



Research on Improving the Working Current of NbO_x-Based Selector by Inserting a Ti Layer

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To achieve the highest possible integration storage density in the V-point structure, the working current of the selector in the one-selection one-resistance (1S1R) structure should match with the resistance random access memory (RRAM). In this study, a selector device is designed with a Ti/NbO_x/Ti/Pt structure through the magnetron sputtering method and achieves excellent performance of threshold switching under ultra-large compliance current (CC) up to 100 mA. Furthermore, both the switching voltages and the OFF-state resistance of the device demonstrate excellent stability even when CC is increased to a milliampere level, attributed from the existence of metallic NbO in the switching layer. This study provides evidence that a Ti/NbO_x/Ti/Pt device has a great potential to drive RRAM in the V-point structure.

Keywords: NbO_x, threshold switching, insulator-metal transition, selector, inserting Ti layer, ultra-large CC

INTRODUCTION

At present, the explosive growth of information has brought great challenges to the existing information storage media, which promotes the rapid development of the next-generation information storage technology with high capacity, high density, and fast read-write access. Given the low-power consumption and the high switching speed (Deng et al., 2013; Tsai et al., 2016; He et al., 2019a), resistive random access memory (RRAM) has been extensively studied in the new generation of storage technology. In order to realize a large amount of information storage, a single RRAM device should be integrated into the crossbar array structure. However, a sneak path current often occurs when operating a single RRAM device inside the crossbar array, causing a misreading of stored information (Aluguri and Tseng, 2016; Diaz Leon et al., 2017). As a result, selectors are connected in series with the RRAM as an effective solution in the crossbar array structure (Kim et al., 2012; Song et al., 2017; Alayan et al., 2017; Park et al., 2017). In terms of the selector materials, the NbO₂-based selector driven by insulator-metal transition (IMT) effect has been widely adopted because of its reliable switching performance (Li et al., 2014; Park et al., 2016; Chen et al., 2018a; Wang et al., 2018), which suppresses the sneak current effectively (Chen et al., 2018b; Chen et al., 2019). Besides, to make RRAM be driven under a large current density, it is very important to ensure the working current of the selector matches with the memory in the one-selector one-resistor (1S1R) device without any electrode between them (Yang et al., 2010; Cai et al., 2018; He et al., 2019b).

In this study, a selector device with a structure of Ti/NbO_x/Ti/Pt was designed and fabricated through the magnetron sputtering method. Meanwhile, its threshold-switching property was

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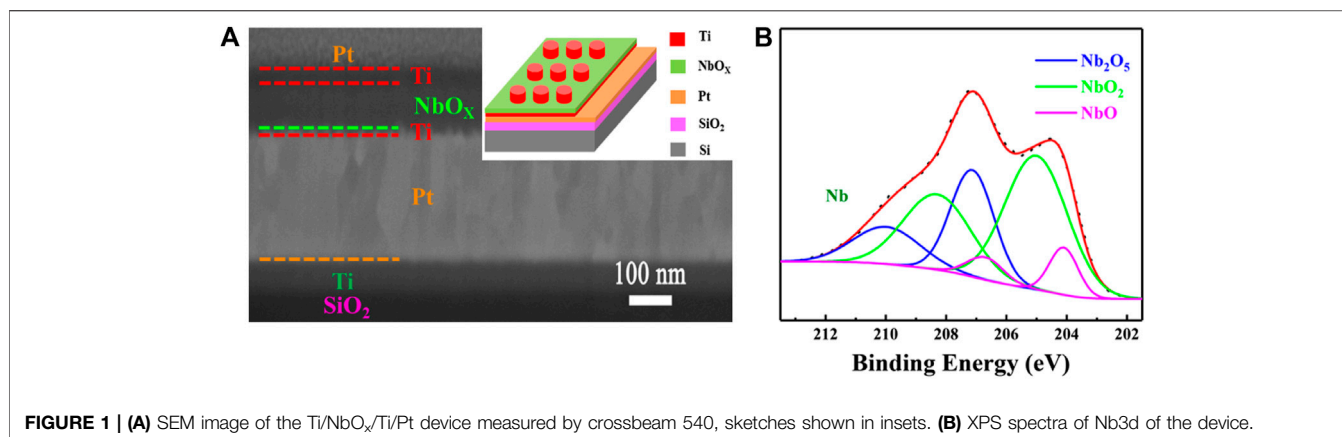
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investigated under different compliance current (CC). Compared with our previous study (Liu et al., 2021), we found that the Ti/NbO_x/Ti/Pt device had a high durability while working under ultra-large CC of the mA level when the inserting Ti layer was introduced into the device. In addition, the threshold voltage of the Ti/NbO_x/Ti/Pt device indicated high uniformity and the OFF-state resistance. This study demonstrates that the performance of a device is improved by the inserting Ti layer, which has great potential to work in the 1S1R device with the V-point structure.

EXPERIMENTS

In the study, a Ti/NbO_x/Ti/Pt selector was fabricated by the magnetron sputtering method. Briefly, an ultra-thin Ti layer, a switching layer NbO_x, and a top electrode Ti were deposited by DC, RF, and DC magnetron sputtering, respectively, to form a high-performance Ti/NbO_x/Ti/Pt structure selector. Additionally, a focused ion beam (FIB, Zeiss Crossbeam 540) scanning electron microscope (SEM) was used to study the cross section of the devices. X-ray photoelectron spectroscopy (XPS; Escalab 250Xi, Thermo Fisher Scientific) was used to characterize the NbO_x oxide composition. Electrical measurements were carried by an Agilent B1500A semiconductor parameter analyzer, in which a bottom Pt electrode was grounded and DC bias was applied to the top Ti electrode.

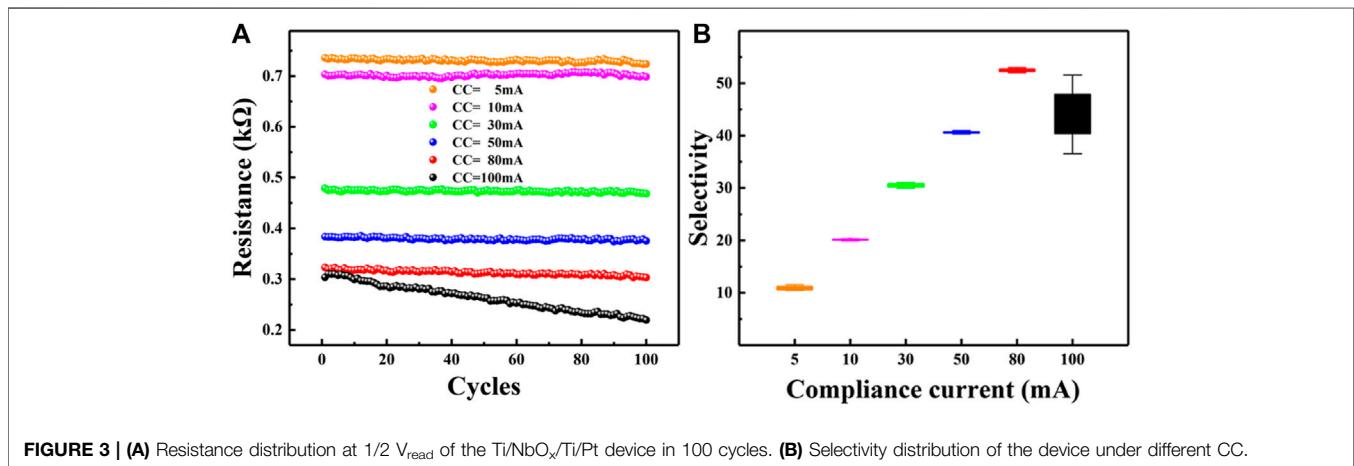
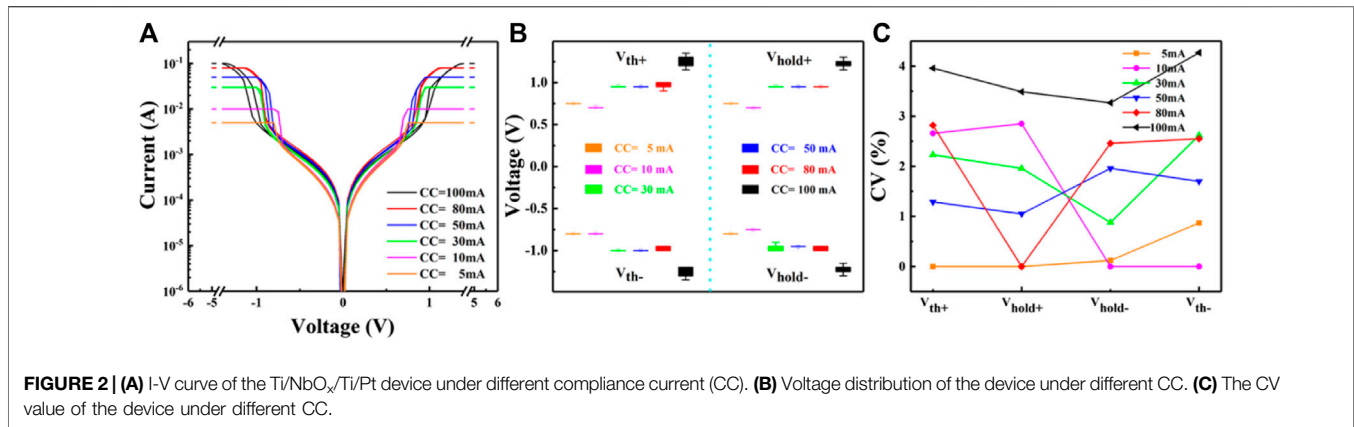
RESULTS AND DISCUSSION

The cross-sectional structure of the fabricated Ti/NbO_x/Ti/Pt device was characterized by the SEM. **Figure 1A** illustrates a cross-sectional SEM image of the device clearly shows the deposited multilayers on the Pt/Ti/SiO₂/Si substrate. The thickness of the top electrode Ti, the switching layer NbO_x, the ultra-thin Ti layer, and the bottom electrode Pt were about 25, 58, 4, and 208 nm, respectively. The sketch of the device was shown as insets. To further study the composition of NbO_x, XPS measurement was employed and the peaks of Nb were performed, shown in **Figure 1B**. Based on the analysis, six diffraction peaks

were found in the NbO_x film, with binding energies of 207.5 and 210.3 eV were corresponded to Nb⁵⁺, 205.6 and 208.4 eV were corresponded to Nb⁴⁺, while two other peaks located at 203.9 and 206.7 eV were corresponded to Nb²⁺, respectively (Jung et al., 2011). Based on the XPS spectrum, we can further quantify the mass proportions of Nb²⁺, Nb⁴⁺, and Nb⁵⁺ in the NbO_x thin film was about 9.22, 49.37, and 41.41%, and the molar ratio of Nb was 38.13%. The selector performance of the device was caused by the NbO₂ phase change driven by IMT; however, the presence of NbO in NbO_x might affect the performance of the device potentially.

I-V measurements were used to characterize the electrical properties of the Ti/NbO_x/Ti/Pt device, as shown in **Figure 2A**. Under 5 mA CC, the current of the device suddenly increased at positive threshold voltage (V_{th+}) of 0.75 V when a positive I-V sweeps from 0 to 2 V, indicating the device state switching from OFF state to ON state. In opposite, the positive hold voltage (V_{hold+}) was measured when the voltage reverse swept from 2 to 0 V; the current decreased rapidly at 0.75 V and the device recovered from ON state to OFF state. Similarly, V_{th-} and V_{hold-} were measured at -0.85 V and -0.85 V in the negative voltage region, respectively. The four voltage values (V_{th+} , V_{hold+} , V_{th-} , and V_{hold-}) increase along with the increase of CC, while the device still kept threshold-switching property even when CC is up to 100 mA. As a comparison, the working current of the other research was low to a high microamps level (Wang et al., 2018; Lee et al., 2020; Gao et al., 2017; Park et al., 2018; Luo et al., 2019), whereas the working current of the Ti/NbO_x/Ti/Pt device has been increased by 10 times or more. This indicated that the Ti/NbO_x/Ti/Pt device has the great potential to drive RRAM under ultra-large working current.

100 cycling of the I-V curves were further employed to analyze the stability of the voltages. **Figure 2B** demonstrated a statistical distribution of device voltage under different CC, illustrating that the voltages were largely increased as CC rose. Meanwhile, the voltages of the device were limited to a small fluctuation range when CC from 5 mA up to 50 mA, which showed remarkable stability. The voltages fluctuation range of the device was slightly increased when CC was increased to 80 and 100 mA, which still showed enough stability. This demonstrated that the device has very stably switching voltages at the mA level of CC.

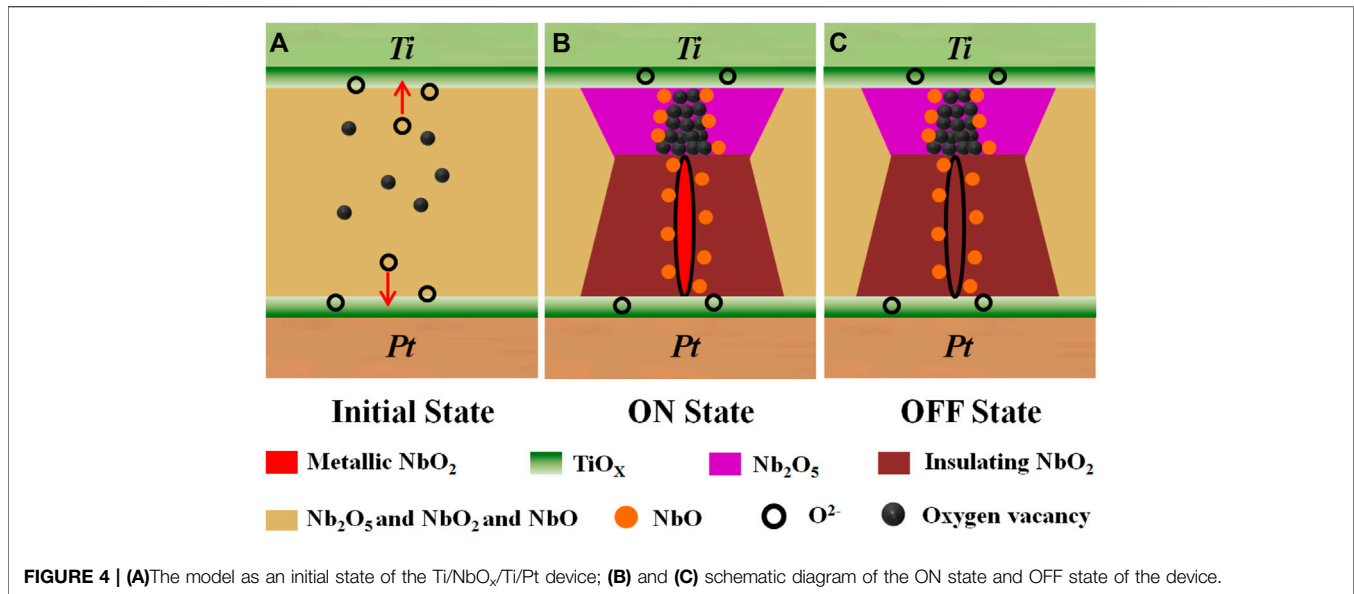


Furthermore, given the mean value was quite different, the coefficient of variation (CV) was used to evaluate the voltage distribution, which was defined as the ratio of standard deviation (σ) with respect to mean value (μ). The CV of the device increased with the increase in the CC, as shown in **Figure 2C**. The CV of the device was smaller than 5% for working under different CC. The smaller the value of the CV, the weaker the voltage fluctuation, which indicated the consistency of the voltage was better. The drift of voltage of the Ti/NbO_x/Ti/Pt device was smaller and exhibited a more reasonable uniformity, which illustrated that the four voltages have outstanding consistency under the mA level CC except 100 mA.

Furthermore, in order to further explore the stability of the Ti/NbO_x/Ti/Pt device, the OFF-state resistance distribution was carefully examined. **Figure 3A** shows the OFF-state resistances of the device from 1 to 100 cycles under different CC. The OFF-state resistance of the device decreased along with the increase in CC from 5 to 100 mA. Besides, OFF-state resistances kept stable during 1–100 cycling under 5–80 mA CC. However, when CC was increased to 100 mA, the resistance decreased as the cycling increased, demonstrated a degraded device performance. Therefore, the Ti/NbO_x/Ti/Pt device illustrated a remarkable stability of OFF-state resistance under tens of the mA level CC, thus it has a great potential to work under ultra-large

current density. In order to confirm the performance of the device, the selectivity, as one of the most important performance parameter, was studied. In **Figure 3B**, the selectivity average value of the device was increased from 11 to 53 as CC increased. The selectivity statistics distribution of the device exhibited remarkable stability distributions when CC was increased from 5 to 80 mA, except for the slight poor trend when CC was 100 mA. The stability of selectivity could inhibit the sneak path current more effectively in crossbar arrays (Zhou et al., 2014). Therefore, the selectivity distribution of the Ti/NbO_x/Ti/Pt device demonstrated that had has the potential to suppress sneak path current in crossbar arrays.

To uncover the high sustainability of the Ti/NbO_x/Ti/Pt device under large CC, the models of initial ON and OFF working states are presented in **Figure 4**. The initial working state of the model is shown in **Figure 4A**. The oxygen ions in the NbO_x film were controlled and diffused into the Ti film; hence, a TiO_x film was formed, given its ability to absorb oxygen ions, meanwhile, created more defects, that is, oxygen vacancy in the NbO_x film (Samanta et al., 2019). Then, driven by a forming voltage, the diffusion of oxygen ions in NbO_x leads to the formation of Nb₂O₅ near the top of the Ti electrode and NbO₂ near the bottom of the Pt electrode. The conducting filament played by oxygen vacancy could



permanently form in the Nb₂O₅ region. In a forward scanning process, the phase of NbO₂ changed from insulating to metallic phase when the DC bias voltage reached V_{th+} , and the device changed from the OFF state to ON state, as shown in **Figure 4B**. At this time, the oxygen vacancy formed by oxygen absorption effect of ultra-thin Ti films could also play an auxiliary role in the stability of the conductive filaments to withstand higher working current. Meanwhile, the NbO, which performed conductively (Liu et al., 2012), was mixed into NbO₂ and Nb₂O₅, and then made that the device could withstand more current pass through, resulting in outstanding sustainability under large CC. Moreover, with conductive properties, NbO could also play an active role in the stable conductive channel formed by NbO₂ and conductive filaments, which reduced the randomness of the conductive channels and therefore improved the stability of the threshold voltage and OFF-state resistance, and in the subsequent reverse scanning process, the device switched from ON state to OFF state and was triggered by the phase transition of NbO₂ from the metallic phase to the insulating phase, as shown in **Figure 4C**. The NbO with conductive properties also had an auxiliary role in forming a path for leakage of current when NbO₂ was in the insulating phase state. In general, because of the existence of an ultra-thin Ti film led to form high conductive properties NbO, the Ti/NbO_x/Ti/Pt device could stay stably under ultra-large CC, thus demonstrated an outstanding property of switching, and provided an effective method to enhance the selector performance.

CONCLUSION

In summary, the Ti/NbO_x/Ti/Pt selector device was prepared by the magnetron sputtering method on the Pt/SiO₂/Si substrate, and the device showed its excellent threshold-switching

properties under ultra-large CC. Furthermore, the threshold voltages and OFF-state resistance display high consistency as well as selectivity, thus better accords with the practical application requirements of the ultra-large operating current device. Besides, a schematic analysis indicated that the share current effect of conductive properties of NbO contributes to the stability of the Ti/NbO_x/Ti/Pt device. This study was provided for improving the work current of selector devices and indicated that the Ti/NbO_x/Ti/Pt selector device had a great potential in driving the RRAM device.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

CL demonstrated all experiments in the study and wrote the manuscript. GM and HW conducted deep review, editing, guidance, and supervision. All authors have read and approved the article for publication.

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