Unipolar resistive switching and current flow mechanism in thin film SnO_2

Arka Talukdar*, Sergio Almeida*, Jose Mireles**, Eric MacDonald*, Joseph H. Pierluissi*, Ernest Garcia***, and David Zubia*

*The University of Texas at El Paso, 500 West University Ave. El Paso TX-79968,
atalukdar@miners.utep.edu, dzubia@utep.edu
**Universidad Autónoma de Ciudad Juárez (Mexico)
***Sandia National Laboratories, Albuquerque, NM

ABSTRACT

Resistive RAMs are two terminal electronic devices that can be used as a nonvolatile memory. It has been shown that resistive RAMs have high switching speed (10 ns), high endurance 10^{12} cycles as well as good retention of 10 years. In this paper we have investigated the switching behavior of Ti/SnO_2/Au metal-oxide-metal devices. I-V characteristics showed Ohmic behavior in the lower resistance state (LRS). In the high resistance state (HRS) current transport mechanisms were Ohmic, Frenkel-Poole and Schottky. The endurance data showed that the devices are very suitable for nonvolatile memory applications.

Keywords: RRAM, resistive switching, SnO_2

1. INTRODUCTION

Resistive switching in metal-oxide-metal (MOM) structures has been investigated in the last few decades due to their potential applications in nonvolatile memories. A wide range of combinations of MOM structures with different materials has been reported to display resistive switching, among them the most popular being Pt/TiO_2/Pt and Pt/TaO_x/Pt structures. Pt/TaO_x/Pt has shown repeatable switching up to 10^{12} cycles [1]. The switching time of resistive RAM is about 10 ns and retention is about 10 years which are also big advantages for these devices [2].

In contrast, SnO_2 has received limited attention even though it has shown promising properties for resistive switching. Nagashima, *et al* analyzed the unipolar resistive switching behavior in Pt/SnO_2/Pt/Si (100), Ti/SnO_2/Pt/Si (100) and Au/SnO_2/Pt/Si(100) structures where the SnO_2 was deposited by the pulse laser deposition method [3]. Almeida, *et al* analyzed the unipolar resistive switching behavior in Ag/SnO_2/Ti/glass structure where the top electrode was high purity Ag paint [4]. Both the structures showed good switching behavior. Additionally, previous work on SnO_2-Si sensors has shown that SnO_2 has good radiation tolerance [5]. SnO_2 has potential for resistance to displacement damage since its Frenkel defect energy (7 eV) is much larger than its band gap (3.6 eV). This combination of properties makes SnO_2 a good candidate for resistive memory applications in general and potentially for radiation hard environments. However, more work is required to fully understand filament formation and current mechanisms in the MOM devices.

In this paper, we have investigated the unipolar resistive switching of SnO_2-based metal-oxide-metal structures (Ti/SnO_2/Au/Cr/SiO_2/Si) where the SnO_2 layer was deposited by reactive RF magnetron sputtering at room. We analyzed the current flow characteristics of the device in the high resistance state (HRS) and low resistance state (LRS).The endurance and the resistance ratio of the devices were analyzed.

2. EXPERIMENT

2.1 Device Fabrication

The fabrication of the resistive MOM structure consists of three steps: (i) deposition of the bottom electrode (Au) (ii) deposition of the active SnO_2 layer and (iii) deposition of the top electrode (Ti). Shadow masks were used to define the active layer (SnO_2) and the top electrode (Ti) as shown in Fig. 1. Au was deposited on a Cr /SiO_2 /Si(100) substrate by the thermal evaporation technique to a thickness of 120 nm. The SiO_2 (200 nm) acts as an insulating layer and the Cr (200 nm) acts as an adhesion layer for the Au.

SnO_2 was deposited on the Au/Cr/SiO_2/Si(100) structure by RF magnetron sputtering using a Sn (99.995% pure) target. A deposition pressure of 5 mTorr was maintained with an O_2 flow of 70 sccm. The power used to deposit SnO_2 was 40 W. The resultant thickness of the SnO_2 was ~45 nm.

The top electrode was deposited by RF magnetron sputtering using a 99.999% pure Ti target. The pressure during the deposition was maintained at 2 mTorr with an Ar flow of 35 sccm. The final thickness of the Ti electrode was 100 nm. Fig. 1 gives a schematic view of the complete MOM structure.

2.1 Device Testing and Results

Electrical characterization was performed using a Keithley 2400 I-V tester. The bottom electrode (Au) was grounded and positive voltage was applied to the top electrode (Ti).
Total of 32 cycles of switching between HRS and LRS were recorded, though the devices indicated that more switching was possible. The voltage was ramped from 0 V to the set voltage which varied from 0.8 to 1.2 V in the HRS as shown in Fig. 2. A compliance current of 10 mA was used to avoid damage in the device when it switched from HRS to LRS. When the devices were in LRS, the voltage was ramped from 0 V to 0.8 V without compliance current. The switching from LRS to HRS was between 0.3 V to 0.6 V (see Fig. 2).

Fig. 3 shows the endurance data of the device. The resistances of the I-V characteristics were calculated at a read voltage of 0.1 V as indicated in Fig. 2. The resistance in HRS ranged from 2.6×10^3 Ω to 1.6×10^5 Ω. The LRS resistance ranged from 3 Ω to 68 Ω. It was observed that the HRS resistance increased as the number of cycles causing the resistance ratio to increase from 10^2 to 10^3. In cycle 11 and cycle 22 (marked by circles in Fig. 3) the HRS resistance showed lower values than the rest of the data. Analysis of those two data points indicated that the device switched from LRS to an intermediate state between HRS and LRS.

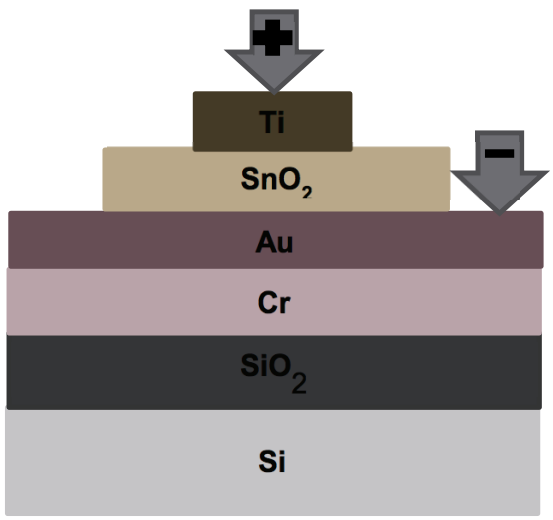

Figure 1: MOM structure on Silicon (101). Area of top electrode (Ti) is $1mm^2$. Area of SnO_2 the device layer is 15 x 30 mm.

3. ANALYSIS AND DISCUSSION

The HRS and LRS I-V data was analyzed further to determine the current transport mechanism in the two states. In the LRS, the current increased proportionally to the voltage from 0 to 0.08 V as shown in Fig. 4. This

indicates Ohmic behavior consistence with conduction through a metallic filament [6] [7]. Above 0.08 V a deviation indicating the onset of switching from LRS to HRS.

The HRS I-V characteristic was governed by three types of current regimes at low, middle and high voltage ranges. In the low voltage range the current increased linearly with voltage indicating Ohmic behavior from 0 V to 0.16 V (See Fig. 5). In the middle voltage range from 0.16 V to 0.42 V the experimental data fitted the linearized Frenkel Poole equation,

$$ln\frac{J}{V} = ln\frac{a}{d} - \frac{q\varphi}{kT} + \frac{\sqrt{\frac{q^3}{\pi\varepsilon d}}}{kT}\sqrt{V} \qquad (1)$$

as shown in Fig. 6, where J is current density, V is the voltage, d is distance between the electrodes, q is the charge of an electron, k is Boltzmann's constant, T is temperature in Kelvin, ε is dielectric constant, φ is the barrier height, a is a constants. In the higher voltage range from 0.42 V to set voltage the experimental data fitted the linearized Schottky emission equation,

$$ln\frac{J}{V} = \ln(bAT^2) - \frac{q\varphi}{kT} + \frac{\sqrt{\frac{q^3}{\pi\varepsilon d}}}{\sqrt{4}kT}\sqrt{V} \qquad (2)$$

as shown in Fig. 7, where A is the Richardson constant and b is a constants. Three sets of experimental data from cycle 11, 21 and 31, were fitted in each case.

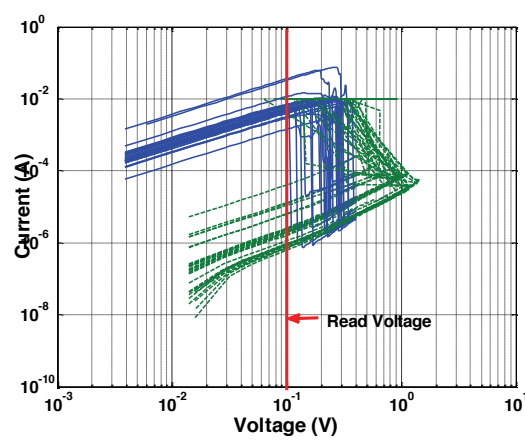

Figure 2: HRS (solid blue lines) and LRS (dotted green line) shows the I-V characteristics of Ti/SnO_2/Au/Cr/SiO_2/Si structure. The red line represents the read voltage.

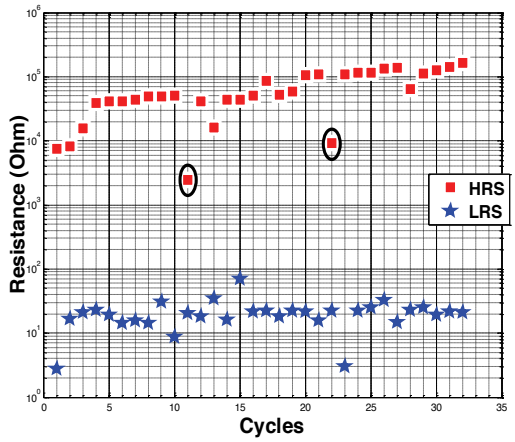

Figure 3: Endurance data of LRS and HRS using resistance data at 0.1 V (indicated by red line in Fig. 2)

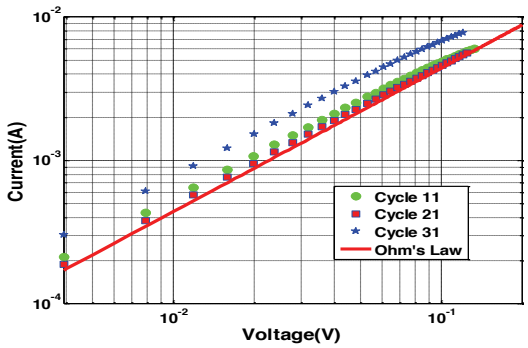

Figure 4: Comparison of I-V characteristics of LRS data with Ohmic behavior indicated by solid line.

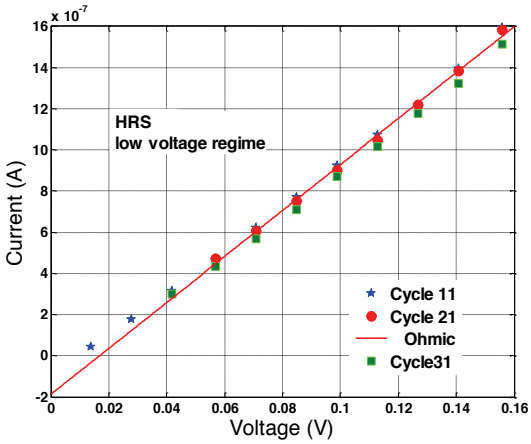

Figure 5: Comparison of I-V characteristics of HRS data from cycle 11, 21 and 31 with Ohmic behavior indicated with solid lines.

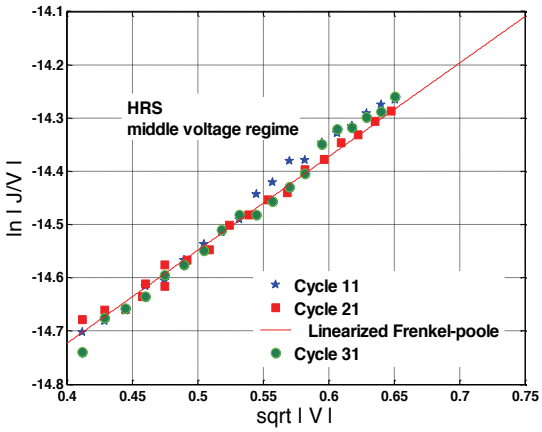

Figure 6: Comparison of I-V characteristics of HRS data from cycle 11, 21 and 31 with linearized Frenkel-Poole equation indicated with solid lines.

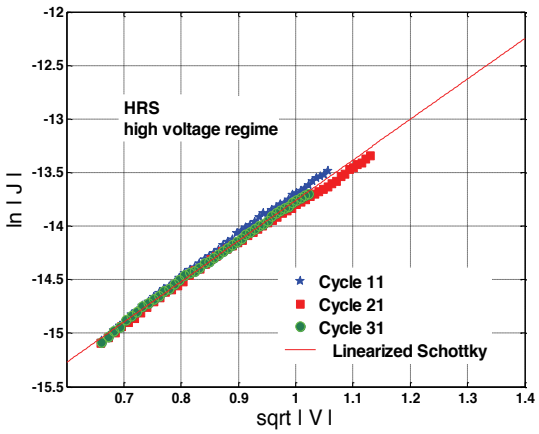

Figure 7: Comparison of I-V characteristics of HRS data from cycle 11, 21 and 31 with linearized Schottky emission equation indicated with solid lines.

4. CONCLUSIONS

Metal-oxide-metal structure was fabricated with Au as bottom electrode, SnO_2 as active layer and Ti as top electrode. $SnO_2$was deposited by RF magnetron sputtering using a Sn target. Repeatable unipolar resistive switching was observed in the MOM structure. I-V analysis showed that in LRS, the current transport mechanism is Ohmic. In HRS Ohmic, Frenkel-Poole and Schottky emission occurs at low, medium and high bias respectively. The order of magnitude of resistance between LRS and HRS was ~10^3 with little variation.

5. ACKNOWLEDGEMENTS

This work was supported by Sandia National Laboratories under contract 1156850. Sandia National Laboratories is a Multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Part of the fabrication process was done in Universidad Autónoma de Ciudad Juárez (Mexico).

REFERENCES

[1] M.-J. Lee, C. B. Lee, D. Lee, S. Ryul, M. Chang, J. H. Hur, Y.-B. Kim, C.-J. Kim, D. H. Seo, S. Seo, U.-I. Chung, I.-K. Yoo and K. Kim, "A fast, high-endurance and scalable non-volatile memory device made from asymmetric Ta2O5− x/TaO2− x bilayer structures.," *Nature materials* , vol. 10, no. 8, pp. 625-630, 2011.

[2] W. Rainer and M. Aono, "Nanoionics-based resistive switching memories," *Nature materials,* vol. 6.11, pp. 833-840, 2007.

[3] K. Nagashima, T. Yanagida, K. Oka and T. Kawai, "Unipolar resistive switching characteristics of room temperature grown SnO2 thin films," *Applied Physics Letters,* vol. 94, p. 242902, 2009.

[4] S. Almeida, B. Aguirre, N. Marquez, J. McClure and D. Zubia, "Resistive switching of SnO2 thin films on glass substrates," *Integrated Ferroelectrics,* vol. 126.1, pp. 117-1124, 2011.

[5] V. GOLOVANOV, L. KHIRUNENKO, A. KIV, D. FUKS, M. SOSHIN and K. G, "Radiation effects in SnO2–Si sensor structures," *Radiation Effects & Defects in Solids,* Vols. 00,No0, pp. 1-5, 2006.

[6] X. Chen, G. Wu and D. Boa, "Resistive switching behavior of Pt/Mg0.2Zn0.8O/Pt devices for nonvolatile," *APPLIED PHYSICS LETTERS,* vol. 93, p. 093501, 2008.

[7] K. M. Kim, B. J. Choi, Y. C. Shin, S. Choi and C. S. Hwang, "Anode-interface localized filamentary mechanism in resistive switching of TiO2 thin films," *Applied Physics Letters,* vol. 91, no. 1, p. 012907 , 2007.