Sensors and Materials, Vol. 30, No. 4 (2018) 933–938
MYU Tokyo

S & M 1551

Bipolar Switching Properties of Bilayer V_2O_5/Sm_2O_3 Thin-film Resistive Random Access Memory Device Prepared by Sputtering Technology

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(Received November 1, 2017; accepted March 7, 2018)

Keywords: resistive random access memory (RRAM), bipolar switching characteristic, postannealing, forming voltage

In this study, V_2O_5 and Sm_2O_3 thin films have been successfully fabricated for application in resistive random access memory (RRAM). The RRAMs with V_2O_5 and Sm_2O_3 films have shown bipolar switching characteristics. Introducing a suitable oxygen concentration in the V_2O_5 film can improve the switching performance. Postannealing of the $V_2O_5/Sm_2O_3/TiN/SiO_2/Si$ device can decrease the forming voltage to 1.1 V.

1. Introduction

As technology continues to progress, the convenience of electronic products reduces the distance between people. Electronic products have become indispensable in people's life. The Internet of Things (IoT) has been one of the fast developing technologies in recent years. Various sensors have been used in IoT systems for detecting physical changes in the environment.(1) For electronic products, memory capacity has crucial effects on electronic computing speed and efficiency. Recently, resistive random access memories (RRAMs) with advantages of simple structure, low power consumption, high-speed operation, multibit operation, small device area, and nonvolatility have attracted considerable attention as a replacement for conventional flash memory in next-generation nonvolatile memory applications.(2,3) Therefore, RRAMs have the potential to be used for the implementation of sensing data acquisition and computing in the sensor systems of IoT.(1–3) Owing to their high dielectric properties, some of the transition metal oxides, such as V_2O_5, TiO_2, MgO, $SrTiO_3$, and

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http://dx.doi.org/10.18494/SAM.2018.1796

ZnO, have been considered as the memory dielectric film for the next generation RRAM.[4–7] Among them, V_2O_5 has the characteristic of metal–insulator transition (MIT) at 280 °C and is also widely used in light and electric switches. The crystal structure, optical parameters, conductivity, etc. of V_2O_5 will change significantly as MIT changes.[8] On the other hand, rare earth oxides (REOs) have shown promising characteristics for high *k* gate insulators in advanced CMOS technology.[9] Among the rare-earth oxides, Sm_2O_3 has a smaller hygroscopic nature owing to its less ionic radius and electropositive nature.[10] In addition, Sm_2O_3 has a large energy band gap (4.33 eV), good chemical stability, good thermal stability, low leakage current density, high breakdown electric field (5–7 MV/cm), less frequency dispersion, and low trapping rates.[11–14] Because of these important properties of Sm_2O_3 and V_2O_5, two RRAM device structures with Pt/V_2O_5/TiN/SiO_2/Si and Pt/V_2O_5/Sm_2O_3/TiN/SiO_2/Si have been investigated in this work for their memory switching properties.

2. Experiment

Two resistive nonvolatile memory structures have been fabricated in this work. For the first RRAM structure, V_2O_5 thin films were deposited onto TiN/SiO_2/Si substrates at room temperature (RT) by radio frequency (RF) magnetron sputtering. A two-inch V_2O_5 target for the sputtering deposition has been made by a ceramic powder process, as shown in Fig. 1. The sputtering condition for the V_2O_5 film deposition was with a RF power of 70 W and with an argon working pressure of 30 mTorr. For the second RRAM structure, Sm_2O_3 thin films were deposited onto V_2O_5/TiN/SiO_2/Si substrates at RT by an RF magnetron sputtering with different oxygen flow rates (0, 2.0, and 3.0 sccm). The sputtering condition for the Sm_2O_3 film deposition was with a RF power of 90 W and an argon working pressure of 30 mTorr. To construct the metal–insulator–metal (MIM) structure for the RRAM, an array of circular Al top contacts with diameter of 50 μm and with thickness of 200 nm was formed by RF magnetron sputtering. The resistive switching (RS) characteristics of the two RRAM devices were measured using an Agilent 4156 C semiconductor parameter analyzer at RT. Current flow from the top to the bottom electrode was defined as positive sweep.

3. Results and Discussion

A V_2O_5 film was deposited on the TiN/SiO_2/Si substrate with RF power of 70 W and without O_2 flow to construct the V_2O_5/TiN/SiO_2/Si RRAM device. For the RRAM device, a forming

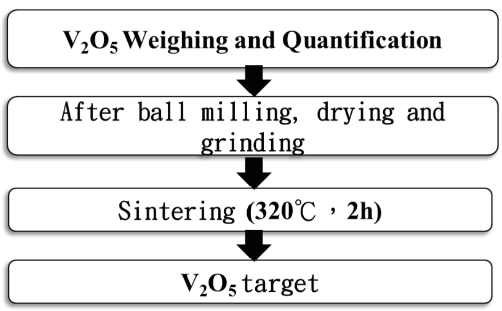
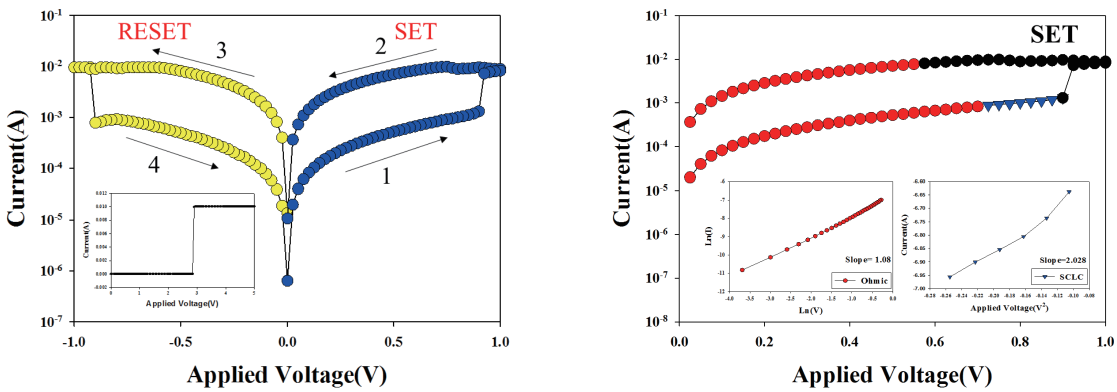


Fig. 1. Process flow of 2-inch V_2O_5 target preparation.

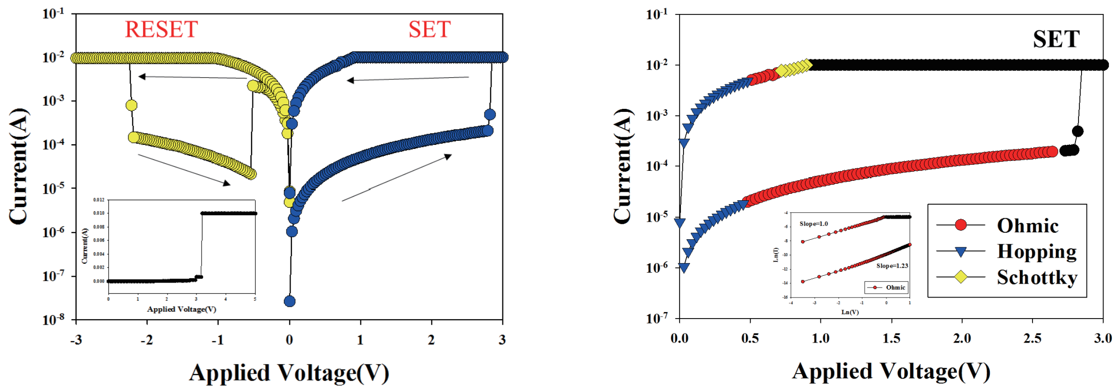
process is needed at the beginning to activate the RS behavior by adding positive and negative biases. A typical bipolar RS *I*–*V* curve of the V_2O_5/TiN/SiO_2/Si device is shown in Fig. 2(a). The V_2O_5/TiN/SiO_2/Si device fabricated without oxygen flow shows a stable bipolar switching characteristic. At the beginning, the device needs a forming voltage of 0.28 V and a compliance current of 10 mA to form the conduction filaments. Once the conduction path has been formed, only small compliance current in the range of 1.0 to 10 mA is required for the bipolar switching. The voltage sweep sequence for the bipolar switching operation of the device is 0 V → 1 V → 0 V → −1 V → 0 V. Within the SET process of the device, two conduction mechanisms, Ohmic and space charge limit current (SCLC) with trap model are dominant, as shown in Fig. 2(b). However, its R_{HRS}/R_{LRS} ratio is only 10, which is insufficient.

To enhance its switching characteristics, the V_2O_5/TiN/SiO_2/Si RRAM device was then made under an oxygen flow rate of 2 sccm, and the device switching characteristics are shown in Fig. 3(a). We found that the forming voltage did not decrease and the R_{HRS}/R_{LRS} ratio increased to over 100. This is because oxygen increases with higher defect densities and



(a) (b)

Fig. 2. (Color online) RRAM switching characteristics of V_2O_5/TiN/SiO_2/Si device (RF power at 70 W, oxygen flow rate at 0 sccm): (a) bipolar *I*–*V* characteristics; (b) current conduction mechanisms during SET (Ohmic and SCLC).



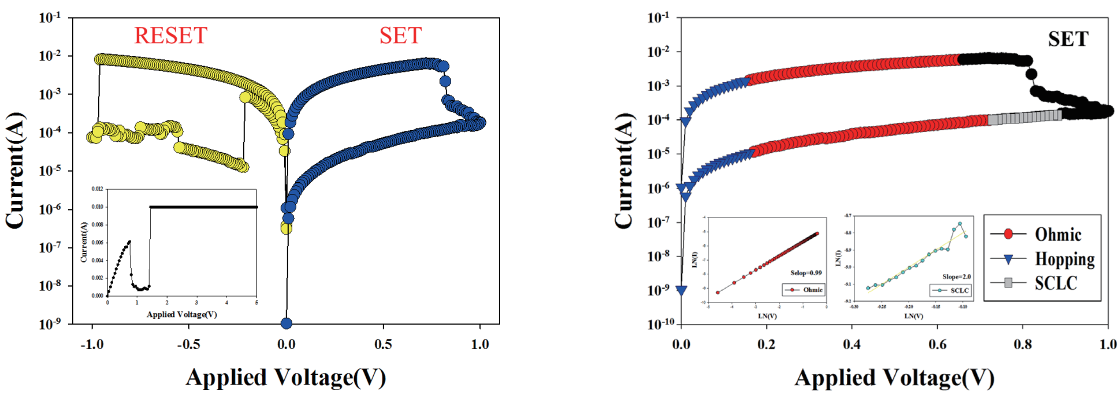
(a) (b)

Fig. 3. (Color online) RRAM switching characteristics of V_2O_5/TiN/SiO_2/Si device (RF power at 70 W, oxygen flow rate at 2 sccm): (a) bipolar *I*–*V* characteristics; (b) current conduction mechanisms during SET (Ohmic, Hopping, and Schottky emission).

carriers have more chances to move in those defects. Within the SET process of the device, three conduction mechanisms, Ohmic, Hopping, and Schottky emission are dominant, as shown in Fig. 3(b).

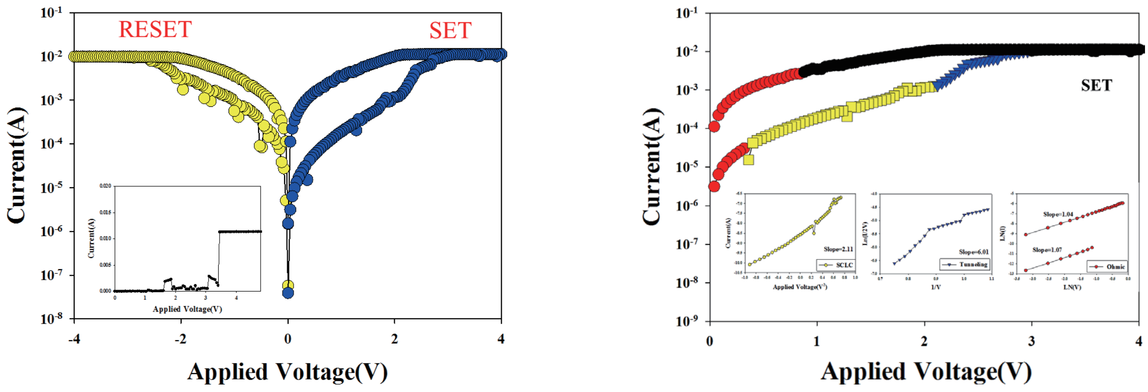
To further increase the oxygen flow rate to 3 sccm, the device switching characteristics of the $V_2O_5/TiN/SiO_2/Si$ RRAM device are shown in Fig. 4(a). The forming voltage of the device is reduced to 1.4 V, but the reset process is unstable and there is a considerable leakage current. Within the SET process of the device, three conduction mechanisms, Ohmic, Hopping, and SCLC are dominant, as shown in Fig. 4(b). The results show that a suitable oxygen concentration involved in the conduction path can enhance the bipolar switching behavior of the $V_2O_5/TiN/SiO_2/Si$ RRAM device.

Sm_2O_3 has a small hygroscopicity owing to its small ionic radius and small positive charge. With this feature, it is expected that adding a Sm_2O_3 film to the $V_2O_5/TiN/SiO_2/Si$ RRAM device can stabilize the Reset state of the device. For the switching characteristics of the $V_2O_5/Sm_2O_3/TiN/SiO_2/Si$ device shown in Fig. 5(a), it is found that not only does the forming voltage increase to 3.4 V, the bipolar switching characteristics also become worse. Within the SET process of the device, three conduction mechanisms, SCLC, Tunneling, and Ohmic are dominant, as shown in Fig. 5(b). Nevertheless, the forming voltage of the $V_2O_5/Sm_2O_3/TiN/SiO_2/Si$ RRAM device was reduced to 1.1 V after a post rapid thermal annealing (RTA) at 400 °C for 1 h, as shown in Fig. 6(a). Within the SET process of the device, two conduction mechanisms, Ohmic and SCLC are dominant, as shown in Fig. 6(b). In some studies, it has been shown that Sm_2O_3 film has polycrystalline structure. Oxygen vacancies can easily drift through its grain boundaries and dislocations, resulting in stable RS behavior.[10] In the research of V_2O_5 film, it has been found that V_2O_5 has a stable reversible switching characteristic, and the current can be controlled by setting the current limit during the set process to reduce the power consumption.[8]



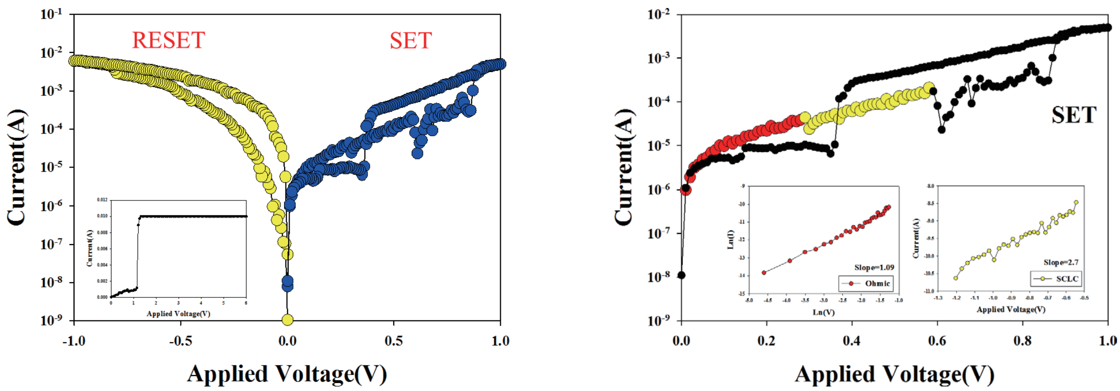
(a) (b)

Fig. 4. (Color online) RRAM switching characteristics of $V_2O_5/TiN/SiO_2/Si$ device (RF power at 70 W, oxygen flow rate at 3 sccm): (a) bipolar *I*–*V* characteristics; (b) current conduction mechanisms during SET (Ohmic, Hopping, and SCLC).



(a) (b)

Fig. 5. (Color online) RRAM switching characteristics of $V_2O_5/Sm_2O_3/TiN/SiO_2/Si$ device (RF power at 90 W, oxygen flow rate at 0 sccm) without postannealing: (a) bipolar *I*–*V* characteristics; (b) current conduction mechanisms during SET (SCLC, Tunneling, and Ohmic).



(a) (b)

Fig. 6. (Color online) RRAM switching characteristics of $V_2O_5/Sm_2O_3/TiN/SiO_2/Si$ device (RF power at 90 W, oxygen flow rate at 0 sccm) with postannealing at 400 °C for 1 h: (a) bipolar *I*–*V* characteristics; (b) current conduction mechanisms during SET (Ohmic and SCLC).

4. Conclusions

In this study, we investigated the bipolar RS characteristics of the RRAM structures incorporating V_2O_5 and Sm_2O_3 films. It is found that a suitable oxygen concentration involved in the conduction path can improve the bipolar switching behavior of the $V_2O_5/TiN/SiO_2/Si$ RRAM device. With a suitable postannealing, the forming voltage can be reduced for the $V_2O_5/Sm_2O_3/TiN/SiO_2/Si$ device.

Acknowledgments

This work was financially supported by the Ministry of Science and Technology of R.O.C. under contract MOST103-2221-E-224-075.

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