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A Novel Ni/WO_X /W ReRAM with Excellent Retention and Low Switching Current

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Abstract

We found that the behavior of WO_X ReRAM is a strong function of the top electrode (TE) material. The work function (WF) of the top electrode determines both the conduction mechanism and the behavior of the forming process. For a low WF electrode, conduction is space charge limited (SCL), while current from a high WF electrode is dominated by thermionic emission. Thermionic emission is indicative of an interface potential barrier, and this subsequently reduces the switching and forming currents, as well as providing a larger resistance ratio. Based on these insights we have proposed and characterized a novel Ni top electrode WO_X ReRAM. The new Ni/WO_X/W device operates at a switching current density < $8x10^5A/cm^2$, with > 100X resistance ratio window, and extremely good data retention of > 300 years at 85 ^oC.

Introduction

Resistance-based memory (ReRAM) has attracted much attention because of its small cell size, simple structure, high speed, and potential for low power operation and 3D stacking [1,2]. WO_X ReRAM is especially interesting because of its good electrical properties and simple process [2-4]. However, devices with TiN top electrode (TE) still require large currents for switching as well as during initial forming. In this work, we examined several different top electrodes in an attempt to search for better performance. We found that the conduction mechanism, the resistance window and the forming behavior strongly depend on the work function (WF) of the top electrode. These findings led to a novel Ni-electrode WO_X ReRAM. The new device outperforms the TiN electrode device in all categories.

Device Fabrication

Figure 1 shows the TEM image of a Ni/WO_X/W cell. The fabrication is fully compatible with CMOS process. The WO_X is formed by converting the top layer of the W plug (0.18μm in size) by a 500^{o}C rapid thermal oxidation (RTO) process [2]. The Ni top electrode (TE) is deposited by PVD.

Impact of Top Electrode Work Function

As shown in Fig. 2, the initial resistance of WO_X devices strongly depends on the WF of the TE material. A low WF TE has low initial resistance, and a high current is needed during forming to bring the resistance from low to high (type I) [2]. In contrast, a high WF TE results in high initial resistance and in this case the forming process (type II) brings the resistance from high to low.

The conduction mechanism of the WO_X ReRAM cell is studied by analyzing the J-V curves. For TiN TE (a low WF material), the J-V curve is well modeled by the space charge limited current (SCLC) theory [Eq.(1)]. For Ni and Pt (high WF materials), the J-V curves are well explained by thermionic emission [Eq.(2)], as shown in Fig.3. The barrier heights of the Ni and the Pt TE to WO_X, extracted from Eq.(2), are 0.18eV and 0.44eV, respectively.

For the TiN/WO_X/W devices, the weak temperature dependence of the current readout and the good linear relationship in the J-V^2 plot (Fig.4) are consistent with the SCLC prediction.

The J-V characteristics of the Ni/WO_X/W device and the Pt/WO_X/W device are sensitive to temperature (Figs. 5 and 6), because of thermionic emission. Barrier lowering by electric field, predicted by thermionic emission, is clearly seen in Fig.7 for both the Ni/WO_X/W and the Pt/WO_X/W cells [5]. The schematics of different conduction mechanisms using Pt, Ni, and TiN TE are depicted in Fig. 8.

Figure 9 shows the resistance window as a function of the WF of the TE. The devices with Ni or Pt TE have large resistance windows > 2 orders of magnitude, substantially better than devices with a low WF TE.

Thus TE work function (the barrier height) determines not only the conduction mechanism but also the subsequent switching current, forming characteristics, and finally the resistance ratio window.

With this insight, we proceeded to design devices with high TE WF. Although Pt has even higher WF than Ni, for the ease of processing we have chosen the Ni/WO_X/W device for further investigation.

Ni/WO_X/W Device Characteristics

The Ni/WO_X/W device is switched by bipolar operation. A positive pulse is used to RESET the device to high resistance state and a negative pulse for SET operation to low resistance state (Fig.10). The transient I-t curves for RESET and SET operations are shown in Fig.11. The RESET and SET currents are ~180uA ($J = 7x10^5$ A/cm²) and ~150uA ($J = 6x10^5$ A/cm²), respectively. They are 5X smaller than the values reported for TiN/WO_X/W devices [2]. The cycling endurance of the Ni/WO_X/W device is > 10K times, and the R window is well maintained by a program-verify algorithm [2] (Fig.12). Also, both the RESET and SET states show good immunity to read disturb when the read voltage is kept under 0.6V (Fig.13). For data retention, the RESET and the SET states are well separated after baking at 150^{o}C for 1600 hours (Fig. 14). As shown in Fig. 15, the predicted data retention is > 10 years at 115^{o}C and > 300 years at 85^{o}C. This excellent stability may be due to that the free energies for W oxide (-2.7 eV) and Ni oxide (-2.6 eV) are similar [1,6] so the driving force for intermixing is small.

Summary

The TE material plays an important role in WO_X ReRAM characteristics. A novel Ni TE WO_X ReRAM shows superior performance than the conventional device with TiN TE.

Reference

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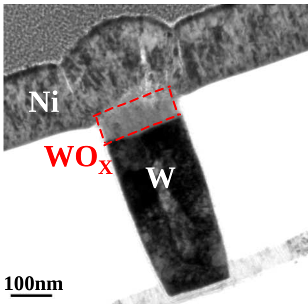

Fig. 1. The cross sectional TEM image of a Ni/WO_X/W ReRAM cell.

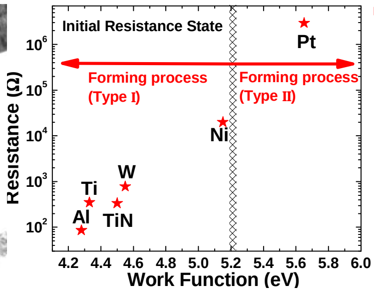

Fig. 2. The initial resistance increases with the WF of the TE. Two types of forming process (I and II) are observed.

SCLC equation:

$$J = \frac{9}{8}\mu_n \varepsilon \frac{V^2}{d^3} \text{...Eq.(1)}$$

Thermionic emission:

$$J = (A^*) * T^2 \exp\left(\frac{q\sqrt{qE/4\pi\varepsilon_i}}{k_B T} - \frac{q\Phi_B}{k_B T}\right)$$

$$J = 1.08E7 * \exp(a\sqrt{V} - b) \text{...Eq.(2)}$$

A^* = Effective Richardson constant = 120Acm^{-2}K^{-2}

T = Absolute temperature

Φ_B = Barrier height $= b * \frac{k_B T}{q}$...Eq.(3)

ε_i = Insulator dynamic permittivity

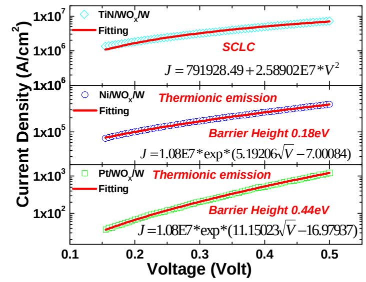

Fig. 3. SCLC fits the J-V curve for the initial state of TiN/WO_X/W, but not the device using Ni and Pt TE. Thermionic emission fits the J-V for Ni/WO_X/W, and Pt/WO_X/W.

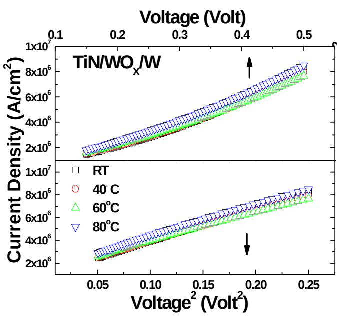

Fig. 4. J-V and J-V^2 curves for TiN/WO_X/W at 25, 40, 60, and 80°C. $J \propto V^2$ and temperature insensitivity are signatures of SCLC behavior.

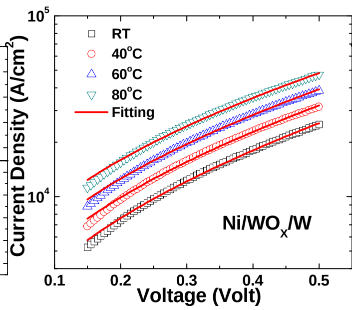

Fig. 5. J-V curves and thermionic emission fitting results for the initial state of Ni/WO_X/W at RT, 40, 60, and 80°C.

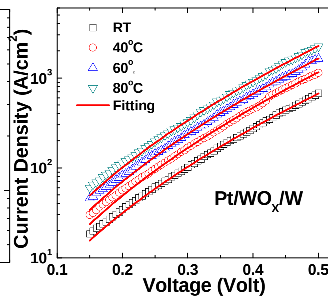

Fig. 6. J-V curves and thermionic emission fitting results for the initial state of Pt/WO_X/W at RT, 40, 60, and 80°C.

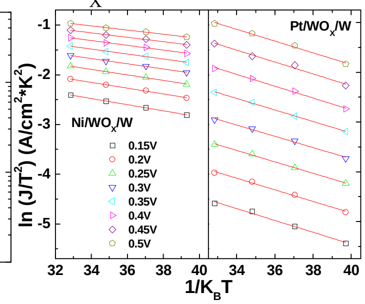

Fig. 7. ln (J/T^2) versus $1/k_BT$ curves for Ni/WO_X/W and Pt/WO_X/W at various bias voltages. The behaviors are well predicted by thermionic emission Eq.(2).

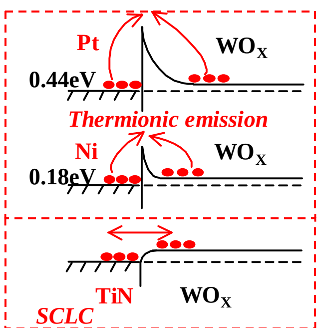

Fig. 8. Schematics of different conduction mechanisms for Pt, Ni, and TiN/WO_X/W.

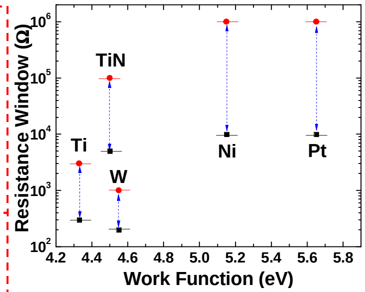

Fig. 9. High WF TE produces a large resistance window. Both Ni/WO_X/W and Pt/WO_X/W show a 100X window and higher RESET resistance .

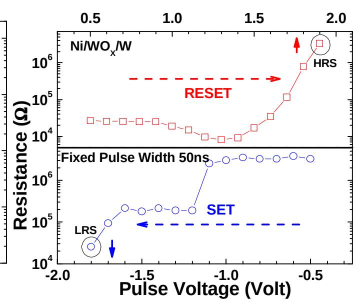

Fig. 10. RESET and SET pulse R-V curves for Ni/WO_X/W after the forming process.

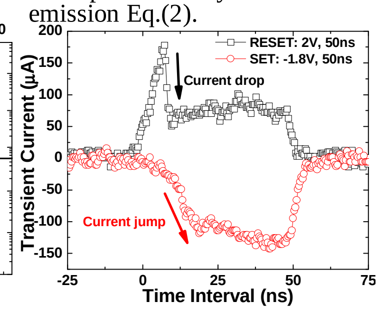

Fig. 11. Transient I-t curves of RESET and SET operations of Ni/WO_X/W cell. The RESET current is about 180uA, and SET current is about 150uA.

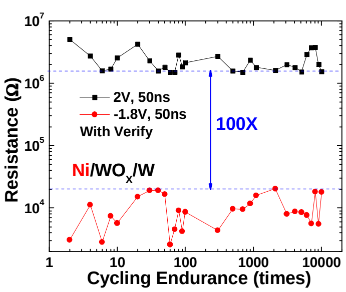

Fig. 12. Cycling characteristics of the Ni/WO_X/W cell. RESET/SET resistance window is well separated at 1MΩ /10kΩ for > 10K cycles.

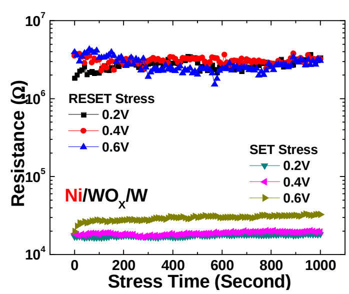

Fig. 13. Read disturb test. Both RESET and SET states show negligible read disturb up to 0.6V.

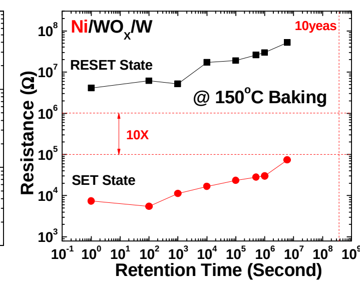

Fig. 14. Data retention of the Ni/WO_X/W cell at 150[0]C. The resistance window is well maintained after 1600 hours.

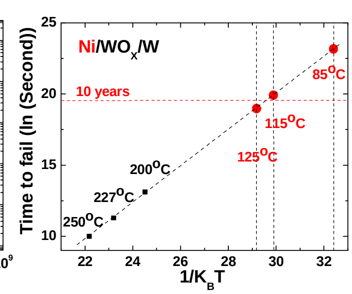

Fig. 15. Arrhenius plot for Ni/WO_X/W cell. Ea is ~ 1.34eV. The retention time is 10years @115°C, and 300 years @ 85°C. The failure criterion was <100kΩ for the SET state.