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Forming-free resistive switching characteristics in tantalum oxide and manganese oxide based crossbar array structure

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ABSTRACT

The fabrication of 5 × 5 crossbar array with a line width of 20 μm was demonstrated. The resistive switching characteristics in the bilayer structure of tantalum oxide and manganese oxide were investigated. The Ag/MnO/Ta_2O_5/Pt devices showed stable bipolar resistive switching properties with high resistance ratio, low switching voltage, and forming-free behavior. The conduction mechanisms of ohmic conduction and Schottky emission had been investigated for resistance switching mechanism.

1. Introduction

Resistive switching in metal oxides has attracted much attention due to potential application for nonvolatile resistive random access memory (RRAM) devices. RRAM devices are expected to be a promising candidate for future memory applications due to their outstanding features, including their simple metal-insulator-metal (MIM) structure, fast operation, low power consumption and excellent scaling potential [1–7]. The simple structure of RRAM devices makes it possible to be fabricated into crossbar arrays of high density memory cells [8]. Depending on the biasing polarities, the switching in RRAM devices can either be bipolar switching or unipolar switching [7]. The applied bias usually results in the formation of two resistance states, high resistance state (HRS) and low resistance state (LRS). The switching of the resistance state from HRS to LRS is termed as SET process whereas the switching from LRS to HRS is called as RESET process.

Different materials have been investigated, including metal oxides [9–11], organic materials [12–14] and solid electrolytes [15] as the switching material in RRAM devices. To improve the performance of RRAM devices, several research groups have contributed to the study of multilayer devices [16–20]. The multilayer devices present better performance over the single layer devices which includes good endurance and retention characteristics, forming-free and compliance-free switching. In our previous works, we presented the improved resistive switching behaviors in bilayer and tri-layer devices [21,22]. In addition, we also investigated the resistive switching properties of Au/Pt-Fe_2O_3 nanoparticles assembly/Ti devices and Au/manganese oxide nanoparticles assembly/Ti devices, which were fabricated in 3 × 3 crossbar arrays with a line width of 20 μm. The two kinds of devices showed stable bipolar resistive switching properties [23,24]. In this study, the resistive switching characteristics in the bilayer crossbar array devices of tantalum oxide (Ta_2O_5) and manganese oxide (MnO) was investigated. The Ag/MnO/Ta_2O_5/Pt devices with 5 × 5 crossbar arrays exhibited forming-free bipolar resistive switching properties with high resistance ratio and low switching voltage.

2. Experimental

5 × 5 crossbar arrays were fabricated on p-type Si substrate. The bottom electrode pattern was made with photolithography using negative photoresist (PR). A 5 nm thick titanium (Ti) adhesion layer and a 10 nm thick platinum (Pt) bottom electrodes were deposited by sputtering. The oxide layers of Ta_2O_5 and MnO were deposited on the bottom electrode lines by RF magnetron sputtering with a Ta_2O_5 target and a MnO target in Ar ambient at room temperature. Ta_2O_5 thin film was deposited with an RF power of 50 W under a working pressure of 20 mTorr and an Ar flow of 20 sccm. And MnO layer was deposited with an RF power of 30 W under a working pressure of 20 mTorr and an Ar flow of 50 sccm. The oxide layer thicknesses of MnO and Ta_2O_5 were 15 nm and 45 nm, respectively. Finally, for the top electrodes deposition, the top lines were perpendicular to the bottom lines. The silver (Ag) top electrode pattern was formed using photolithography and deposited by thermal evaporation. The thickness of Ag layer was 100 nm. The line width of bottom and top electrodes was 20 μm. The schematic

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illustration of the devices is shown in Fig. 1. There were 25 memory cells in the crossbar array. The cross-sectional structure of the devices was analyzed with scanning electron microscopy (SEM, Hitachi S-4800). The samples for SEM analysis were prepared *via* focused ion beam (FIB). The electrical characterization on Ag/MnO/Ta_2O_5/Pt crossbar array structures was performed using Agilent 4156B semiconductor parameter analyzer. For all *I*—*V* measurements, the Ag top electrode was biased and the Pt bottom electrode was grounded. During the SET process, a compliance current (I_{cc}) of 1 mA was used to prevent the devices from hard breakdown.

3. Results and discussion

Fig. 2 shows the cross-sectional view SEM micrograph of Ag/MnO/Ta_2O_5/Pt device. The thicknesses of MnO layer and Ta_2O_5 layer were ~15 nm and ~45 nm, respectively. The width of electrode line in crossbar array structure was 20 μm. So, the size of each memory cell was 20 × 20 μm^2. Initially the Ag/MnO/Ta_2O_5/Pt devices remained at HRS. Under a positive bias, the device switched from HRS to LRS. Afterward, when a negative voltage was applied the resistance state changed to HRS. Therefore, the devices showed typical bipolar resistive switching characteristics. Moreover, no electroforming step was required for the devices to initiate the electrical resistance switching. This electroforming free phenomenon could be ascribed to the abundant defects (oxygen vacancies) in the oxide layers formed during sputtering process [25,26]. Fig. 3(a) shows the resistance switching *I*—*V* characteristics of one memory cell in the crossbar array. The voltage was swept in the positive direction from 0 to +2 to 0 V. And then, a negative voltage was swept from 0 to −2 to 0 V. The curves showed a set voltage (V_{SET}) of +0.8 V and a reset voltage (V_{RESET}) of −1.1 V, respectively. At the reading voltage of +0.2 V, the current ratio of LRS to HRS was found to be ~3.89×10^6. Previously, manganese oxide nanoparticle based, titanium oxide based, and Ta_2O_5 based devices with 3 × 3 crossbar arrays were investigated and showed resistance ratios of 1.3×10^2, 66, and 45, respectively [23,27,28]. Furthermore, the switching voltages were lowered from +5/+4 (−5/−4) V in manganese oxide nanoparticle based and Ta_2O_5 based devices to +2 (−2) V in MnO/Ta_2O_5 bilayer devices [23,28]. Compared to the single layer based devices, the resistance ratio and switching voltage were considerably improved in the bilayer crossbar array devices. The reliable switching characteristics of the devices were investigated. Stable switching behaviors with a switching cycle up to 100 cycles were obtained. To further understand the switching stability, the cumulative probability distributions for R_{HRS}, and R_{LRS} were plotted and are shown in Fig. 3(b). A quite narrow distribution of HRS and LRS was obtained. The average resistance ratio of HRS to LRS was found to be ~4.53×10^5 at a reading voltage of +0.2 V. Therefore, the as-fabricated Ag/MnO/Ta_2O_5/Pt devices with 5 × 5 crossbar arrays presented good uniformity. Table 1 shows the V_{SET}, V_{RESET} and resistance ratio of all the 25 cells in the crossbar array. Here, all the cells worked. And the high resistance ratios were obtained in all memory cells.

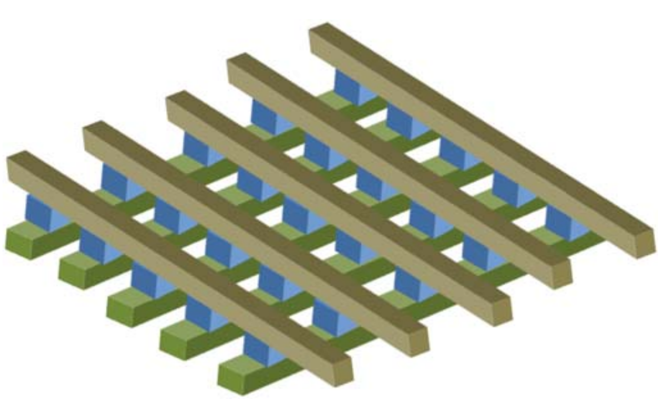

Fig. 1. Schematic of Ag/MnO/Ta_2O_5/Pt devices in a 5 × 5 crossbar array.

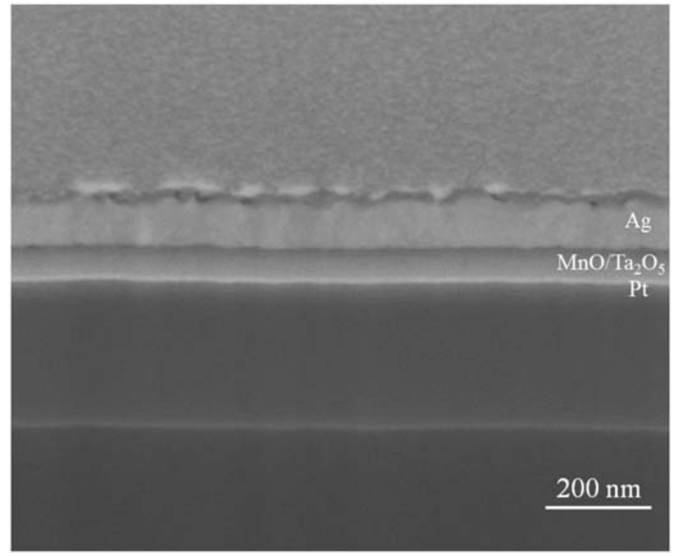

Fig. 2. Cross-sectional SEM image of Ag/MnO/Ta_2O_5/Pt devices in a 5 × 5 crossbar array.

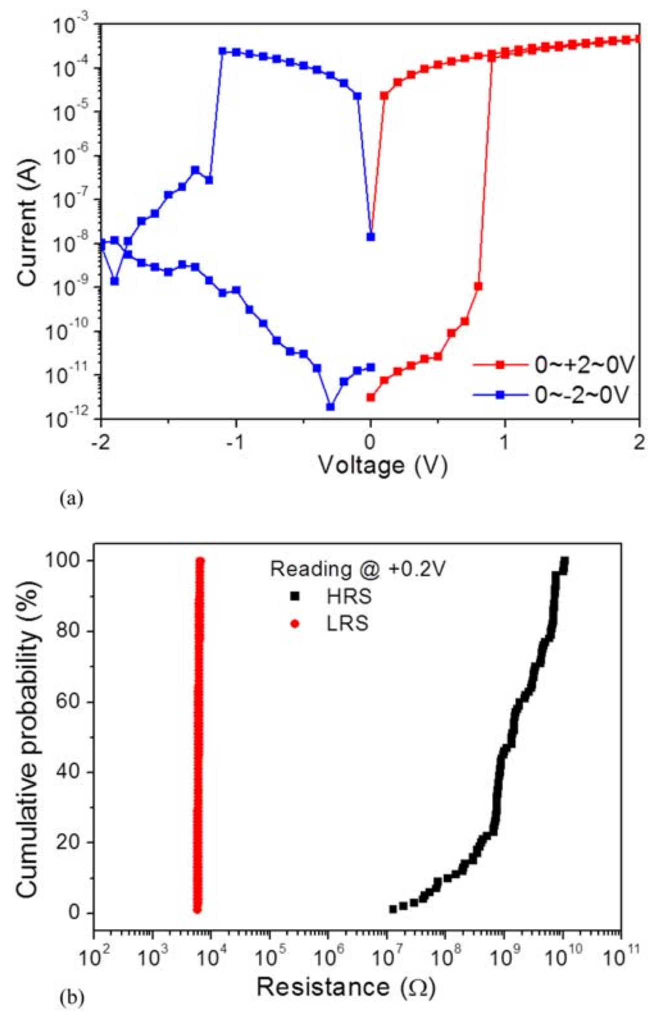

Fig. 3. (a) *I*—*V* curves of Ag/MnO/Ta_2O_5/Pt devices. (b) Distribution for HRS and LRS of Ag/MnO/Ta_2O_5/Pt devices.