Highly Uniform and Reliable Switching Properties in NbO$_x$ Based RRAM Devices

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1. Introduction

We report excellent switching uniformity and reliability of RRAM device with W/NbO$_x$/Pt structures. Scaling down active device area ($\Phi = 250$ nm) can significantly minimize the extrinsic defects related non-uniform switching which was normally observed in large area ($\mu$m scale) device. Electro migration of oxygen ions under the bipolar electric field and lightning-rod effect localized at WO$_x$/NbO$_x$ interface can explain the improved switching behavior. Excellent device characteristic such as lower switching voltages, fast switching speed (100 ns), high temperature retention ($> 10^7$ sec, 85°C), stable cycling endurance (10$^7$ cycles), almost 100% device yield, and excellent device to device uniformity are obtained.

2. Experiments

Metal Nb films with a thickness of 18 nm was deposited (DC sputtering) on Pt/Ti/SiO$_2$/Si substrates and also in 250 nm via hole structure. NbO$_x$ films were formed by rapid thermal annealing at various oxidation conditions (for example, 500°C for 10 mins with an oxygen flow rate of 50 sccm). W or Pt top electrodes with 50 nm thickness were deposited on these films by DC sputtering using a shadow mask. The morphology and thickness of the films were investigated by scanning electron microscopy (SEM).

3. Results & Discussion

To confirm the crystallinity of the as-fabricated films, X-ray diffraction analysis was carried out. Multiple peaks in XRD pattern (Fig. 1) indicate that the film annealed at 500 °C was polycrystalline. To get the elemental information of our films, we executed X-ray photoelectron spectroscopy (XPS) depth profiling. Fig. 2a and 3a show that a very thin layer of native niobium pentoxide was formed on the surface of the films upon atmospheric exposure. According to the bulk region XPS fitting results, the NbO$_x$ film is non-stoichiometric (Fig. 3b). When the NbO$_x$ matrix came into contact with metallic W, oxygen from NbO$_x$ diffused into W due to higher energy during the DC sputtering, thereby leading to the formation of the upper oxidized layer of WO$_x$ (Fig. 2b). The further fitting results in Fig. 4a and 4b verified the formation of WO$_x$/NbO$_x$ bilayer structure, which will play the key role for the observed bipolar switching and uniformity in our devices.

After electroforming process, the filamentary bipolar switching (I-V) is demonstrated using large area (50x50 $\mu$m$^2$) device employing Pt and W top electrode, as shown in Fig. 5. In comparison with Pt/NbO$_x$/Pt structure, the W/NbO$_x$/Pt structure shows a lower reset current, stable on/off ratio, and lower set voltage (Fig. 6). Considering the similar Gibbs free energy [1] of formation of NbO$_x$ and WO$_x$, the resistive switching mechanism can be attributed to oxygen exchange between the bilayer NbO$_x$ and WO$_x$ oxides as shown in Fig. 7. Many studies demonstrated that in n-type binary oxide films, the formation of conducting filaments take place from the cathode interface to the anode and suggested that the filaments thus formed have a treelike shape. When positive bias is applied to the top electrode, O$^-$ moves from the NbO$_x$ to upward and further oxidize W, subsequently forming thin interfacial WO$_x$ and tree like oxygen vacancy filament at the top interface. When negative bias is applied, localized filaments were ruptured due to local heating at the interface and repulsion of O$^-$ ions from the top interface. This WO$_x$/NbO$_x$ is functionally similar to ZrO$_2$/HfO$_2$ bilayer structure [2], which can be described as lightning rod effect localized at the tip of filaments.

As shown in Fig. 8 with using 250 nm hole structure, we observed significantly improved switching behaviors due to the reduction of the extrinsic defects. Statistical distribution of switching parameters with respect to Nb thermal oxidizing temperature is shown in Fig. 9. Much tight distribution was observed using thermal annealing temperature of 500 °C. Set and reset voltage distribution and current distribution of two resistance states of 100 cycles data are shown in Fig. 10a and 10b. Significantly improved device to device uniformity is also shown in Fig. 11. The data retention property at high temperature (85° C) is shown in Fig. 12a. We confirmed the fabricated device shows large On/Off ratio and stable resistance states without any noticeable degradation. The switching endurance of the RRAM device is studied (Fig. 12b) with a 100 ns pulse width and no degradation is seen after 10$^7$ cycles.

4. Summary

The formation and performance of bilayer structures of binary oxides NbO$_x$ and WO$_x$ are demonstrated for use in resistance memory applications. Our proposed device shows excellent switching uniformity, good endurance and retention at 85°C, which shows considerable potential for massive applications in high-performance nonvolatile memory devices.

Acknowledgments

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References

Fig. 1 XRD pattern of NbO$_x$ film oxidized at 500 °C.

Fig. 2 XPS depth profiling for NbO$_x$ film (a) without W top electrode and (b) with W top electrode.

Fig. 3 Fitting results of Nb XPS spectra in NbO$_x$ film for (a) surface at etch time of 2 min and (b) bulk region at etch time of 12 min.

Fig. 4 Fitting results of XPS spectra for (a) W and (b) Nb at etch time of 8 min, which shows the interfacial WO$_x$/NbO$_x$ structure.

Fig. 5 Typical I-V characteristics of large area devices with Pt or W top electrode.

Fig. 6 Cumulative probability distribution of cycling endurance of large area devices with Pt or W top electrode.

Fig. 7 Schematic diagram of proposed resistive switching model in WO$_x$/NbO$_x$ bilayer structure.

Fig. 8 I-V characteristics of nano scale W/NbO$_x$/Pt device. Inset shows schematic view of 250 nm via hole structure.

Fig. 9 Set/reset voltage distribution of nano scale devices dependence on Nb thermal oxidizing temperature.

Fig. 10 Cumulative probability distribution of (a) set/reset voltages and (b) currents for HRS and LRS (100 cycles) in nano scale devices.

Fig. 11 Cumulative probability distribution of set/reset voltage (50 fresh nano scale devices).

Fig. 12 (a) Retention properties at 85 °C and (b) pulse endurance characteristics in nano scale devices.