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Doped Sb_2Te_3 Phase-Change Materials for High Performance Artificial Synaptic Device

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Abstract. In this work, N-O codoped fast-speed Sb_2Te_3 chalcogenide materials fabricated by reactive sputtering were systematically investigated using X-ray diffraction and sheet resistance measurements in order to greatly improve the thermal stability of chalcogenide-based synapses. Experimental results exhibited that crystallization temperature can be greatly increased by doping N and O into Sb_2Te_3. The resistivity of Sb_2Te_3 was also significantly increased after doping. These results imply that high performance synaptic devices with high stability and low writing current become possible if the doped chalcogenide materials with high crystallization and resistivity are used in the devices.

1. Introduction

There are more and more complicated data required to be stored and processed in the internet of things (IoT) era. For instance, cognitive and rapid data processing technologies become essential when we develop future's self-driving cars. However, these technologies are currently based on the von Neuman architecture where large amounts of data need to be shuttled back and forth at high speeds during the execution of these computational tasks [1]. The performance bottleneck and significant power inefficiency are often caused in this traditional architecture. In recent years, researchers in the world are trying to solve these problems by using some novel architectures such as our brain, which is composed of innumerable neurons and synapses. Until now, many materials such as polymer, graphene, sulfide and oxide have been proved to mimic the fundamental synaptic functions [2]. For example, Ohno et al. demonstrated controllable short-term plasticity and long-term plasticity based on formation of Ag filament using Ag_2S sulfide [3]. Tan et al. demonstrated metaplasticity which stores the previous changes of synaptic plasticity and different behaviors according to the history of synaptic plasticity using WO_3 oxide [4]. However, these materials are often not able to provide a stable and fast change, which is required in cognitive and image processing. In recent years, chalcogenide-based synapses attract much attention around the world, which are based on low-power-consumption and stable amorphous-crystalline phase change [5]. Conventional Sb_2Te_3 chalcogenide is a p-type semiconductor and widely used in the phase change devices. In this work, N-O codoped Sb_2Te_3 chalcogenide phase-change materials fabricated by reactive sputtering are systematically investigated using X-ray diffraction (XRD) and sheet resistance measurements in order to greatly improve the thermal stability of chalcogenide-based synapses.

2. Experimental method

A series of about 200-nm-thick Sb_2Te_3, N-O codoped Sb_2Te_3 film samples with a 20-nm-thick ZnS-SiO_2 capping layer on a Si or glass substrate was prepared by changing the flow rate during sputtering. The chalcogenide films and the capping layers were deposited using radio frequency sputtering equipment (MNS-3000-RF, ULVAC, Inc.) at a background pressure below 5×10^{-5} Pa and a sputtering pressure of 0.2 Pa. The crystal structures of these films were characterized by an X-ray diffractometer

(RINT 2000, Rigaku Co.) after the films were annealed on a hot plate. The sheet resistance, as a function of the annealing temperature of the films, was measured using square-shaped film samples defined by Ti electrodes.

3. Experimental results

Fig. 1(a) shows XRD patterns of undoped Sb_2Te_3. Several peaks were observed even in the as-deposited Sb_2Te_3 film. This indicated that the Sb_2Te_3 film crystallized during sputtering. This is in good agreement with the fact that the crystallization temperature of Sb_2Te_3 film is below 100 ℃. These peaks in the XRD patterns remained until 200 ℃. The Sb_2Te_3 film was identified as a face centered cubic (FCC) crystal structure from these peak positions. The crystal structure of Sb_2Te_3 belongs to space group $R\bar{3}m$. The appearance of a pattern at 250 ℃ implied that a phase transformation of the Sb_2Te_3 films from FCC to the other phase occurred between 200 and 250 ℃. The phase was identified as a hexagonal (HEX) crystal structure according to the XRD pattern at 250 ℃. Compared with XRD patterns of Sb_2Te_3, no peaks were observed in the as-deposited, 100 ℃ and 150 ℃ annealed N-O codoped Sb_2Te_3-N1.0-O1.0 films as shown in Fig. 1(b). The numbers after N and O represent the flow rate (sccm) of gas when the films were sputtered. This indicated that these films were amorphous. The doped Sb_2Te_3 films annealed at temperatures from 200 to 350 ℃ had only a HEX structure. The experimental conditions for film preparation and summary of phase changes of the films are shown in Fig. 1(c). And according to our calculation from the peaks of XRD patterns, the crystal was refined from around 7 nm to 2 nm in diameter by codoping.

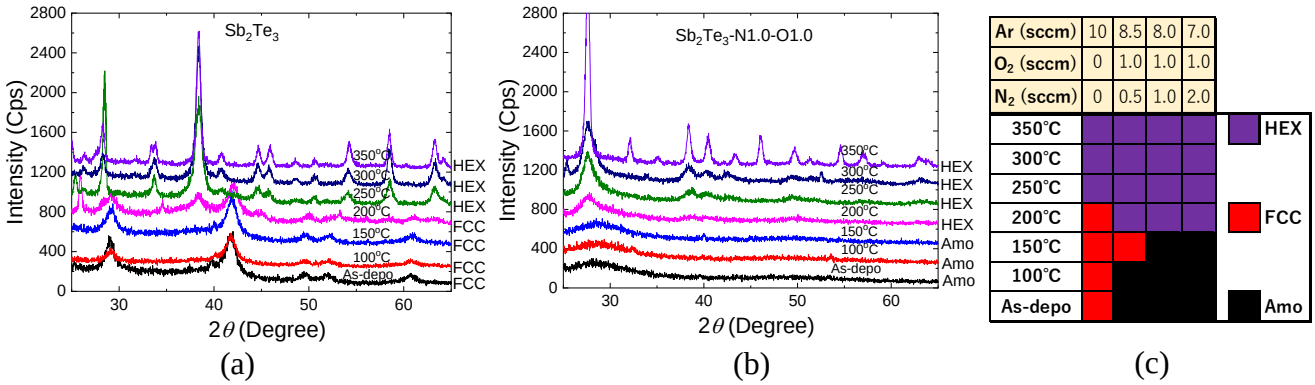

Fig. 1 (a) XRD patterns of undoped Sb_2Te_3, (b) XRD patterns of doped Sb_2Te_3, (c) Experimental conditions for film preparation and summary of phase changes of the films.

Fig. 2 shows the sheet resistance of Sb_2Te_3 and N-O codoped Sb_2Te_3 films as a function of annealing temperature up to 350 ℃. The sheet resistance of the as-deposited Sb_2Te_3 film was as low as around 30 kΩ because the as-deposited Sb_2Te_3 film was crystalline. The sheet resistance of the Sb_2Te_3 film decreased gradually when the film was annealed at the temperature in a range of 100 ℃ to 350 ℃ because crystal growth and the phase transition from FCC to HEX occurred. N-O codoped Sb_2Te_3 films had a much higher sheet resistance than the as-deposited crystalline Sb_2Te_3 film. The sheet resistance changes of all of these doped films exhibited a similar trend with increasing the annealing temperature. It should be

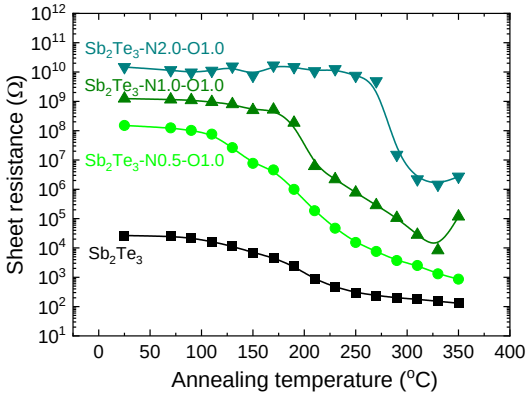

Fig. 2 Sheet resistance as a function of annealing temperature

noted that Fig. 1(c) suggests that the FCC-HEX change for Sb_2Te_3-N2.0-O1.0 sample occurred in the range from 150 to 200 ℃ but the resistivity drop in Fig. 2 took place at a temperature of about 275 ℃. The big difference between resistance change temperature and phase change temperature strongly suggests that the resistivity change should be caused mainly by the crystal growth, instead of the phase transition from FCC to HEX. At the temperature of 200 ℃, sheet resistance of crystalline N-O codoped Sb_2Te_3 was much higher than that of Sb_2Te_3. The increase in sheet resistance might be caused by the formation of oxide and nitride with a high resistivity in N-O codoped Sb_2Te_3. According to our finite element analysis, the increase in resistivity is favorable for synaptic device because lower writing current is available.

4. Conclusion

From above experimental results, it is clear that the crystallization temperature increased to above 250 ℃ after codoping N and O into Sb_2Te_3. This implies that the thermal stability can be greatly improved if the codoped Sb_2Te_3 materials are applied to the artificial synaptic devices.

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