

Formation of Threshold Switching Chalcogenide for Phase Change Switch Applications

Ki Su Bang and Seung-Yun Lee*

Department of Advanced Materials Engineering, Hanbat National University, Daejeon 305-719

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The programmable switches which control the delivery of electrical signals in programmable logic devices are fabricated using memory technology. Although phase change memory (PCM) technology is one of the most promising candidates for the manufacturing of the programmable switches, the threshold switching material should be added to a PCM cell for realization of the programmable switches based on PCM technology. In this work, we report the impurity-doped $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) chalcogenide alloy exhibiting threshold switching property. Unlike the GST thin film, the doped GST thin film prepared by the incorporation of In and P into GST is not crystallized even at the postannealing temperature higher than 200°C . This specific crystallization behavior in the doped GST thin film is attributed to the stabilization of the amorphous phase of GST by In and P doping.

Keywords : Chalcogenide, Programmable switch, Phase change memory, Threshold switching, Doping, Crystallization

I. Introduction

The phase change switch is a type of programmable switches that are contained in a programmable logic device (PLD). The manufacturing technology is based on phase change memory (PCM) technology [1-4]. The role of the switch in PLD is to control the delivery of electrical signals between logic blocks while the switches are located between logic blocks. Currently, static random access memory (SRAM) [5] and flash [6] technologies have been already commercialized and are being widely used. PCM technology [7,8], as next-generation switch manufacturing technology, is considered to have great potential of commercialization due to non-volatility and high speed of PCM.

PCM cells include phase change materials, as active materials, that consist of chalcogenides [9,10] containing chalcogens or antimonides containing antimonies [11,12]. Phase change materials undergo a reversible phase change according to external energy input between high-resistance amorphous and low-resistance crystalline phases

Programmable switches are comprised of pass transistors and memory cells; pass transistors transmit electrical signals through channel regions, and memory cells control on/off states of pass transistors. If normal PCM cells are applied in a switch device, electrical signals are transferred toward logic blocks unnecessarily since the pass transistor gets turned on unavoidably during memory cell pro-

* [E-mail] sy_lee@hanbat.ac.kr

gramming. To solve this trouble, a threshold switching material that shows only threshold switching properties should be added to a PCM cell [3,4]. A threshold switching material [13] has a property that it goes back to a high resistance of more than 100k ohms upon the removal of the electric field although it keeps a low resistance of hundreds of ohms during the application of the electric field that exceeds the threshold value. In the consideration of compatibility and manufacturing cost, threshold switching materials whose composition is similar to that of phase change materials should be secured. Thus, in this study, chalcogenide thin films were formed after impurities were doped on $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) alloys, which are widely known for a phase change material, and then the electrical and physical properties of the films were evaluated. In order to investigate the switching behaviors of GST and impurity-doped GST thin films, surface morphology and sheet resistance changes by postannealing were comparatively analyzed, and current variations with applied voltage were measured.

II. Experimental Procedures

GST and doped GST films were prepared by RF magnetron sputtering. As sputtering targets, 2-inch-GST and doped GST targets were used, respectively. P-type silicon wafers were used for the substrate. A $1.0 \times 1.0 \text{ cm}^2$ InP single crystal wafer was attached on the surface of a 2-inch-GST target to make the doped GST target. In order to minimize contamination from the target surface, pre-sputtering was conducted for approximately 10 minutes before film deposition. With 50W of electric power applied, under the pressure of 1.3×10^{-3} torr, the films were formed. To investigate changes of properties of the chalcogenide thin film with temperature, 20-minute post-annealing was done in an Ar ambient. The surface

morphology of two kinds of chalcogenide thin films were observed using scanning electron microscopy (SEM), and the sheet resistance was measured through a 4-point probe method. The elements included in the doped GST film were determined by Auger electron spectroscopy (AES). Crystallization behavior in the doped GST chalcogenide films was observed using differential scanning calorimetry (DSC).

A test structure as shown in Fig. 1 was made to measure the current-voltage characteristics of chalcogenide thin films. A 300 nm-thick TiW film, as the bottom electrode, was formed under the silicon wafer. A 200 nm-thick chalcogenide thin film was deposited on the silicon wafer, and then, a 300 nm-thick TiW film was deposited. A metal mask was positioned on the specimen, sputtering was performed and then, round-shaped TiW top electrodes with a diameter of $200 \mu\text{m}$ were formed. The current that flowed through the test structure when voltage was applied to the top and bottom electrodes was measured using a probe station and a semiconductor parameter analyzer.

III. Results and Discussion

Fig. 2 shows the AES spectrum of the surface of

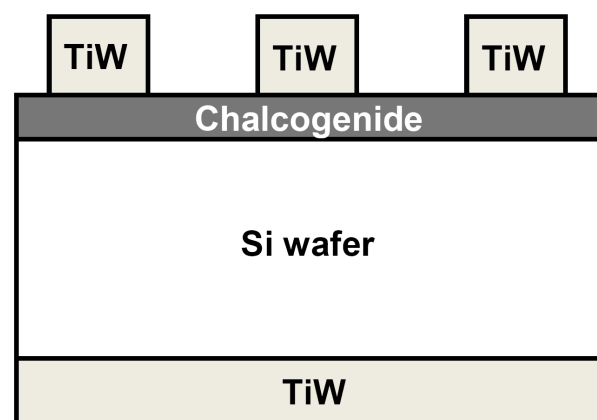


Figure 1. Schematic of a test structure including a chalcogenide thin film.

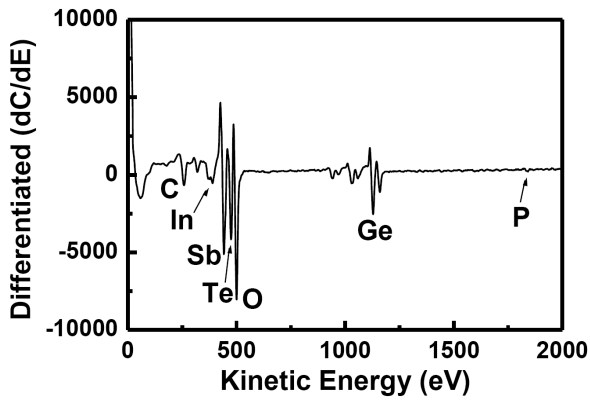


Figure 2. AES spectrum of the surface of a doped GST thin film.

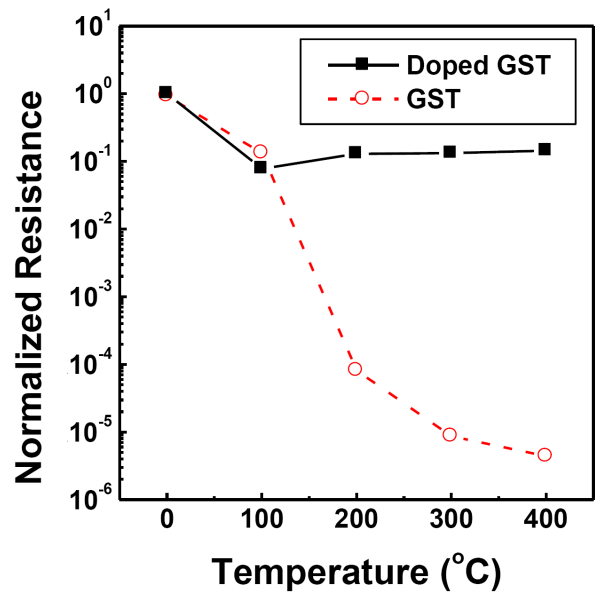


Figure 4. Normalized resistance changes of doped GST and GST thin films annealed at various temperatures.

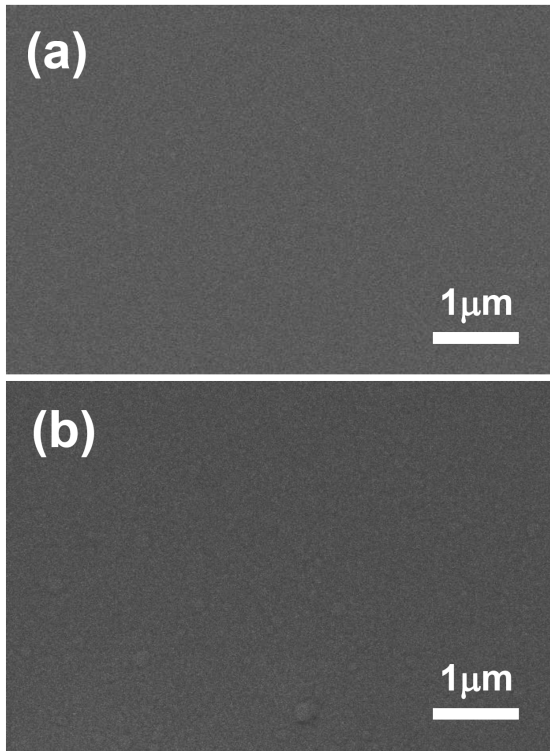


Figure 3. Plan-view SEM images of (a) doped GST and (b) GST thin films annealed at 300°C.

the doped GST thin film formed by sputtering. The In LMM peak and P KLL peak are observed at approximately 390 eV and 1840 eV, respectively, in addition to the peaks of Ge, Sb and Te that compose the matrix of GST. Thus, in case of sputtering using the doped GST target, it was found that the In and P doping elements were easily added to the matrix.

The surface morphology of GST and doped GST thin

films where postannealing was done at 100°C and 200°C was examined, and then, it was found that both the chalcogenide thin films kept flat-surfaced similarly to as-deposited specimens. On the other hand, Fig. 3 shows the different results of surface morphology of GST and doped GST thin films annealed at 300°C. The surface structures of the two types of chalcogenide thin films were dissimilar to each other. The doped GST film showed flat surface whereas the GST film had a number of round agglomerates. From these results, a conclusion is made that In and P that are added to GST play a critical role in maintaining flat surface of the GST film.

As seen in Fig. 4, variations of normalized resistance of GST and doped GST thin films with annealing temperature increase were compared. The normalized resistance was calculated by dividing the sheet resistance value of the film by the sheet resistance value of the as-deposited specimen. When the doped GST film was annealed at 100°C, a decreased resistance value was measured compared to the as-deposited specimen, but relatively constant resistance

values were measured during annealing at over 200°C. On the other hand, resistance values of the GST film were greatly reduced with annealing temperature increase. Resistivity variations according to annealing temperatures of GST films are known to be associated with the generation of phases with different resistivity values [14]. If the GST thin film is in amorphous state, high resistivity similar to that of insulators is shown, whereas if the GST thin film is in crystalline state, relatively very low resistivity is shown. The resistance variations of the GST thin film as observed in Fig. 4 correspond to the resistance reduction occurring during the transition from the amorphous phase to the crystalline phase of face centered cubic (FCC) structure at crystallization temperatures between 100°C and 200°C [14]. Differently from the GST thin film, in the doped GST thin film, resistance reduction did not occur with annealing temperature increase. Therefore, it implies that the crystallization of the GST thin film is inhibited by In and P doping, which is supported by the results of DSC as in Fig. 5. An exothermic peak was observed on the GST film at approximately 153°C due to the

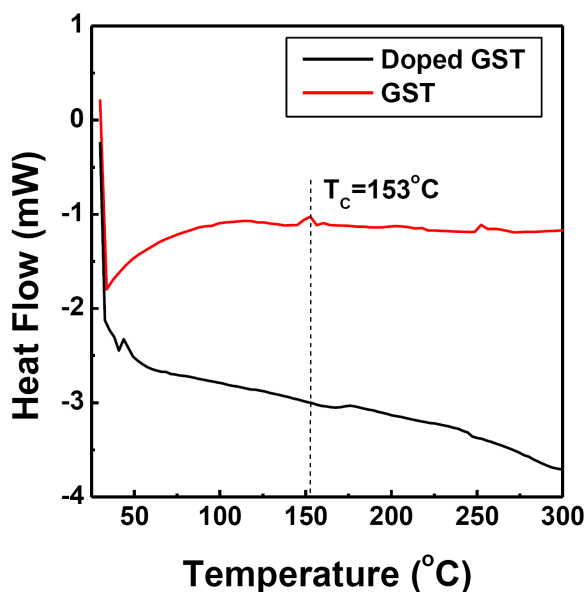


Figure 5. DSC thermogram of doped GST and GST (heating rate of 10°C/min).

crystallization from the amorphous phase to the crystalline phase, but not observed on the doped GST thin film. Thus, it is concluded from the results of resistance variations with annealing temperature and DSC that GST and doped GST films exhibit different crystallization behaviors and the doped GST thin film does not show a phase change from an amorphous phase to a crystalline phase, differently from the GST thin film. Difference of surface morphology that is observed in Fig. 3 can also be explained by difference of crystallization behaviors of the two chalcogenide thin films. In other words, the doped GST thin film keeps flat-surfaced without crystallization, but, since crystallization takes place in the GST thin film, grains are produced and round agglomerates are observed.

The reason for the inhibition of crystallization in the GST thin film with In and P doping might be due to the fact that both In and P enhance stability of the amorphous phase. It is known that the addition of In to a Te-based chalcogenide like GST results in the stabilization of the amorphous phase because the formation of Te metal crystals becomes difficult [15]. Besides, it was reported that if group VA elements such as P that has a larger coordination number than chalcogens are added to a Te-based chalcogenide, as network connectivity increases, the phase change from an amorphous phase to a crystalline phase is inhibited [16]. Eventually, the doped GST thin film formed by the incorporation of In and P into GST can remain in an amorphous phase despite a prostannealing process at over 200°C because the doping elements inside the doped GST thin film can contribute to the stabilization of the amorphous phase. On the other hand, if the stability of an amorphous phase is increased, the phase change resulting from memory switching is inhibited. Thus, the doped GST thin film can be more likely a threshold switching material. Fig. 6 shows the current-voltage characteristics of the doped GST thin film that were measured using the test structure containing the doped GST thin film,

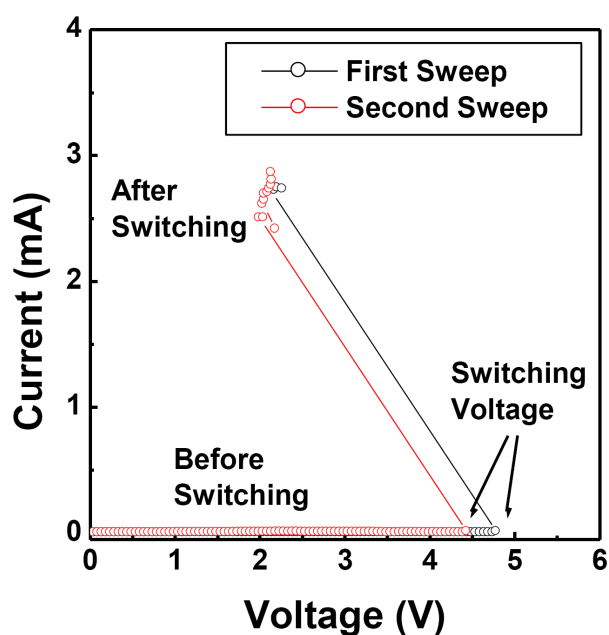


Figure 6. Current vs voltage for a test structure including a doped GST thin film.

The doped GST thin film did not show memory switching but revealed threshold switching properties at 4.4 to 4.8 V of switching voltage. Since threshold switching materials come back to the original high resistance state after the termination of voltage sweep, the current-voltage characteristics of repeated threshold switching are shown as in Fig. 6. However, since resistance in memory switching materials such as GST is decreased due to the occurrence of memory switching during the first sweep, threshold switching does not occur in the memory switching materials during the second sweep. Conclusively, if adequate doping elements are added to GST, crystallization can be prevented, and chalcogenides that exhibit only threshold switching properties can be secured.

IV. Conclusions

Doped GST thin films were formed using the doped GST target through sputter deposition, and the prop-

erties of doped GST and GST thin films were comparatively analyzed. The doped GST film was flat-surfaced during postannealing at 300°C, which was different from the GST thin film. As annealing temperature was increased, the sheet resistance of the GST thin film was greatly reduced, whereas the sheet resistance of the doped GST thin film was relatively constant. The surface morphology and resistance characteristics of the doped GST thin film are attributed to the fact that In and P addition to GST inhibits the crystallization of the amorphous phase of GST. Unlike GST, the doped GST thin film showed only threshold switching behavior. Thus, when adequate doping elements are added to the GST thin film, threshold switching chalcogenides can be secured for realization of the phase change switches.

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