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Role of $InGaO_x$ resistive switching characteristics on the performances of resistance random access memory of Pt/IGO/TiN device

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ABSTRACT

In this study, the Pt/IGO/TiN resistance random access memory (ReRAM) is investigated by the fabrication of co-sputtering the Ga_2O_3 and In_2O_3 targets to form the $InGaO_x$ (IGO) film. The Pt/GaO_x/TiN structure was fabricated as comparison device. In addition to the bipolar resistance switching characteristic shown in GaO_x film, the unipoar switching characteristic is also obtained in IGO device. The switching mechanisms between bipolar and unipolar in the IGO device are investigated by measuring the resistance values in various temperatures. From the results, the proportional relationship between resistance value and temperature among the bipolar switching characteristics illustrates that the switch is caused by the generation/recombination of oxygen vacancies. However, the unipolar switching behaviors can be attributed to metallic filament due to the trend of increasing resistance with the increasing temperature.

1. Introduction

Resistive random access memory (RRAM) devices are considered a great potential candidate for next-generation nonvolatile memories [1–4] due to those properties such as good scalability, fast operation speed, and low operating power consumption [5,6]. Up to now, the resistive switching was observed from various materials such as perovskite oxides [7,8], organic materials [16] and transition metal oxide materials [9–12]. In order to improve the stability of switching characteristics, some methods were used to stabilize the switching behavior such as Cu diffusion [13], Ni-doped SiO_2 [14], and embedding metal nanocrystals in active layer [15]. Although the resistance switching mechanism has not been clarified, two major models for switching mechanism have been proposed, i.e. oxygen vacancy dominated filament and metallic filament. For the oxygen vacancy filament model, the switch behavior is caused by the generation/recombination of oxygen vacancies [17,18]. The metallic filament model indicating that the formation and rupture of the filaments leads to the switch of the resistance by thermal heating [19–22]. This work investigated the Pt/IGO/TiN device and analyzed the coexistence of unipolar and bipolar resistive switching behavior in different types of filaments.

In this work, the indium gallium oxide ($InGaO_x$) is chosen for switching layer due to the indium and gallium atom are used widely application optoelectronic device, such as solar cells [24] and thin film transistor (TFT) [25]. As the IGO film exist the resistance switching behavior, TFT can combine with RRAM device and the IGO-based RRAM device usefully combine with device process. In previous research, the GaO_x film is related to the oxygen vacancy [23]. Hence, the role of indium in GaO_x film can be investigated by comparing with the resistance switching behavior of GaO_x based RRAM.

2. Experiment

The resistance switching devices were fabricated on TiN/SiO_2/Si substrate. 30-nm-thick GaO_x film was deposited on the TiN bottom electrode (BE) by RF sputtering the Ga_2O_3 target in Ar (30 sccm) and O_2 (10 sccm) ambiance, defined as sample A. Similarly, sample B was fabricated by co-sputtering the Ga_2O_3 and In_2O_3 target to 30-nm-thick $InGaO_x$ (IGO) film in the same ambiance. Finally, the Pt top electrode (TE) was capped on the insulator layer by DC sputtering, as shown in the inset of Fig. 1. The resistance switching characteristics were measured by Agilent B1500 semiconductor parameter analyses at room temperature and the composition of IGO films are analyzed by X-ray photoelectron spectroscopy (XPS, JEOL JPS 9010 MX).

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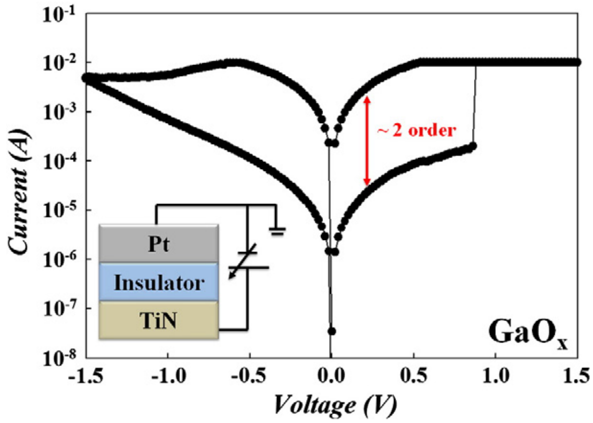

Fig. 1. The bipolar switching characteristics of sample A. The inset is the schematic diagrams of the device.

3. Results and discussion

Fig. 1 shows the current–voltage (I–V) characteristics of sample A. Among the electrical operation, bias was applied on the TiN bottom electrode and grounded on Pt top electrode. The conduction filaments were formed during the forming process which sweeps the voltage from 0 V to 10 V with 500 μA current compliance. Afterward, the low resistance state (LRS) is achieved after the forming process. When the voltage swept from 0 V to −1.5 V, the current decreased leading the resistance state to switch from LRS to high resistance state (HRS), called reset process. Subsequently, the resistance state was switched to LRS through set process by sweeping voltage from 0 V to 2 V with 10 mA compliance current. Hence, the bipolar switching I–V characteristic is presented in GaO_x structure (sample A).

The same operation condition of sample A are also biased to sample B. Consequently, similar bipolar resistance switching behavior can also be performed in the Pt/IGO/TiN device (sample B), as shown in Fig. 2(a). It is interesting that, the switching behavior can switch not only through opposite polarized bias but also through the same polarized bias. After the resistance state was switched to HRS, it can be switched to LRS by applying higher negative voltage (−4 V), as shown in Fig. 2(b). However, the LRS can still be switched back to HRS during the same reset process. The unipolar switching behavior which shows the same switching polarized behavior is obviously shown in $InGaO_x$ based RRAM device. Comparing the resistive switching characteristic of sample A with sample B, the additional unipolar switching characteristic exhibited in sample B might be attributed to the doped indium atoms. Hence, the Pt/IGO/TiN device exhibits the coexistence of bipolar and unipolar resistance switching behaviors after the forming process.

In order to investigate the difference between the unipolar and bipolar switching behaviors, the variation in the resistance values including the HRS and LRS are observed among various temperatures. The resistance values of the HRS and LRS were extracted from 0.2 V while the temperature increases from 300 K to 400 K, as shown in Fig. 3. Fig. 3(a) and (b) show the trend of resistance value versus temperature (R–T trend). The resistance of the HRS decreases as the temperature increases. Since the conduction filaments are blockaded by the formation of insulators during reset process, the R–T trends of HRS of these two samples both demonstrate that the conduction characteristics are dominated by the insulator behaviors. As shown in Fig. 3(c), the LRS of unipolar switching behavior was metal-like because the resistance values were increased with the increased temperature. Hence, the conduction filaments of unipolar are considered as metallic filaments. However, the R–T plot of bipolar switching behavior shows the resistance value of LRS was decreased as the temperature increases, as shown in Fig. 3(d). Through this result, it can be demonstrated that conductive filaments of bipolar switching mode are not composed of metallic filaments. The switching mechanism would conform to the generation/recombination of oxygen vacancies.

In order to investigate the composition of IGO film, X-ray photoelectron spectroscopy (XPS) analyses were performed. Fig. 4(a) shows the XPS analysis of O 1s for IGO film. By the analysis method of Lorentzian–Gaussian functions, two peaks which are centered at 531.4 eV and 530.9 eV can be distinguished. Through the previous research, these two peaks can be attributed to Ga−O and In−O bonds, respectively, as shown in Fig. 4(a). Fig. 4(b) and (c) shows the XPS of Ga 3d5/2 and In 3d5/2, respectively. In the Ga 3d5/2 photoemission spectrum shown in Fig. 4(b), the peaks at 18.4 eV and 20.4 eV are respectively assigned to Ga-Ga and Ga-O bonds of Ga2O3 [26]. For the photoemission spectrum of In 3d5/2, the In-In (444.4 eV) and In-O (445.2 eV) bonds of In2O3 are also obtained [27]. The result indicates that the indium atoms react with gallium oxide during the fabrication process. Through the quantitative analyses of peak area between these elements, the composition ratio between oxygen, gallium, and indium are estimated to be 44:43:13.

Dual resistance switching behaviors, i.e. unipolar and bipolar are presented in the device of Pt/IGO/TiN. According to the temperature-dependent analyses and results above, both oxygen vacancies dominated filaments and metallic filaments are believed to exist in sample B [22]. During the forming process by applying a positive voltage to TiN, the metal–oxygen bonds are broken by electrons and thereby formed the leakage paths composed of oxygen vacancies and metal filaments, as shown in Fig. 5(a). After the forming process, conductive filaments are formed and made the resistance state from initial state to LRS.

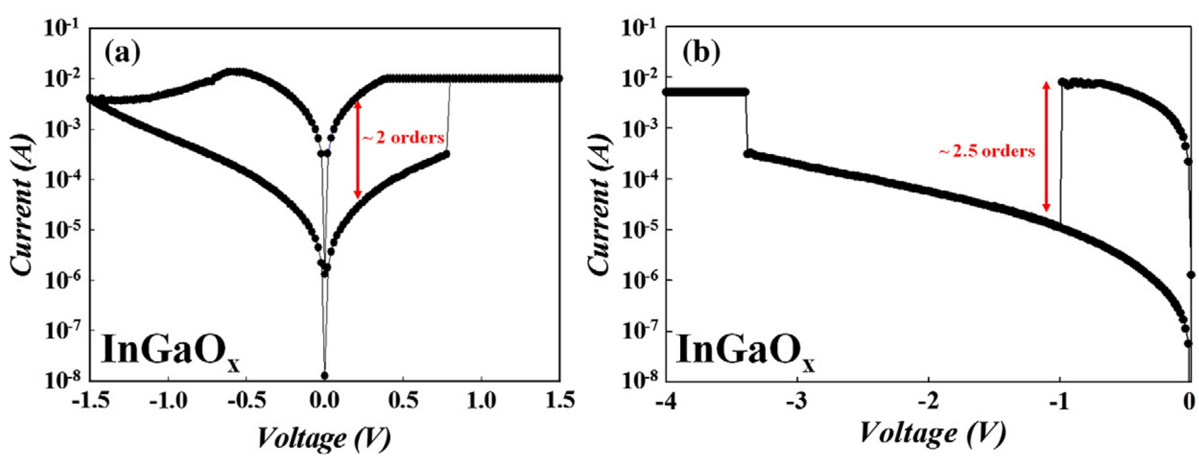

Fig. 2. (a) The bipolar switching characteristic of sample B. (b) The unipolar switching characteristic of sample B.