

Electric-field-enhanced atomic transport in phase change materials as the origin of the set-stuck failure in PRAM

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ABSTRACT

Electromigration in molten and crystalline $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) was characterized using pulsed DC stress to an isolated line structure. In the electromigration of molten GST, the effects of N- and Bi-doping on the electromigration were also studied to find the solution for inhibiting the electromigration. When a single pulse ($\sim 10^{-3}$ s) was applied to the lines, both undoped and doped GST lines were melted by Joule heating, and Ge and Sb atoms migrate to the cathode, whereas Te atoms migrate to the anode. This elemental separation in the molten GST was caused by an electrostatic force-induced electromigration. The migration rate of the constituent atoms in the undoped GST was similar to that in Bi-doped GST, but was decreased by N-doping. Under applying a 10 MHz pulsed DC, the melting by Joule heating was inhibited, and electromigration in the crystalline state was detected. All constituent elements migrated to the cathode, which is originated from the electromigration by hole-windforce. In addition, we investigated the effect of the back diffusion force due to chemical potential differences between in an intermetallic compound and a eutectic alloy from the comparison of the electromigration rates between in GST and in $\text{Ge}_{15}\text{Sb}_{85}$.

Key words: $\text{Ge}_2\text{Sb}_2\text{Te}_5$, electromigration, doping, etc.

1. INTRODUCTION

Phase change random access memory (PRAM) exploits the resistance difference between the amorphous and crystalline phases in chalcogenide alloy. Because the two phases are switched by electric Joule heating, PRAM suffers from the electrical stressing with high current density and thermal cycling. The severe operational conditions in PRAM cause several reliability problems, such as *set-stuck* and *reset-stuck* failure.^{1,2} It has been reported that endurance failures of PRAM are induced by stoichiometric changes (*set-stuck*) and void formation (*reset-stuck*) in the phase change material.³ When a high electric field or current is applied to materials, electric field- or current-induced atomic transport, electromigration, occurs and induces the stoichiometric change in the phase change material. Therefore, electromigration can be the origin of the *set-stuck* failure because of the repetitive electrical stressing during the PRAM operation. However, the electromigration behavior in phase change memory has not been thoroughly investigated because it is difficult to study in tiny and asymmetric PRAM cell structures, and numerous read and write operations are needed to evaluate the electromigration characteristic in the cell. Therefore, we employed a model study to investigate the electromigration in PRAM using a line-shape structure with large size (20 μm length, 2 μm width, and 300 nm thickness) in order to simplify the physical origin and to ease the analysis and pulsed DC stressing. The electromigration behavior in the phase change materials needs to be studied in both the molten and solid phases because the phase change material repeatedly changes between a molten phase and a crystalline phase. Moreover, the study on the solution for inhibiting the electromigration is also necessary to improve the reliability of PRAM. The addition of an external dopant can be a solution to inhibit the electromigration, as well as to improve the electrical property or thermal stability of PRAM.^{4,5} Dopants are classified into interstitial-type, such as C, N, and O, and substitutional-type, such as Bi, Sn, and Se, according to the atomic site that dopants occupy. Because they induce different bonding characteristics, microstructures, and other physical properties, the effects to the electromigration will be also different. In this study, we investigated the electromigration behavior in the molten and the crystalline phase change materials using the model study. In addition, the effects of N- and Bi-doping on the electromigration of

molten $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) were studied by comparing the atomic migration rate of doped GST with that of undoped GST.

2. EXPERIMENTS

We applied pulsed-DC stress to the undoped, N-doped, and Bi-doped GST lines which were made using the lift-off method. (Fig. 1) GST films were deposited using DC magnetron sputtering onto a thermally oxidized Si-wafer with oxide thickness of 10 nm. N was doped in GST film with 4.3 at. % by N_2 gas flowing during DC sputtering. Bi-doped GST was prepared by co-sputtering of $\text{Ge}_2\text{Sb}_2\text{Te}_5$ and $\text{Ge}_2\text{Bi}_2\text{Te}_5$, and powers for the targets were 80 and 40 W, respectively. Bi concentration was 6.6 at. %, and the consequent stoichiometry was $\text{Ge}_2\text{Bi}_{0.6}\text{Sb}_{1.4}\text{Te}_5$. The lines were isolated by Mo contact pads to prevent artifacts from a large source/sink of diffusing atoms in the case of using GST pads. This line structure also was passivated with Si_3N_4 film to prevent the vaporization of element. Pulsed-DC was performed using a pulse generator by two methods: the first is a dc-type single pulse of 6.5 V for undoped and Bi-doped GST and 5 V for NGST with a duration on the order of milliseconds. The second is repetitive electrical pulse with high frequency (10 MHz) with a current density of 0.5 MA/cm^2 which allows the observation of electromigration in the crystalline state. The voltage drop and the current across the line were monitored using an oscilloscope with 50Ω input impedance. The compositional variation was observed in the longitudinal direction with the change in the duration of the applied electrical stress. The concentration of each element was detected by wavelength-dispersive X-ray spectroscopy (JXA-8900R).

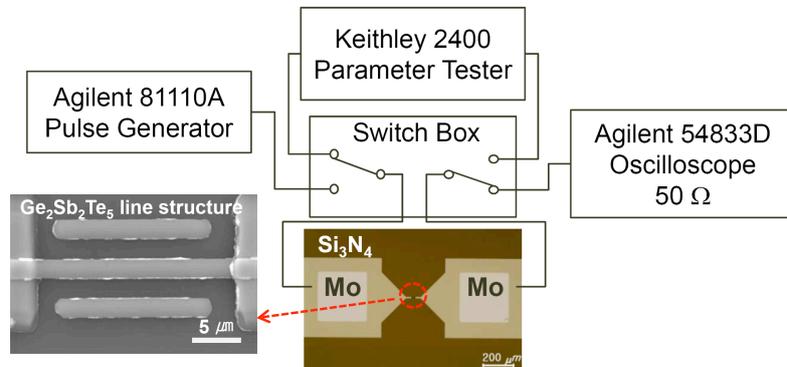


Figure 1. Optical microscope image and magnified SEM image of $\text{Ge}_2\text{Sb}_2\text{Te}_5$ line test sample with Mo contacts and a diagram of the test setup used in this experiment.

3. RESULTS & DISCUSSION

Electromigration of molten-phase GST could be observed using high-amplitude millisecond-duration pulse. When the DC-type pulse of 6.5 V was induced to the undoped GST line, the line was melted by Joule heating, and the Ge and Sb atoms migrate to the cathode, whereas Te atoms migrate to the anode (Fig. 2(a)). The direction of migrating atoms can be explained by the diffusion of ionized atoms in the molten state by electrostatic force. The electronegativity of Ge, Sb, and Te is 4.6 eV, 4.85 eV, and 5.49 eV, respectively.⁶ Therefore, Te atoms become anions, whereas Ge and Te atoms become cations. The difference of drift velocity in the electromigration is clearly shown in the comparison of the number of migrated atoms (Δn_i) across the center of the line normalized by the initial number concentration (C_i) versus diffusion time. (Fig. 3) In addition, the migration rate was quantified by calculating the product of the diffusion coefficient and the effective charge (DZ^*) of constituent atoms. The DZ^* for Ge, Sb, and Te in molten phase of undoped GST was calculated from the number of migrated atoms to be 3.81 , 4.26 , $2.66 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, respectively. (Fig. 4) Using the reported diffusion coefficients,⁷ Z^* values are calculated to be 0.28, 0.38, and -0.29 for Ge, Sb, and Te.

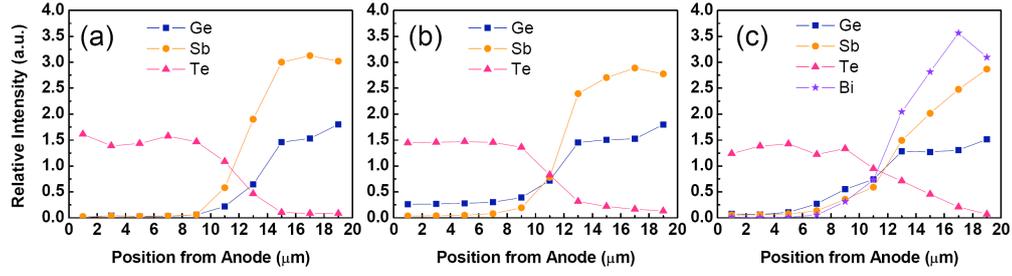


Figure 2. Composition profiles from WDS analysis after electromigration in *molten* phase shown as a relative peak intensity of (a) the GST line, (b) the N-doped GST line, and (c) the Bi-doped GST line compared to standard samples.

The elemental separation by electromigration was also observed in the molten phase of N-doped GST and Bi-doped GST lines. The directions of atomic migrations in the doped GST lines were same to those in the GST line, which indicated that N- and Bi-doping did not affect the ionization tendency of the constituent elements (Fig. 2(b),(c)). However, the doped GST lines showed the differences in the DZ^* values of Ge, Sb, and Te from un-doped GST. In N-doped GST, the DZ^* of Ge, Sb and Te were $1.57, 2.65, 1.66 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, respectively, which are smaller than those in undoped GST indicating that the nitrogen dopant retarded the diffusion of Ge, Sb, and Te (Fig. 4).⁹ Especially, Ge shows the largest decreasing rate in the DZ^* value. The decrease in DZ^* may be caused by the decrease of free volume because N atoms occupy the vacancy sites or grain boundary, and the formation of germanium nitride induces the large decrease in DZ^* of Ge. In Bi-doped GST, DZ^* of Ge and Sb were similar to those in undoped GST, but DZ^* of Te was slightly decreased to $2.02 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$. Bi-doping cannot inhibit the electromigration of GST because Bi as the substitutional dopant merely affects the free volume in GST (Fig. 4).

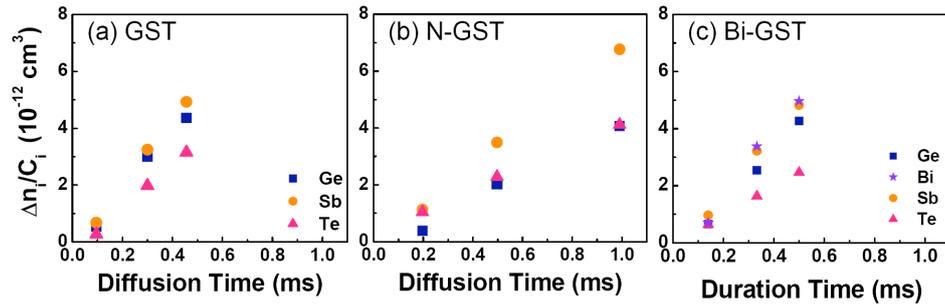


Figure 3. Number of migrating atoms (Δn_i) in (a) the GST line, (b) the N-doped GST line, and (c) the Bi-doped GST line normalized by the initial concentration (C_i) of each element.

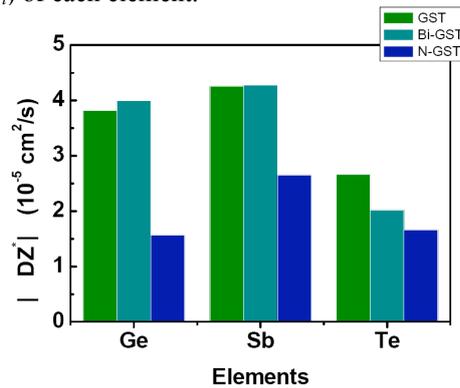


Figure 4. DZ^* of constituent elements in the un-doped, N-doped, and Bi-doped $\text{Ge}_2\text{Sb}_2\text{Te}_5$.

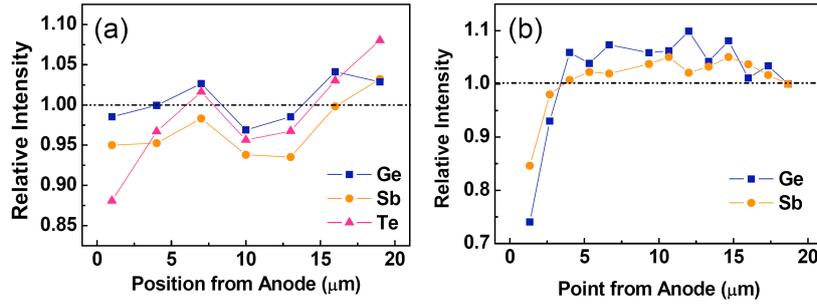


Figure 5. Composition profiles from WDS analysis after electromigration in *crystalline* phase shown as a relative peak intensity of (a) the GST line and (b) the Ge₁₅Sb₈₅ line compared to standard samples.

The electromigration in the crystalline phase of phase change materials was compared between in intermetallic compound (GST) and eutectic alloy (Ge₁₅Sb₈₅). Under a repetitive pulse of 10 MHz with a current density of 5.0×10^5 A/cm², the undoped and doped GST line was maintained in a solid state and melting was not observed. After the stress for 20 h, Ge- and Sb-rich region near the anode are observed, whereas Te-rich region are observed near the cathode (Fig.) in undoped GST line. In order to confirm the direction of mass flow, comparisons of the relative intensity from WDS of each element were also investigated (Fig. 5). The relative intensity is taken to be the normalized characteristic peak intensity by the peak intensity from a dummy pattern that is not connected to probing pads. The relative intensity reveals that all constituent elements migrate to the cathode. The mass transport of all atoms to the cathode means that atoms are migrated by the hole-wind force. It is well known that GST has p-type

conductivity because of the intrinsic vacancies. Based on k -factor analysis, we could also calculate the DZ^* to be 2.19, 2.97, 11.36×10^{-15} cm² s⁻¹ for Ge, Sb, and Te, respectively.⁸ Because the flux of Te is about twice as the flux of Ge and Sb, atomic concentration shows Ge- and Sb-rich phases near the anode and a Te-rich phase near the cathode. The Ge₁₅Sb₈₅ line also showed the mass transport of constituent elements from the anode to the cathode in crystalline phase. Therefore, it is known that electromigration in Ge₁₅Sb₈₅ induced by the hole windforce. However, the DZ^* values in Ge₁₅Sb₈₅ are calculated to be 9.92, 3.82×10^{-15} cm² s⁻¹ for Ge and Sb, respectively, which are larger than those in undoped GST. Especially, the DZ^* value of Ge in Ge₁₅Sb₈₅ is about five times higher than that in GST. The smaller DZ^* values in GST indicate that the back driving force which is caused by the increase of chemical potential of elements due to concentrational variations retards its electromigration in the intermetallic compound. In the eutectic alloy, Ge₁₅Sb₈₅, concentrational variation of constituent elements does not cause the increase of the chemical potential. In addition, the DZ^* values in the both crystalline state is ten order of magnitude smaller than in the molten state. Therefore, the phase change volume in PCM is vulnerable to the failures due to the compositional variation of phase change materials during the reset operation.

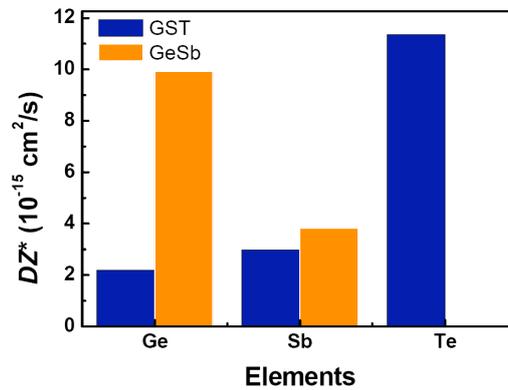


Figure 6. Comparison of DZ^* values of constituent elements in the crystalline GST and crystalline Ge₁₅Sb₈₅.

4. CONCLUSION

We showed that the model study using a line structure is useful to investigate the failure mechanism and to evaluate the resistance against failure of phase change materials without the need to manufacture complex cell structures and conduct a large number of endurance tests. This study on electromigration for the mechanism of compositional variation may provide useful information to improve the endurance characteristics of PRAM. It is also expected that the role of dopants can be understood through a study with other doping elements using this test method, and such a study will provide the most appropriate dopant selection to improve the reliability of PRAM.

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Biographies

Young-Chang Joo received the B.S. and M.S. degree in metallurgical engineering from Seoul National University, Seoul, Korea in 1987 and 1989, respectively, and Ph. D degrees in electronic materials from Massachusetts Institute of Technology (MIT), Cambridge, MA, USA. From 1995 to 1997, he was with Max-Planck-Institute for Metal Research, Stuttgart, Germany as visiting scientist. From 1997 to 1999, he was with Advanced Micro Devices, Inc. (AMD), CA, USA as Senior Device Engineer working on reliability issues of advanced interconnects. He joined Seoul National University, Seoul, Korea in 1999 and is currently a professor in Department of Material Science and Engineering. His current research interests include electromigration, stress migration, and TDDB of damascene Cu interconnects, reliability of electronic packaging including 3-D packaging, processing and materials of flexible devices, as well as reliability of new memory devices such as Phase Change memories.