

# Degradation Mechanism and Curing Method of Phase Change Memory (PCM) Device Characteristics during Cyclic Programming

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## ABSTRACT

Using a phase change memory device composed of  $\text{Ge}_2\text{Sb}_2\text{Te}_5$  (GST), we studied the mechanism of the SET-stuck failure (SSF), *i.e.* persistence of a low resistance state during write/erase (W/E) cycling. The SSF state was characterized by increased RESET current and decreased threshold voltage, which were thought to be due to depletion of Ge and enrichment of Sb inside the active volume of GST. We found that the SSF-PCM could be restored to have its initial device characteristics by a small number of RESET pulses of reverse bias-polarity, implying that electromigration is the major cause of the SSF of a PCM. The repaired device was demonstrated to have a comparable endurance to that of the initial device.

**Key words:** phase change memory, reliability, electromigration

## 1. INTRODUCTION

As Flash memories approach their limitations in scaling and reliability, a race for developing highly scalable next generation non-volatile memories is going on. Phase change memory (PCM) devices, based on the reversible phase transition between amorphous and crystalline state of a chalcogenide material, have been attracting much interest owing to its excellent properties such as high scalability, fast operation speed, high reliability, and compatibility with conventional CMOS processes<sup>1-2</sup> and is now on the verge of commercialization. Nevertheless, reliability issues of the device have not been much studied but have been getting all the more important for success in the market. In fact, according to some recent reports on the reliability of high density PCM devices<sup>3-4</sup>, the write/erase (W/E) cycling endurance has been degraded from  $10^{12}$  in the early stage of PCM development to about  $10^5$  nowadays, no better than that of Flash memories. Therefore, in-depth studies of the failure mechanism during W/E cycling of PCM devices are in great need.

There have been a few reports which characterized the cycling endurance and analyzed the failure mechanism of PCM devices<sup>5-6</sup>. In those reports, a PCM cell ended up with either type of failure, RESET-stuck (RSF) or SET-stuck failure (SSF) during W/E cycles. At RSF or SSF state, a PCM cell can no longer be programmed to the other state from the high or low resistance state, respectively. Although it was reported that SSF was the more common failure mode<sup>1</sup> and was due to Ge-depletion and Sb-enrichment inside the active volume of the phase change material in previous studies using Energy Dispersive X-ray Spectroscopy (EDS)<sup>5,7</sup>, the origin driving such compositional redistribution was not discussed in those reports. Herein, we provide experimental evidences that the electromigration (EM)<sup>8</sup> of components of the phase change material plays a critical role in the SSF mode of a PCM during W/E cycling.

## 2. EXPERIMENTS

We fabricated PCM devices with a pore-type structure and the fabrication process is described in Fig. 1(a)~(d). As a phase change material, we used  $\text{Ge}_2\text{Sb}_2\text{Te}_5$  (GST) deposited by RF-sputtering, the most widely used material for commercial development of PCM's. The film was found to have composition of  $\text{Ge}_{23.23}\text{Sb}_{24.12}\text{Te}_{52.65}$  in at. % from x-ray fluorescence analysis. A scanning electron microscope (SEM) image of the cross-section of a device is shown in Fig. 1(e). Device characteristics were investigated by the measurement system shown in Fig. 1(f), where a load resistor was used as a current limiter and an oscilloscope with the internal resistance of  $50 \Omega$  was connected in series with the device in order to monitor the waveform of a pulse during operations.

During W/E cycling, we monitored the changes in device characteristics such as the minimum current required for RESET programming ( $I_R$ ) and the threshold voltage ( $V_{th}$ ) of a device because these characteristics tend to vary sensitively with the state of the device during repeated operations<sup>9</sup>. Presuming that the SSF of a PCM may be caused by EM of components of the phase change material, we imposed RESET pulses of reverse bias polarity and examined the changes in  $I_R$  and  $V_{th}$  of SSF-PCM devices to find if they might result in reverse EM, curing the SSF-PCM. Upon reverse pulse (RP) operations, we performed an extended W/E cycling test to confirm a complete recovery of the device characteristics from the SSF state.

## 3. RESULTS & DISCUSSION

Fig. 2(a) shows the DC current-voltage (I-V) characteristic of a PCM device before W/E cycling test. A PCM device in its RESET state shows a threshold switching behavior in its I-V characteristic curve, which is thought to be due to trapping and de-trapping of charge carriers by trap states in the amorphous chalcogenide phase change material<sup>10-11</sup>. For our device,  $V_{th}$  was 0.8 V in the initial state.

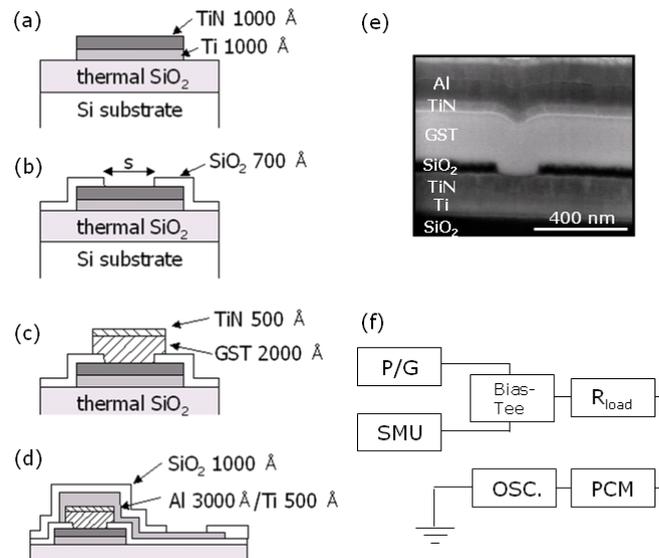


Fig. 1 (a)~(d) Sequence of fabrication process; (a) Bottom electrode (BE) patterning, (b) Pore patterning by electron beam (E-beam) lithography followed by reactive ion etching (RIE) process ( $s=200 \times 200 \text{ nm}^2$ ), (c) top electrode (TE) GST patterning, (d) m metal line patterning, passivation and pad opening process. (e) Cross-sectional scanning electron microscope (SEM) image of a PCM device, (f) schematic illustration of the measurement system.

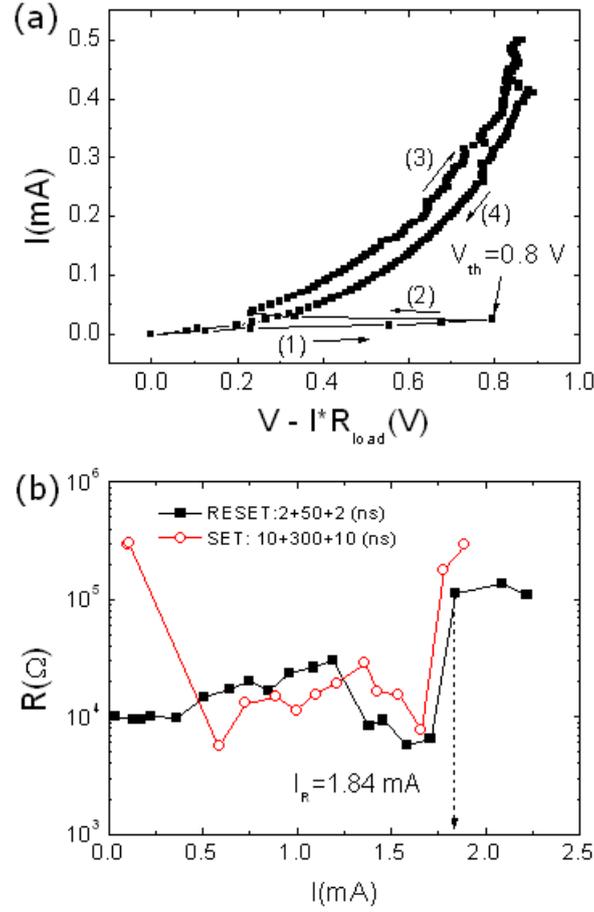


Fig. 2. Device characteristics of a PCM device before W/E cycling test; (a) DC I-V curve of a RESET-programmed PCM device, (b) R-I curve during RESET and SET programming process.

Fig. 2(b) shows the resistance of the device as a function of the amplitude of the current pulse (R-I curve) during the RESET and SET programming where leading edge (LEE), pulse width (PW), and trailing edge (TRE) of a pulse are indicated in the form of LEE+PW+TRE in the figure. From the RESET R-I curve,  $I_R$  was found to be 1.84 mA. For the SET R-I curve, we repeated the R-I measurement for varying PW of a SET pulse (not shown here) and found that the minimum SET PW was 100 ns. But SET resistance decreased with increasing SET pulse width up to 300 ns and then was saturated. From these results, we determined the operating conditions for a W/E cycling test as follows; 1.95 mA ( $\sim 1.9$  V), 2+50+2 ns for RESET operation and 0.6 mA ( $\sim 0.6$  V), 10+300+10 ns for SET operation.

The results of a W/E cycling test with the above operating conditions is shown in Fig. 3(a). The device showed no failure up to  $5 \times 10^5$  W/E cycles before reaching the SSF state. From Fig. 3(b), it should be noted that  $I_R$  increased to 2.03 mA in the SSF state; RESET programming can still be made but with a slightly increased current! As for  $V_{th}$  of the device, it slowly decreased after  $1 \times 10^4$  cycles and then drastically after  $4.6 \times 10^5$  cycles before threshold switching no longer took place after  $6.9 \times 10^5$  cycles as shown in Fig. 3(c).

These changes in  $I_R$  and  $V_{th}$  may be well explained on the basis of a recent experimental finding *i.e.* Ge-depletion and Sb-enrichment mentioned above. Firstly, as for the increase in  $I_R$ , it is thought to be caused by decreased dynamic resistance ( $R_{dyn}$ ), the resistance of the device above the melting temperature of GST, due to excessive metallic Sb contents. Since a decrease in  $R_{dyn}$  would lessen Joule heating at the same current, the minimum current ( $I_R$ ) to melt a certain volume of GST is expected to increase. Secondly, as for the decrease in  $V_{th}$ , it can be also understood along the same line in reference to a recent report where  $V_{th}$  of a PCM device using  $Ge_2Sb_2Te_5$ ,  $Ge_1Sb_2Te_4$  and  $Ge_1Sb_4Te_7$  was

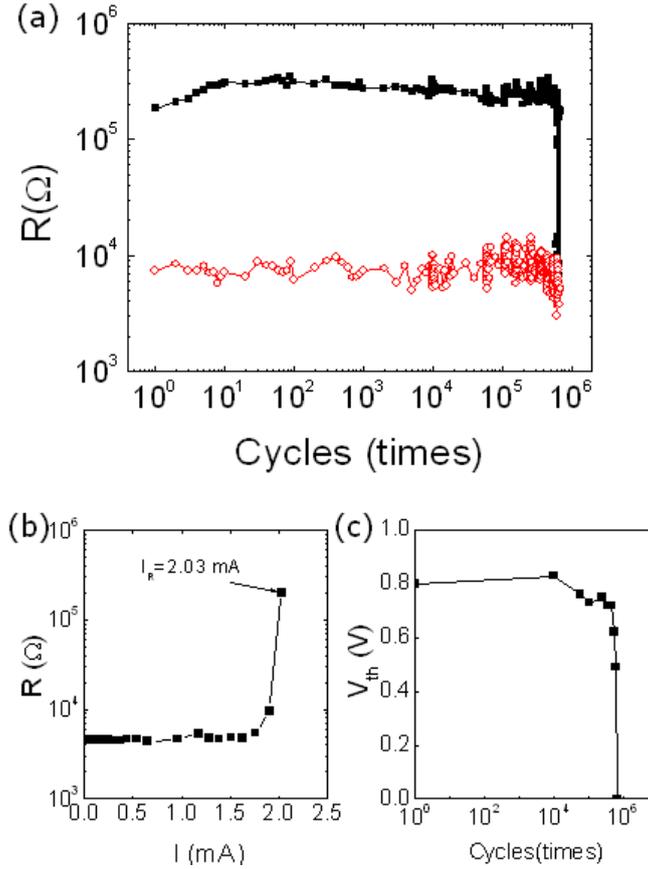


Fig. 3 (a) Result of a W/E cycling test of the PCM device shown in Fig. 2, (b) R-I curve of the device in the SSF state after  $6.9 \times 10^5$  cycles, (c) the change of  $V_{th}$  during the cycling test.

measured<sup>13</sup>. In the report,  $V_{th}$  was found to decrease with decreasing Ge/Sb ratio for a nearly constant portion of Te in the respective unit cell (Ge:Sb:Te=22:22:56 for  $Ge_2Sb_2Te_5$ , 14:29:57 for  $Ge_1Sb_2Te_4$ , and 8:33:58 for  $Ge_1Sb_4Te_7$ ). Therefore, the changes of device characteristics seem to support the results by EDS that the SSF is caused by Ge-depletion and Sb-enrichment.

As for the origin driving such compositional redistribution, we suspected EM as the most probable since the current density was about  $5 \times 10^6$  A/cm<sup>2</sup> and the temperature exceeded 700 °C during RESET operations, a sufficient condition for EM to take place. In order to find out if EM is indeed responsible, we examined the effect of RP operations with the opposite bias polarity (TE: grounded, BE: +) to that (TE: +, BE: ground) of the normal operations. We expected RP operations to measurably cure the SSF-PCM device if the SSF state was reached by EM of components of the phase change material. To provide a sufficient driving force for the reverse EM, we used a RP of the same duration (50 ns) as that of the normal RESET pulse but of the increased amplitude by about 10%, *i.e.* 2.2 mA. We examined the change in  $V_{th}$  and  $I_R$  of the device during successive RP operations and the results are shown in Fig. 4(a) and Fig. 4(b), respectively. Notice that  $V_{th}$  was recovered to 0.58 V after two RP operations and to 0.77 V after ten RP operations, which was nearly the same as the initial  $V_{th}$  (0.8 V). In addition,  $I_R$  was recovered to 1.84 mA after five RP operations, which was exactly the same as the initial  $I_R$ . With the device recovered from the SSF state by ten RP operations, we performed a W/E cycling test to observe that the device could endure another  $1 \times 10^5$  cycles (Fig. 4(c)). Tens of devices with the same device structure were tested and most of them (over 90 %) were repaired by similar RP operations.

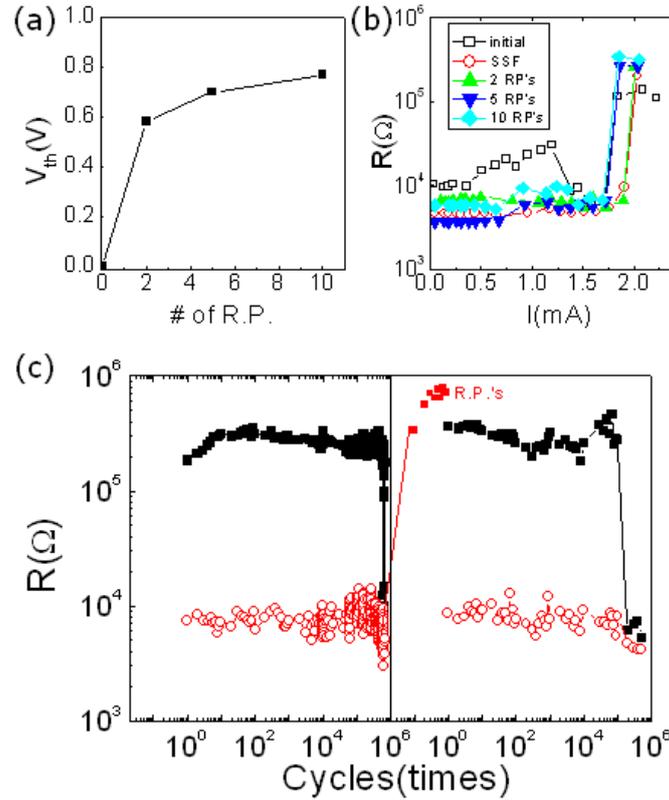


Fig. 4 Change of (a)  $V_{th}$  and (b) R-I curves of a SSF-PCM device after RP operations, (c) a W/E cycling test of a PCM device repaired from SSF state by ten RP operations (right side). For comparison, the result of the initial W/E cycling test is shown in the left side.

We believe that these results give unequivocal evidences that EM is a major cause of the SSF of a PCM device. As to how such a small number of RP's are able to repair the SSF-PCM device, it may be understood by considering that the restoring force would consist of the reverse EM force reinforced by the diffusion force to remove the concentration gradient due to the compositional redistribution during normal operations to SSF. More quantitative study including the optimization of RP operations for extending lifetime of a PCM device will be followed.

#### 4. CONCLUSION

In conclusion, we observed that  $V_{th}$  decreased and  $I_R$  increased with W/E cycles of a PCM device and these changes were consistent with recent results addressing Ge-depletion and Sb-enrichment as a cause of SSF. In addition, we found that the W/E cycling endurance as well as the above device characteristics could be recovered by several RP operations with the reverse polarity to that of the normal operation. From these results, we believe that the SSF of a PCM device is brought about by compositional redistribution due to EM of components. We also suggest that a deliberate design of a programming method based on this mechanism can be applied to high density PCM devices for extended lifetime.

This study was supported by National Research Program for 0.1 Terabit Non-Volatile Memory Devices, sponsored by the Korean Ministry of Commerce, Industry, and Energy (MOCIE).

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