Feasibility of Schottky diode as selector for bipolar-type resistive random access memory applications

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The feasibility of Schottky diode as selector has been investigated for possible application in bipolar-type resistive random access memory (RRAM) devices. In order to evaluate the feasibility of Schottky diode as selector for bipolar-type RRAM applications, a full device simulation has been performed utilizing a Schottky diode + bipolar-type RRAM structure (1SD-1R). On the other hand, we confirmed its successful operation under experimental results with Ni/TiO_x/W Schottky diode + Pt/HfO_2/Cu bipolar-type RRAM structure. Furthermore, by applying a lower Set voltage in the 1SD-1R structure device, the Reset current and Reset voltage are found to decrease due to the reduced compliance current. Such dependence provides the possibility of lower power consumption in the 1SD-1R structure device. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4870465]

Resistive random access memory (RRAM), based on resistive switching between a high resistance state (HRS) and a low resistance state (LRS) by the application of an appropriate voltage has been proposed as one of the most promising candidates for next-generation nonvolatile memory application due to its overwhelming advantages for easy fabrication, simple structure, excellent scalability, fast switching speed, high integration density, and good compatibility with the CMOS technology.[1–8] Depending on the bias polarity of its program and erase operations, RRAM device is categorized as bipolar-type and unipolar-type. In the case of a bipolar-type RRAM device, the polarity between switching from the HRS to the LRS (Set process) is reversed compared to the switching from the LRS to the HRS (Reset process). On the contrary, the same polarity is used for the Set and Reset operations in a unipolar-type RRAM device.

For RRAM, because of its simple capacitor-like structure composed of an insulating or resistive material sandwiched between two electron-conductive electrodes, it is highly promising for use in crossbar array with the smallest cell size of $4F^2$ (F is the minimum feature size) for high density nonvolatile memory applications.[9,10] However, a crossbar array consisting of only RRAM cell suffers unavoidable cross-talk interference due to leakage current paths through neighboring unselected cells with low resistances,[9–11] leading to a misreading problem, a fatal hindrance in practical memory applications. The integration of a selecting diode to each RRAM cell is one of the most familiar solution to diminish the sneak current in crossbar array,[11–16] because the one diode-one resistor structure can not only achieve $4F^2$ density but also has high potential for three-dimensional (3D) stackable integration to further increase density to $4F^2/n$.[12,13] So far, different types of diodes for unipolar-type RRAM crossbar array has been demonstrated.[11–16] However, bipolar resistive switching with wide separation of Set and Reset voltages at opposite polarities ensures reliable programming, in contrast to the smaller separation at the same polarity for the unipolar resistive switching. Therefore, it is necessary to investigate the feasibility of a kind of diode as selector for bipolar-type RRAM crossbar array applications.

In this letter, a Schottky diode and a bipolar-type RRAM connected in series is proposed with the Schottky diode as the selector for the bipolar-type RRAM crossbar array. To evaluate the feasibility of Schottky diode as bipolar-type RRAM selector, we utilized a Schottky diode + bipolar-type RRAM (1SD-1R) structure and confirmed its successful operation by integrating the Ni/TiO_x/W Schottky diode and a Pt/HfO_2/Cu bipolar-type RRAM cell in series, which provides a feasible way to realize high-density bipolar-type RRAM cross-bar array. In addition, lower Reset current and Reset voltage can be achieved by applying a lower Set voltage during the Set process.

In order to evaluate the feasibility of Schottky diode as selector for bipolar-type RRAM applications, a commercial available Schottky diode SD41 was used for simulation. The experimental bipolar-type 1SD-1R structure device presented in this study was fabricated as follows. 40 nm TiO_x films were first deposited on the W bottom electrode (BE) by an atomic layer deposition system at 250 °C using $TiCl_4$ and H_2O as the Ti-precursor and the oxygen source, respectively. Then, 20/60 nm Ti/Ni top electrode (TE) with areas of $200 \times 200\,\mu m^2$ was deposited by electron beam evaporation followed by a lift-off photolithographic process to form the Ni/TiO_x/W Schottky diode. After that, $100 \times 100\,\mu m^2$ bipolar-type RRAM device cells, consisting of three sequential layers of Pt/HfO_2/Cu (with thickness of 50/20/50 nm, respectively) were stacked in succession on the Ti adhesion layer by electron beam evaporation at room temperature.

Figure 1(a) shows the typical *I-V* curve of the commercial available Schottky diode SD41. As can be seen from Fig. 1(a), the Schottky diode SD41 exhibits high current and exponential current increase for a positive voltage. More satisfactorily, different from the conventional p-n junction diode that cannot be used as a selector for a bipolar-type RRAM because the current flow through the series p-n

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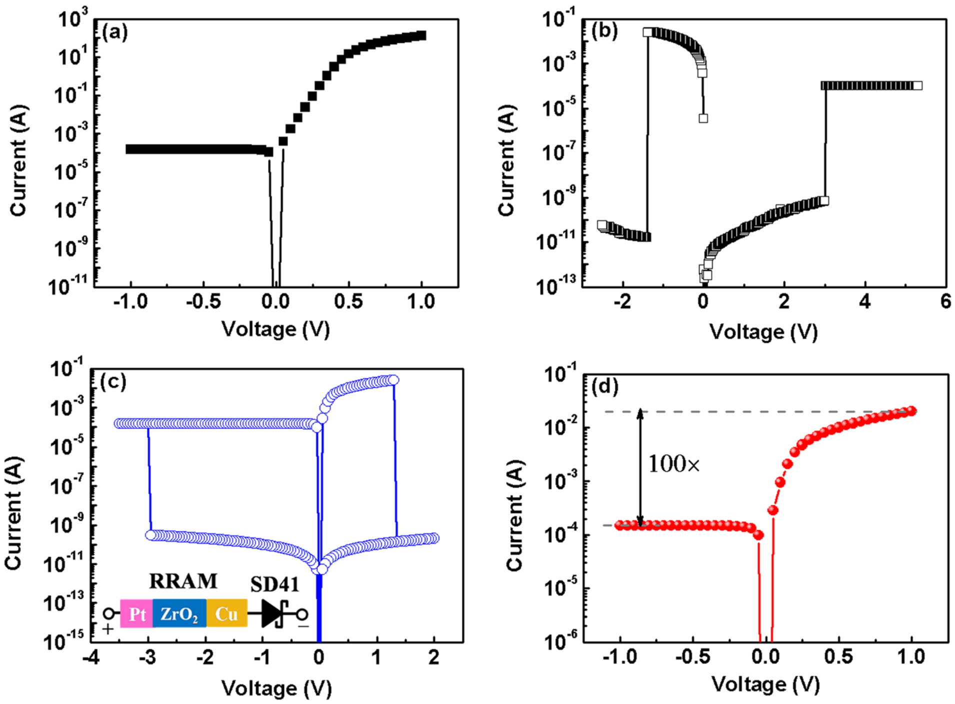

FIG. 1. (a) *I–V* characteristics of the commercial available Schottky diode SD41. (b) Typical resistive switching characteristics of the $Cu/ZrO_2/Pt$ bipolar-type RRAM cell. (c) Simulation *I–V* curve of the combined 1SD-1R device with $Pt/ZrO_2/Cu/SD41$ structure. The inset of (c) shows the schematic structure of the combined 1SD-1R device. (d) *I–V* curve of the simulation 1SD-1R device at LRS.

junction diode under a reverse bias condition is extremely low, the reverse current of the SD41 is over 100 μA. In our previous work,[17] a current value of 100 μA has been used as the compliance current during the Set operation for the $Cu/ZrO_2/Pt$ bipolar-type RRAM cell, as shown in Fig. 1(b). According to these results, we can infer that the reverse current of 100 μA for the SD41 Schottky diode can be used to achieve the Set operation for a bipolar-type RRAM cell. In order to examine the feasibility of Schottky diode as selector for bipolar-type RRAM cell to suppress the sneak current in crossbar array, a full device simulation has been performed by connecting the SD41 Schottky diode and a bipolar-type RRAM structure in series. The parameters of the bipolar-type RRAM used in simulation are as follows: the Set voltage is -3 V, the reset current is 25 mA, the resistance values of the HRS and LRS are 10^{10} Ω and 50 Ω, respectively. During the simulation, the cathode of the SD41 Schottky diode is used as the BE of the 1SD-1R device, and the Pt BE of the $Cu/ZrO_2/Pt$ bipolar-type RRAM cell served as the TE of the 1SD-1R device. The bias voltage during the simulation is applied on the TE of the 1SD-1R device, and the BE of the 1SD-1R device is grounded, as illustrated in the inset of Fig. 1(c). Figure 1(c) shows the simulation results of the combined 1SD-1R structure device, namely, $Pt/ZrO_2/Cu/SD41$. Under negative bias, the storage node can be switched from a HRS to a LRS, while under reverse bias the storage node switched back to HRS again. As expected, the 1SD-1R device shows obvious rectifying effect at LRS, a rectifying ratio over 100 at ± 1 V can be obtained at the LRS, as shown in Fig. 1(d), indicating that the 1SD-1R structure device can be used to suppress the sneak current in bipolar-type RRAM based crossbar array.

However, the simulation 1SD-1R structure is not suitable for 3-dimensional (3D) stacked structures to further increase the memory density due to high temperature processes for silicon-based Schottky diode. Compared with silicon-based diode, oxide diodes may be the best choice to rectify unwanted leakage current paths because oxide diodes can be fabricated over any substrate even at room temperature and thus formed in 3D stacked structures.[13,14] To further confirm the feasibility of oxide-based Schottky diode as selector for bipolar-type RRAM cross-bar applications. We fabricated a 1SD-1R memory device with $Pt/HfO_2/Cu/Ti/Ni/TiO_x/W$ stacked structure, where $Pt/HfO_2/Cu$ is a bipolar-type RRAM cell and $Ni/TiO_x/W$ is an oxide-based Schottky diode. Figure 2(a) shows the *I-V* characteristics of the $Pt/HfO_2/Cu$ bipolar-type RRAM cell (blue line) and the $Ni/TiO_x/W$ Schottky diode (red line). As can be seen from the blue line, by sweeping the voltage from zero to a negative voltage up to the Set voltage, an abrupt increase of device current reaches

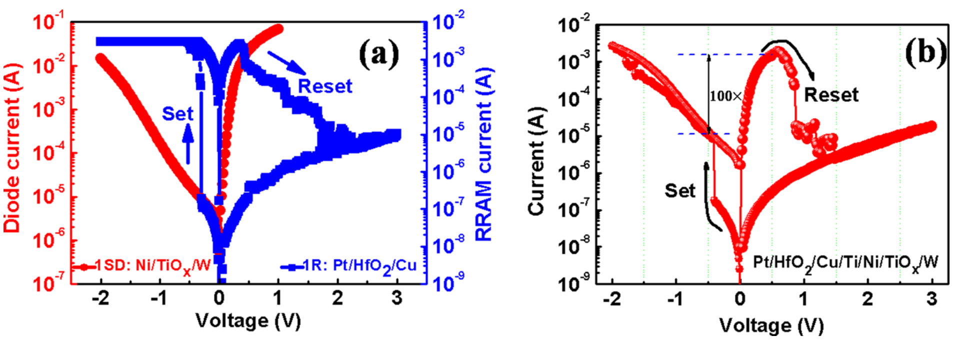

FIG. 2. (a) *I-V* characteristics of the $Ni/TiO_x/W$ Schottky diode (Red line) and $Pt/HfO_2/Cu$ bipolar-type RRAM cell (Blue line). (b) Typical *I–V* characteristic of the integrated 1SD-1R structure device. The integrated 1SD–1R structure device exhibits bipolar resistive switching characteristic and an obvious rectifying behavior with a rectifying ratio over 100 can be obtained by ± 0.5 V read voltage at LRS.

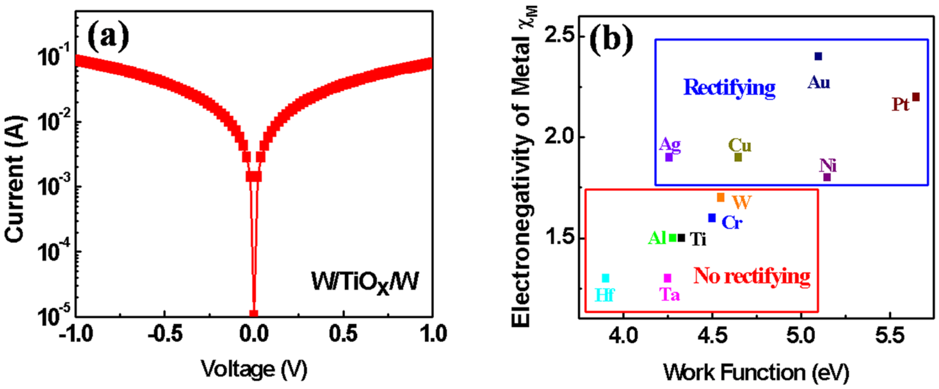

FIG. 3. (a) *I-V* curve of the W/TiO_x/W device. (b) Dependence of rectifying behavior on TE metals with different work function and electronegativity.

to compliance current and the RRAM cell switches from HRS to LRS. Afterwards, by sweeping the voltage from zero to a positive voltage, a sudden drop of device current can be observed at the Reset voltage, and the RRAM cell switches to HRS again. According to our previous work,[18,19] the bipolar resistive switching of the Pt/HfO_2/Cu RRAM cell is believed to be related to the formation and dissolution of conductive filaments inside the HfO_2 layer. For the Ni/TiO_x/W Schottky diode, the reverse current of the Ni/TiO_x/W Schottky diode at -1 V is over 100 μA, which is high enough for bipolar-type RRAM to perform the Set operation, indicating that the Ni/TiO_x/W Schottky diode can be used as selector for bipolar-type RRAM to configure 1SD-1R structure.

Figure 2(b) shows the *I–V* characteristic of the integrated 1SD-1R memory device with the Pt/HfO_2/Cu/Ti/Ni/TiO_x/W stacked structure. The integrated 1SD-1R structure exhibits typical bipolar resistive switching characteristic. When a negative voltage sweep (0 V $\rightarrow$ -2 V) is applied to the Pt TE, the current of the device increases rapidly at the Set voltage and the 1SD-1R structure device switches from HRS to LRS. As expected, the 1SD-1R structure shows obvious rectifying effect at LRS, the positive current of the LRS is over 100 times higher than the negative value at a 0.5 V readout voltage, as shown in Fig. 2(b). This result indicates that the 1SD-1R structure device can be used to suppress the sneak current in crossbar array. When the 1SD-1R structure is LRS, by applying a positive voltage sweep (0 V $\rightarrow$ 3 V), resistive switching from LRS to HRS is obtained at the Reset voltage, where the current decreases abruptly.

To understand where the dominant Schottky barrier is located, a W/TiO_x/W structure is fabricated. For the W/TiO_x/W device, symmetric and high leakage currents are observed between ± 1 V, as shown in Fig. 3(a), indicating that the TiO_x/W interface is Ohmic contact. By using metal Ni as the TE, the Ni/TiO_x/W device exhibits nonlinear diode characteristics. Due to the Ohmic contact of the TiO_x/W interface, the rectifying *I–V* characteristics of the Ni/TiO_x/W device can be attributed to the Schottky contact at the Ni/TiO_x interface. To further study the dominant effect of various metal materials on the rectifying characteristic of metal/TiO_x interface, various metal materials (Ti, W, Al, Cr, Hf, Ta, Cu, Ag, Ni, Au, and Pt) with different work function of 3.9–5.6 eV and electronegativity of 1.3–2.4 have been deposited as TE in the structure of TE/TiO_x/W. It is found that

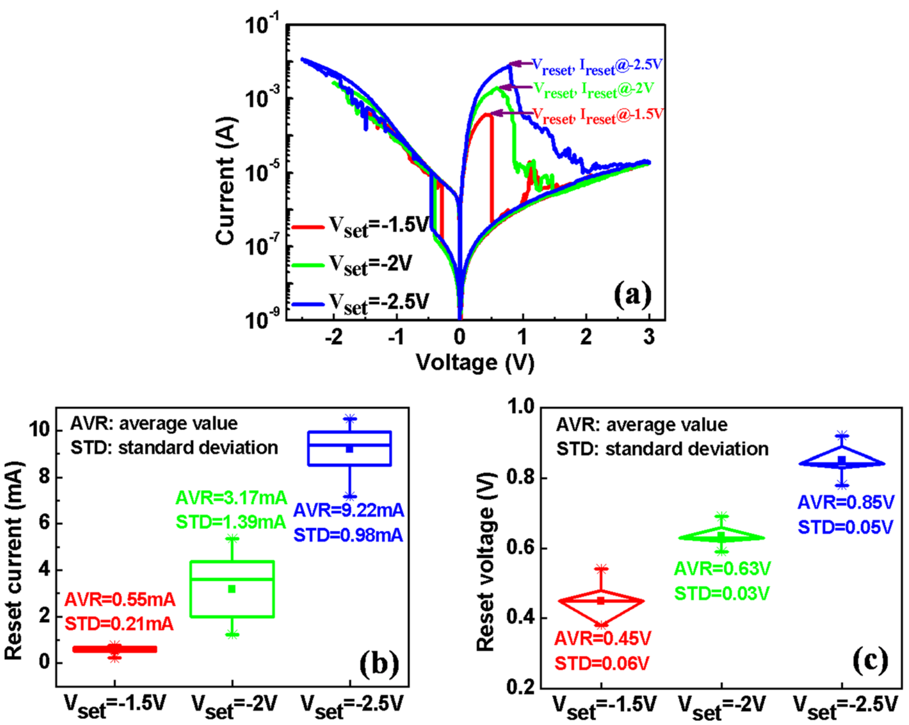

FIG. 4. (a) Comparison of *I-V* characteristics in the 1SD-1R device by controlling V_{set}. (b) Dependence of Reset current on different V_{set} in the 1SD-1R device. (c) Dependence of Reset voltage on different V_{set} in the 1SD-1R device.

TE/TiO_x/W (TE = Ti, W, Al, Cr, Hf, and Ta) devices show almost symmetric linear *I-V* curves, while TE/TiO_x/W (TE = Cu, Ag, Ni, Au, and Pt) show rectifying *I-V* curves (data not shown here). The dependence of rectifying behavior of the TE/TiO_x/W structure devices on work function and electronegativity of TE metals are summarized in Fig. 3(b). A symmetric *I-V* curve can be observed in the TE/TiO_x/W structure device if the electronegativity of TE is low. In contrast, the rectifying behavior is obtained only with high electronegativity of TE. Based on these results, it is concluded that the *I-V* characteristics of the fabricate TE/TiO_x/W structure devices strongly depend on the electronegativity of TE metals rather than the work function of TE metals, similar results have also been demonstrated by Zhong *et al.*[20]

Figure 4(a) compares the *I-V* characteristics of the 1SD-1R device with different Set voltage (V_{set}) during the Set process. It is found that the Reset current and Reset voltage of the 1SD-1R device reduce with the decrease of V_{set}, as shown in Figs. 4(b) and 4(c), respectively. This result can be attributed to the decreased compliance current by applying a low V_{set} during the Set process. Such dependence provides the possibility that lower power consumption can be achieved in the 1SD-1R device by further decreasing the value of V_{set}.

In conclusion, a bipolar-type 1SD-1R memory device concept is proposed by the theoretical simulation, and it is also demonstrated by the integration of the Ni/TiO_x/W Schottky diode and a Pt/HfO_2/Cu bipolar-type RRAM cell. These results suggest that the Schottky diode is a promising candidate for using as selector to suppress the undesired sneak current in bipolar-type RRAM crossbar array. In addition, lower Reset current and Reset voltage are obtained by applying a lower Set voltage, indicating that lower power consumption can be achieved in the 1SD-1R structure device by further decreasing the Set voltage during the Set process.

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