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Research progress on Sb-rich nanostructured films for phase-change memory

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Abstract. In the era of big data, the demand for data storage is increasing. Researchers are currently seeking to develop a non-volatile, high-speed, highly reliable, and low-energy storage medium. Phase change memory is a effective memory of them. This paper focuses on exploring different characteristics of thin films such as $Ge_2Sb_2Te_5$, Sb_2Te, $Ge_2Sb_2Te_5$/ZnSb (GST/ZS) stacked thin films, Ru-doped Sb_2Te, and MnTe/GeTe stacked thin films to analyze which stacked thin film for phase change memory can meet the requirements for high speed and thermal stability. Single-matter materials can improve stability to data and material loss by combining with Sb groups or stacking with their related materials to form new phase change materials.By controlling the temperature and resistance of $Ge_2Sb_2Te_5$ film can have a better selection of optimization; Sb_2Te film doped with C to get a higher improvement in the nature of the film, but the lack of stability; after stacking the two to better solve this problem.

1.Introduction

In recent years, computer technology has been developing rapidly, leading to increased storage requirements for computer systems. To adapt to the advancements in computer technology, researchers suggest using new Non-Volatile Memory (NVM) technology to replace traditional storage techniques.Phase change memory is a type of non-volatile memory, and rich Sb-based nanostructured composite stacked thin films exhibit higher thermal stability and storage reliability. This material also boasts a faster phase change speed at optimal ratios.These thin films have an extremely rapid crystallization speed, which facilitates quick data storage in phase change memory units. By stacking and combining these films, a complete phase change occurs within them, and the crystallization mechanism within the films contributes to excellent thermal stability of the material system.

Read-only memory (ROM) can only read stored information and cannot be written to using conventional methods. It includes masked ROM, programmable ROM (PROM or EPROM), electrically erasable PROM (EEPROM), and flash memory; flash memory is non-volatile and retains information even after power is turned off, with the advantages of low cost and high density. Random access memory (RAM) can be classified into bipolar and MOS types. Bipolar RAM has faster read speeds but higher power consumption and cost, primarily used in high-speed cache memory. MOS RAM is further divided into static RAM

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(SRAM) and dynamic RAM (DRAM), known for low power consumption and high density, making it the preferred choice for most applications. However, traditional semiconductor memories still fall short of meeting current development needs.

Research on the properties of amorphous materials began in the 1950s and 1960s. In 1968, American scientist Stanford Ovshinshy discovered that sulfur-based phase change material thin films could achieve reversible switching of resistance states induced by electrical pulses, with the film's resistance value remaining unchanged even after pulse removal [1,2]. The first 256-bit semiconductor phase change memory was introduced in Electronics in 1970. Over the past 15 years, phase change memory (PCM) has emerged as a superior alternative to NAND flash memory, offering high density, durability, and fast read/write times, suitable for use as non-volatile DRAM .

Phase change materials utilize the different characteristics of crystalline and amorphous states to store information, with "0" and "1" represented by different resistance levels [4]. Phase Change RAM (PCRAM) stores information based on resistance levels, with common operations including SET, RESET, and Read [3].

The non-volatile nature, small size, and low power consumption of phase change materials have established them as promising materials for future data storage solutions. Additionally, the unique advantages of phase change materials position them favorably in the field of radio frequency reconfigurable devices [4].

2. Phase change materials

The concept of phase change memory was introduced, marking the transition of phase change materials from a Te-based system to an Sb-based system. The alloy GeTe exhibits good thermal stability but slow crystallization speed, while Sb_2Te_3 has poor thermal stability but fast crystallization speed. Therefore, by combining these two alloys and readjusting the proportions, a stable alloy with high phase change speed is formed.

2.1 $Ge_2Sb_2Te_5$-based phase change thin films

$Ge_2Sb_2Te_5$ is currently recognized as a phase change material with promising application prospects. When GeTe is used as the Te-based system alone, the crystallization speed is relatively slow. To accelerate the crystallization speed, Sb is added to replace Ge, as Sb_2Te_3 has a faster crystallization speed than GeTe. Finally, by combining these three elements, a stable alloy with high phase change speed is formed. According to experimental studies, as the temperature increases, the resistance of $Ge_2Sb_2Te_5$ continues to decrease. The crystallization temperature is approximately 175°C, resulting in a resistance decrease of over 4 orders of magnitude. At 225°C, the resistance undergoes a drastic change again [5]. These two changes are attributed to the transformation from the metastable FCC structure to the stable HEX structure [6,7]. The durability of phase change memory is closely related to the phase change material. Research on the performance of $Ge_2Sb_2Te_5$ is necessary to enhance its performance. Using the Arrhenius equation, the failure time of $Ge_2Sb_2Te_5$ films can be calculated. Experimental results show a significant enhancement in the intensity of the HEX structure diffraction peaks. Compared to other phase change materials, $Ge_2Sb_2Te_5$ exhibits superior preferred orientation [5].

2.2 Sb_2Te-based phase change thin films

According to research, the amorphous state of Sb_2Te is primarily in a octahedral structure, making it relatively easy to crystallize. Pure Sb has a relatively high tendency to crystallize, so it is generally used as the base material, with additional elements added to achieve a relatively stable substance with fast crystallization speed [8]. Phase change nanomaterials exhibit high thermal stability and fast operation speeds. Experimental evidence demonstrates that C-Sb_2Te exhibits excellent thermal stability and high operational speed, surpassing traditional $Ge_2Sb_2Te_5$ in terms of performance [9]. According to the experimental results of Donghua University, the crystallization temperature of C doped with Sb2Te3 is 240°C at a power supply of 30 w; the crystallization temperature of C doped with Sb2Te3 is 245°C at a power supply of 40 w [10]. Experimental results show that Sb_2Te doped with high-purity graphite C has higher thermal stability, with a higher crystallization temperature (234°C), good data retention (153°C), low thickness and density variations (0.89%), and other advantages. Additionally, the phase change unit device of the doped material features fast phase change speed (5 ns), low voltage (2 V), low power consumption, and high reliability [11]. Therefore, C-Sb_2Te exhibits excellent characteristics such as high reliability and strong thermal stability. Although the Sb-Te binary system is a typical phase change material with a faster crystallization rate than GST, its lower crystallization temperature cannot guarantee sufficient data retention capability in devices, and the low crystalline resistivity is not conducive to reducing RESET current.

2.3 Issues faced by phase change materials

Phase change materials currently need to be adjusted in size to accommodate storage device sizes, but further research on the nanoscale dimensions of the materials is also necessary. Sb_2Te thin films have the characteristic of easy crystallization, and targeted research on this characteristic is still lacking further investigation and treatment. Although Sb_2Te has features such as fast phase change speed and high reliability, in the broader commercial industry applications, there is still a lack of performance for multiple uses, and its reusability is not high. Therefore, continuous exploration and improvement are needed.

2.4 Ru-doped Sb_2Te phase change materials

Since doping with the usual common N, Ga, etc. maintains the stability of the data, but there is a serious phase separation, so scientists by doing many experiments to compare the discovery of Ru thermally stable, fast crystallization speed, low power consumption phase change memory. Phase change storage materials are in the lowest free energy position in the crystalline state, however, the amorphous state is a substable state with higher energy, and to maintain sufficient stability, it is necessary to overcome the energy barrier. It has been investigated that the Ru doping crystallization activation energy is significantly increased, therefore improving the data retention and thermal stability of Sb_2Te phase change materials [12]. According to Zhao Zongyan et al. experiments show that Ru doping can improve the stability and read-write speed of Sb_2Te and Sb_2Te_3, Ru forms stronger covalent bonds with the surrounding Sb and Te, which improves the stability of the structure; by adding Ru doping, Ru can take the place of the five-atom layer of Sb in Sb_2Te_3, which reduces the interlayer spacing and thus improves the crystallization temperature as well. The fast reversible phase transition properties of Sb_2Te are also maintained by this doping [13]. The Ru-doped Sb_2Te has a 10-year data retention of 112°C, a crystallization temperature of 229°C, a speed of 6 ns, and an 85% reduction in power consumption compared to Sb, all of which are attributed to the crystal film containing Ru, which has also emerged as a high-speed and thermally-stable phase-change memory material [14].

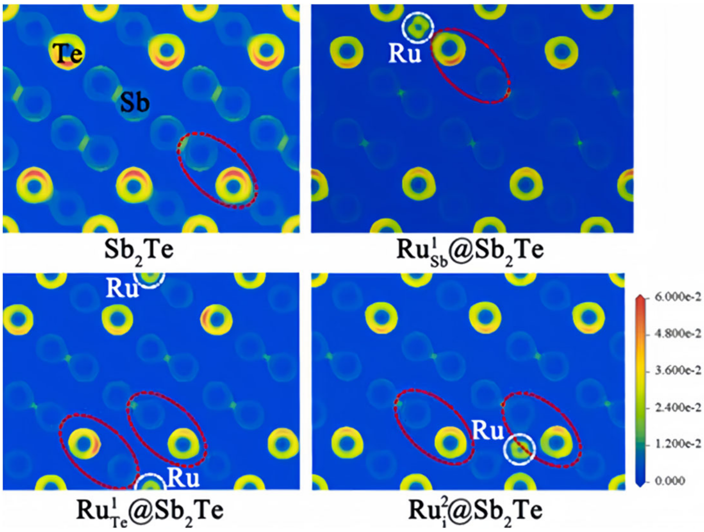

Fig. 1. Ru-doped Sb_2Te and Sb_2Te_3 [13].

3. Nano composite multilayer thin film structure

Due to the shortcomings of slow crystalisation and weak stability of a single-structure film, scientists have adopted a composite structure to change the shortcomings of a single structure and improve the performance of the film. Nano multilayer film is a novel film developed based on monolayer film and composite film. Composite materials are now the most common way to enhance material properties and create new systems. In order to improve the thermal stability of Sb-Te amorphous, other substances are introduced to improve its thermal stability. However, $Ge_2Sb_2Te_5$ still faces some issues: it has a low crystallization temperature of approximately 150°C, poor stability in amorphous state, slow crystallization speed leading to long SET time, and a high melting point of approximately 620°C for GST resulting in high RESET pulse voltage and energy consumption [12].

3.1 The stack thin film of $Ge_2Sb_2Te_5$ /ZnSb (GST/ZS) exhibits

Doping or stacking is an effective method to address these issues. The rate of density change of Ge2Sb2Te5 /ZnSb (GST/ZS) stacked films before and after crystallization was tested by XRD by M. Tian et al. By controlling the phase change properties of $Ge_2Sb_2Te_5$ /ZnSb, the multilayer [ZnSb (8 nm) / GeSb (4 nm)] thin films achieve a crystallization temperature, crystallization activation energy, and ten-year data retention of 220°C, 2.61eV, and 168°C, respectively. The mutual restriction between the thin films inhibits the growth of grains. The results demonstrate that Doping with ZnSb favors the stability of phase change memory and reduces the risk of data loss. This is due to the large increase in crystallization temperature relative to undoped $Ge_2Sb_2Te_5$. The change rate before and after crystallization is only 3.9%, thus enhancing the reliability of information storage [15]. According to the research by Cheong et al. [16], in order to shrink the external voltage required for the effective phase transition region, the storage is constantly undergoing a reversible transition, and a stacking of Sb-rich GSTs will be used to speed up the rate. Since fatigue and energy consumption are inversely proportional, fatigue will also be significantly improved. ZnSb doping suppresses the phase transition from the face-centered cubic phase to the hexagonal phase, and under stacking according to certain ratios, the Zn-Sb and Zn-Te bonds maybe present in an amorphous state. Reversible repetitive optical switching behavior can be observed with laser irradiation at specific ratios, while ZnSb doping is in charge of the switching and remains stable during the chemosynthesis cycle. These excellent features suggest that $Ge_2Sb_2Te_5$/ZnSb films are also one of the potential phase change materials.

4. Conclusion

Phase change memories play a great role in computer storage. In this paper, the phase transition properties of $Ge_2Sb_2Te_5$ thin films, Sb_2Te thin films, $Ge_2Sb_2Te_5$ /ZnSb (GST/ZS) stacked thin films, Ru-doped Sb_2Te, and MnTe/GeTe stacked thin films were investigated.Through the study of the materials, the nanocomposite stacked thin films containing Sb-rich bases have a higher thermal stability and high storage reliability, and they have the advantage of more stability and reliability in computer storage. with the advantage of more stability and reliability. However, the crystallization rate of GST is slower than that of Sb_2Te, and Sb_2Te can not be guaranteed to have stable data storage capacity at low temperature, and the two stacks make the data storage capacity of Sb_2Te become better; or the performance of Sb_2Te can be changed by doping with Ru. The position of doping with Ru instead of Sb is not only easy to realize but also very beneficial for improving the performance of phase-change memories. However, as the size of phase-change memories continues to shrink, the nano-size of the material is also a concern in the study of phase-change materials and needs to continue to be explored for research. Nowadays, phase change materials will still have the situation of fast loss, and in the future, it is also necessary to use different stacking methods for composite thin film materials to reduce the cost of consumption without affecting the external voltage.

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