for GST in amorphous and crystalline phases. (e) Negative Seebeck coefficient of TiN.

Table 1. parameters of materials. Taken from Refs. 12,13.

| Material | \( \rho_{\text{elec}} (\Omega \text{ m}) \) | \( \kappa (\text{W/m K}) \) | \( C (\text{J/Kg K}) \) |
|----------|---------------------------------|-------------------|-----------------|
| SiO\(_2\) | \(10^{14}\) | 1.3 | 1050 |
| TiN | \(10^{-6}\) | 14 | 784 |
| W | \(5.4 \times 10^{-8}\) | 175 | 132 |

3 Results

3.1 Scaling the cross section of pillar-type TiN

Figure 2 shows the effect of scaling pillar-type TiN, while the diameter of TiN changes in different values \(d_{\text{TiN}}= 50, 100, 150, 200 \) and 250 nm. In Figure 2a, with the diameter of TiN decreasing, to process a reset operation, the minimal programming current becomes lower, and the energy consumption decreasing either. In Figure 2c, it demonstrates that with the scaling of TiN, the dominated heating area generally concentrates and moves toward the GST/TiN interface. Figure 2b shows that with the cross section of TiN scaled down, the rate of current reduction caused by Peltier effect decreases while the rate of current reduction caused by Thomson effect increases. Overall, the total rate of current reduction decreases.
3.2 Scaling the thickness of GST layer

Figure 3 shows the effect of scaling the thickness of GST layer, while the thickness changes in different values $h_{GST} = 50, 100, 150, 200, 250$ and $300$ nm. Figure 3a shows that both the programming current and the energy consumption increasing with the thickness decreasing, and the slope becomes larger when thickness is below 200 nm. In Figure 3c, it demonstrates that with the thickness scaling down the dominated heating area generally shrinks in the vertical direction. Figure 3b shows that considering different thermoelectric effects scaling the thickness of GST layer has different impact on the programming current in a reset operation. With the thickness of GST layer scaled down, the ratio of current reduction caused by Peltier effect decreases and the ratio of current reduction caused by Thomson effect slightly increases. Overall, the total rate of current reduction decreases.
3.3 Isotropic scaling the size of PCM device

Figure 4 shows the effect of isotropic scaling the size of PCM device, while the rate of scaling changes in different values 0.2, 0.4, 0.6, 0.8 and 1. Figure 4a shows the minimal programming current and corresponding energy consumption decrease at the end of a reset operation with the size of PCM device scaled down. Different thermoelectric effects have distinct impact on the programming current shown in Figure 4b. When the size of PCM device shrinks, the rate of current reduction caused by Peltier effect generally decreases, while the rate of current reduction induced by Thomson effect remains stable.
4 Discussion

With the cross section of TiN scaled down, both the increase of resistance of PCMs and the reduction of amorphous region for requirement of reset operation result in a smaller programming current. In this process, the prerequisite for a reset operation is the formation of an amorphous region which totally covers GST/TiN interface. Therefore, smaller the cross section of TiN, smaller the amorphous region covering heater, which means the area needed to be heated above the melting point in GST layer becomes smaller. In addition, the smaller cross section leads to a larger resistance of heater, which results Joule heating generated more efficiently via a fixed pulse current. On the other hand, with the cross section of TiN scaled down the weight of Peltier effect becomes lower owing to a significant decrease of the GST/TiN interface where the Peltier effect occurs, and the impact of Thomson effect on reset operation relatively increases due to an increasing temperature gradient caused by centralization of temperature distribution.

When scaling down the thickness of GST and keeping other conditions constant, although the volume needed to be heated above the melting point in the GST layer decreases due to the shorter thickness, the area that covers the interface and needs to be heated above the melting point remains constant, which means that relatively more region outside the GST layer is heated, leading to a notable heat diffusion. During a thickness reduction from 300 nm to 200 nm, the dominated heating region is within the GST layer, while the heat diffusion is relatively weak, keeping the energy consumption basically constant. As the thickness is further reduced, to generate the same melting cover at the interface, heat diffusion becomes serious, while simultaneously the resistance of PCM device is lowered, making programming current and energy consumption increased. With the thickness of GST layer decreasing, the point of top temperature moves toward the GST/TiN interface, so the Peltier effect becomes less predominated for reset operation. On the other hand, it is harmful for reset operation that the Peltier effect leads to the heat diffusion occurring outside the GST layer, that explains the decreasing rate of current reduction by Peltier effect. In terms of Thomson effect, the temperature gradient in the vertical direction increasing dramatically with the thickness scaled down means the generation of heat by Thomson effect increasing as well. In addition, the point of top
temperature moving toward interface leads to an increasing impact of Thomson effect on reset operation.

With the size of the PCM device scaled down isotropically, because of the isotropic scaling, the temperature distribution ratios in different sizes remain the same, only the heating area decreases with the size scaled down, resulting in lower energy consumption. Nevertheless, inner temperature of GST layer increases more rapidly that leads to more serious heat diffusion toward outside. Due to the covered area at the interface decreasing, the Peltier effect weakens and the rate of programming current reduction declines. On the other hand, because of the equilibrium between a larger temperature gradient and a lower programming current, the Thomson effect has a basically constant impact on the heating efficiency, as well to maintain a stable effect on the programming current.

5 Conclusion

To put it in a nutshell, we have investigated thermal property and switching operation of PCM device based on a simulation of PCM device with different types of scaling. The simulation results show that the device scaling has an influence on temperature distribution, volume of the molten region, heat diffusion and switching operation of PCMD with the consideration of the thermoelectric effects. This simulation provides useful insights to understand the switching operation of the PCMDs under the impact of thermoelectric effects. The process is instrumental for a complete understanding of device operation and hence provides valuable feedback for fine-tuning the device design so as to enhance its efficiency.

This work was funded by National Key Research and Development Plan.

References

1. Geoffrey W. Burr, Matthew J. Breitwisch et al, Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena, 28, 223 (2010)
2. H. -S. Philip Wong, Simone Raoux et al, Proceedings of the IEEE. 98, 2201 (2010)
3. Y. N. Hwang, J. S. Hong et al, in VLSI Technology, Systems, and Applications, International Symposium, pp29–31 (2013).
4. A. Pirovano, A. L. Lacaita et al, IEEE Transactions on Electron Devices, 51, 452 (2004).
5. Raoux S., Burr G. W. et al, IBM Journal of Research and Development, 52, 465 (2008).
6. Raoux S., Welnic W et al, Chemical Reviews, 110 (1), 240 (2010).
7. D. Ielmini, A. Lacaita et al, IEEE Electron Device Letters. 25(7), 507–509 (2004).
8. Y. N. Hwang, S. H. Lee et al., in IEDM Technical Digest, 2003, pp. 893–896.
9. U. Russo, D. Ielmini et al, IEEE Transactions on Electron Devices, 55, 2 (2008).
10. D. Ielmini, Physical Review B, 78, 035308(2008).
11. J. H. Park, S.-W. Kim et al, Journal of Applied Physics 117, 115703 (2015).
12. J. Lee, M. Asheghi et al., Nanotechnology, 23(20), 205201 (2012).
13. D.-S. Suh, C. Kim et al, Applied Physics Letters, 96, 123115 (2010).
14. U. Russo, D. Ielmini et al, IEEE Transactions on Electron Devices, 55, 2 (2008).
15. Y. Won, J. Lee et al, Applied physics letters, 100, 161905 (2012).
16. I. Cinar, O. B. Aslan et al, Journal of Applied Physics, 117, 214302 (2015);
17. L. W. da Silva, M. Kaviany, IEEE Transaction on electron devices, 47(10–11), 2417-2435 (2004)