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High-density 1S1R Flexible Bipolar Resistive-switching Memory

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Introduction

Soaring demand for greater portability, flexibility, and lower cost in consumer electronics have inspired recent rapid development of flexible electronics [1]. One major prerequisite for low-cost flexible electronics is the compatibility of low-temperature fabrication. Several emerging nonvolatile memories, including resistive-switching random access memory (RRAM), have been proposed for flexible memory applications using a minimum $4F^2$ crossbar array structure and low-temperature fabrication [2]. However, the sneak current issue at read has limited the implementation of high-density memory with sufficient read margin in passive one-resistor (1R) crossbar array. A nonlinear selection device can be integrated into memory arrays to suppress sneak current, such as one MOSFET transistor-one resistor (1T1R) and one bipolar junction transistor-one resistor (1BJT1R). However, their high-temperature processes and large areas of unit cells are undesirable [3-4]. One diode-one resistor (1D1R) and one bipolar selector-one resistor (1S1R) are regarded as promising structures for flexible memory applications. In particular, the 1S1R architecture has greater potential for high-density crossbar array than the 1D1R architecture [5]. In this study, we fabricated and characterized flexible bipolar nonlinear Ni/TiO_2/Ni selectors and reproducible Ni/HfO_2/Pt resistive-switching (RS) memory elements under mechanical bending strains. In addition, vertically stacked Ni/TiO_2/Ni/HfO_2/Pt 1S1R cells were fabricated at room temperature on a plastic substrate. Combining the advantages of an all bit-line pull-up (All-BLPU) scheme with the nonlinear 1S1R memory cell, extremely large array size of 60 Mb can be achieved for flexible memory applications.

Experimental Procedures

To fabricate the flexible bipolar selector, a symmetrical structure of Ni/TiO_2/Ni was deposited by reactive magnetron DC sputtering. The Ni top electrodes were defined by shadow mask. As for the flexible memory element, a RS layer of HfO_2 and Ni top electrodes were deposited on a tri-layer structure of Pt/Ti/SiO_2 as bottom electrodes. The vertically stacked 1S1R cells were fabricated using only three shadow masks to pattern bipolar selectors and memory elements. All processes were completed at room temperature on a flexible polyimide (PI) film. Robust flexible devices under mechanical bending strain are shown in Fig. 1.

Results and Discussion

Fig. 2 illustrates the symmetric and nonlinear *I-V* characteristics of the bipolar selector. The current increased exponentially by about 3 orders of magnitude from ±1 V to ±2 V. *I-V* curves remained stable and reproducible after hundreds of successive voltage sweeps. Slight deviations of the extracted nonlinearity under bending was observed in Fig. 3.

The Ni/HfO_2/Pt memory element demonstrates typically bipolar RS with extremely tight resistance distribution for high resistance state (HRS) and low resistance state (LRS) under both flat and bending conditions in Fig. 4 and Fig. 5. However, the HRS current under bending increased. Fig. 6 shows that both HRS current at flat and bending states were dominated by Ohmic conduction at low bias. The extracted activation energy of the Ohmic conduction was 0.7 eV and 0.47 eV for flat and bending states, respectively. Therefore, it was postulated that the increased HRS current was caused by shallow bulk defects induced by bending strain in HfO_2. A mechanical stress vehicle shown in Fig. 7 was used to demonstrate electrically resilient characteristics under successive bending cycles. The resistance of HRS and LRS were sturdy after 10^3 bending cycles, as shown in Fig. 8. Fig. 9 shows excellent retention characteristics of HRS and LRS at both flat and bending states for up to 10^4 sec.

To evaluate the stored data in a $N\times N$ crossbar array, a pull-up voltage (V_{pu}) was applied to the selected bit line while the selected word line was grounded, as shown in Fig. 10 (a) and (b). All unselected word lines were floating, while unselected bit lines can be either floating or pulled up. The former is referred to as the one bit-line pull-up (One-BLPU) scheme, and the latter is referred to as the all bit-lines pull-up (All-BLPU) scheme. The worse-case scenario is defined as the data pattern which gives a lowest voltage swing between reading HRS and LRS. In One-BLPU, it is referred to as: when the selected bit is at its HRS(LRS), all unselected cells are at their LRS(HRS). The worse-case scenario in All-BLPU is: when the selected bit is at its HRS, all the unselected cells are at their LRS; when the selected bit is at its LRS, the unselected cells in region 1, 2, and 3 are at their LRS, LRS, and HRS, respectively.

In order to prevent read interference through the parasitic sneak current path, the nonlinear bipolar selector was vertically stacked on the bipolar RRAM. Fig. 11 shows the nonlinear bipolar 1S1R RS *I-V* characteristics and the numerical fittings used in SPICE simulation. The simulated read margin of the 1S1R cell using both One-BLPU and All-BLPU are shown in the inset of Fig. 11, where the read margin was further improved by pulling up unselected bit lines. The maximum array size was estimated to be 60 Mb with at least a 10% read margin.

Conclusion

Highly nonlinear bipolar selectors, reproducible memory elements and vertically stacked 1S1R cells were successfully fabricated at room-temperature on plastic substrates. Combining the merits of the nonlinear resistance in 1S1R and the All-BLPU scheme, the maximum crossbar array size was estimated to be 60 Mb, showing the promise of flexible bipolar RRAM for high-density crossbar memory array.

References

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[3] S. S. Sheu, et al., in *Symp. on VLSI Circuits*, 2009, p.82–83.
[4] H. Wang, et al., in *IEDM Tech Dig.*, 2010, pp. 664–667.
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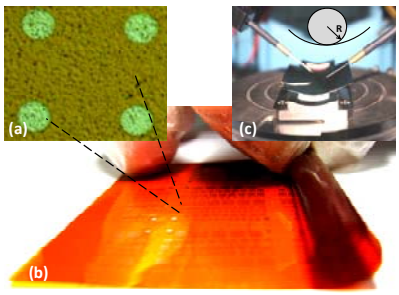

Fig. 1 (a) Optical microscope image of the fabricated devices (b) Robust flexibility under mechanical bending strain (c) Devices under test on a concave stage with 10 mm radius.

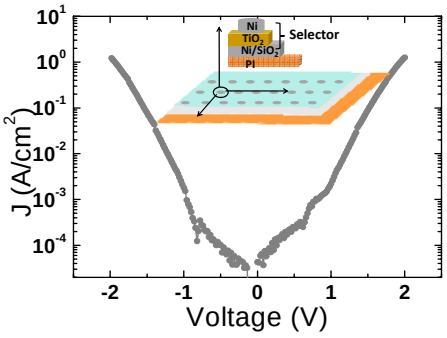

Fig. 2 Symmetric and nonlinear *I-V* characteristics of bipolar selectors.

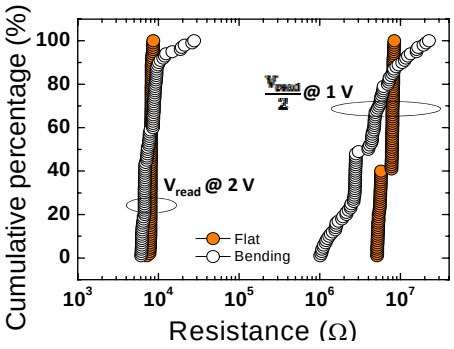

Fig. 3 Cumulative percentage of resistance of Ni/TiO_2/Ni selector at 1 V and 2 V at flat and bending states.

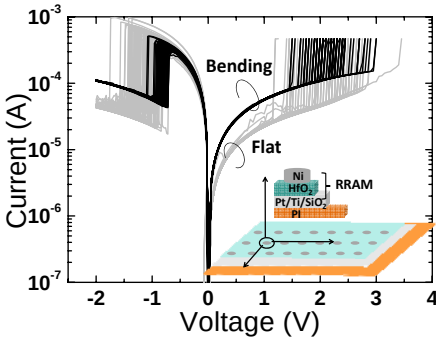

Fig. 4 Typically bipolar RS *I-V* curves under 100 consecutive switching at flat and bending states.

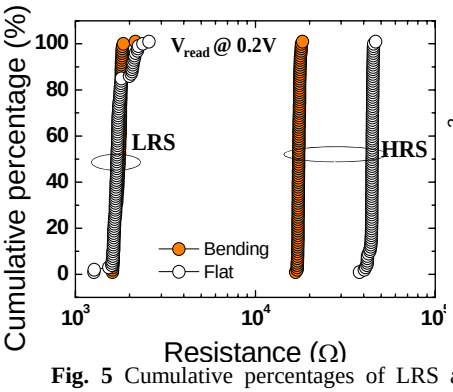

Fig. 5 Cumulative percentages of LRS and HRS resistance of the Ni/HfO_2/Pt device at flat and bending states.

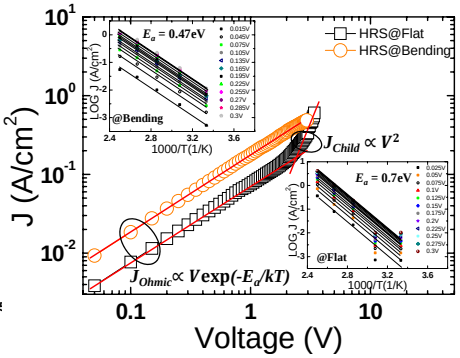

Fig. 6 *I-V* curves in HRS under both flat and bending states with their fitting results using SCLC mechanism. The insects show the extraction of activation energy.

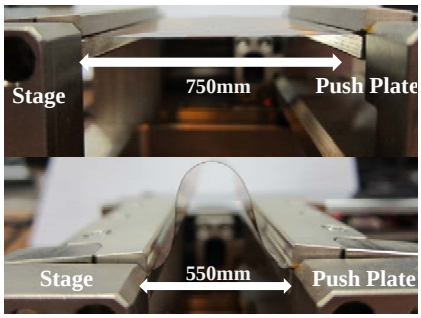

Fig. 7 Mechanical stress vehicle used for the successive bending test.

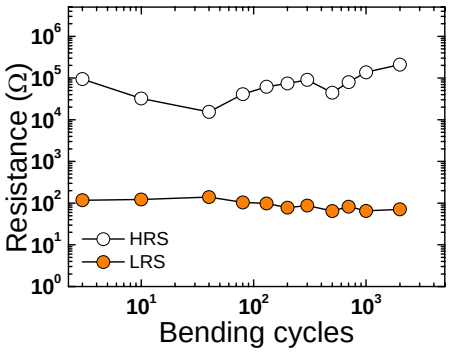

Fig. 8 Resistance of HRS and LRS were sturdy after 10^3 bending cycles

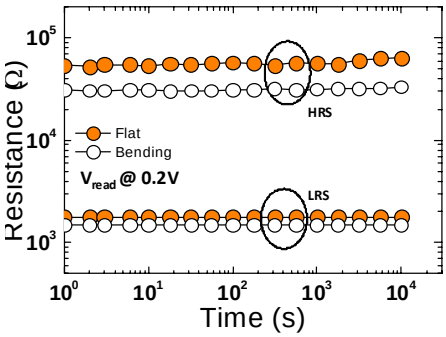

Fig. 9 Excellent retention of HRS and LRS at both flat and bending states for up to 10^4 sec.

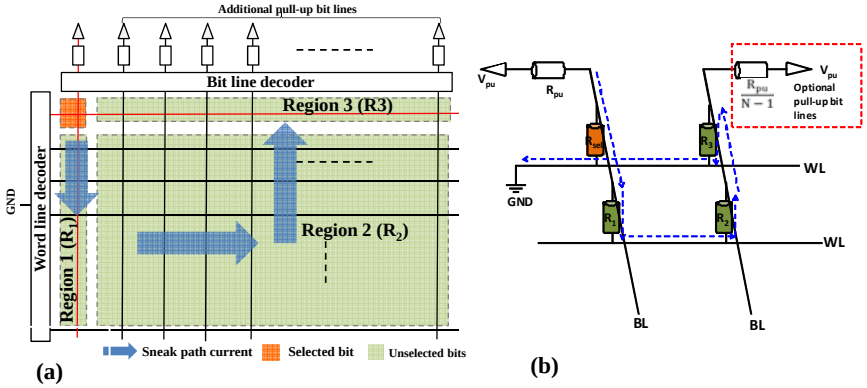

Fig. 10 (a) Read scheme for a *N*×*N* crossbar array. The sneak current path is indicated by blue arrows. (b) Equivalent circuit model for the *N*×*N* crossbar array.

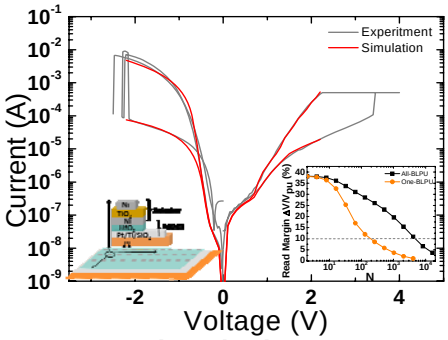

Fig. 11 Nonlinear bipolar 1S1R RS *I-V* characteristics and the numerical fittings used in SPICE simulation. Inset shows calculated read margin using both One-BLPU and All-BLPU read schemes.