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Metal oxide resistive switchung memory: Materials, properties and switching mechanisms

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A R T I C L E I N F O

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A B S T R A C T

With the continuously changing landscape of the computer technologies, a new memory type is needed that will be fast, energy efficient and long-lasting. It shall combine the speed of random access memory (RAM) and non-volatile in the same time. Resistive RAM (RRAM) is one of the most promising candidates in this respect. RRAM has attracted a great deal of attention owing to its potential as a possible replacement for flash memory in next-generation nonvolatile memory (NVM) applications. A brief summary of binary metal oxide RRAM is given in this review. We discuss the RRAM technology development based on published papers, including the mechanism of resistive switching in transition metal oxides, resistive switching materials, device structure, properties, and reliability such as endurance and retention of the device. We also provide possible solutions through innovations in device materials, structures, and understanding the device physics.

1. Introduction

Along with logic integrated circuits (ICs), the memory ICs form major portion of semiconductor device production. Non-volatile memory (NVM) devices are reportedly increasing interest for modern microprocessor-based devices which run a variety of functions within computer, cars, mobile phones, digital cameras, portable electronic gadgets and other so many wireless products. Current nonvolatile memory technology, flash memory, is based on charge storage and this technology is rapidly reaching its physical limits. Therefore, non-charge based nano-scale memories are being intensively studied for next generation nonvolatile memory applications, such as ferroelectric RAM (FeRAM), magnetic random access memory (MRAM), phase change random access memory (PCRAM), and resistive random access memory (RRAM). Among all of the emerging technologies, RRAM is one of the most promising candidates, due to its simple constituents, high density, low power, large endurance, fast write, read and erase speeds and excellent scalability as shown in Table 1. The device structure is simple capacitor-like metal-insulator-metal (MIM) structure as shown in Fig. 1a. On the application of a proper electrical signal, the resistance of the MIM structure can be switched from one state to other and the structure retains current resistance state until an appropriate electrical signal is applied to change it, representing its non-volatile nature. Recent work on the oxide based resistive switching memory can be traced back to the discovery of hysteresis I-V characteristics in perovskite oxides such as $Pr_{0.7}Ca_{0.3}MnO_3$ [1,2], $SrZrO_3$ [3], $SrTiO_3$ [4], etc. in the late 1990s and the early 2000s. Since Samsung demonstrated NiO memory array integrated with the 0.18 μm silicon CMOS technology in 2004 [5], research activities have been focused on binary oxides such as NiOx [6], TiOx [7], CuOx [8], ZrOx [9], ZnOx [10], HfOx [11], TaOx [12], AlOx [13], etc., because of the simplicity of the material and good compatibility with silicon CMOS fabrication process. There are different types of memory devices based on the selector used/not used in it like one transistor one resistor, one diode one resistor and complementary resistor switch, etc [14]. To be precise, the schematic and circuit diagram of the resistive memory device with a one-transistor-one-resistor (1T1R) structure is shown in Fig. 2. Here each resistor in the cross bar array works as a storage element and each transistor is used to select the particular storage node to be accessed and reduces the sneak path current problem.

Investigation of the resistance switching behavior in various types of materials and structures attracts broad interest about its memory application from 2004 to present. Among those resistive-switching materials, binary metal oxides are the most promising for practical applications because their compatibility with CMOS BEOL processing. Therefore, RRAM reveals high potential being a main NVM device to possibly replace the currently flash memory in the future. In this review, we focus on the binary metal–oxides RRAM and review their projected resistance switching mechanisms, materials belongings and device characteristics, and key routine metrics and their device scaling

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Table 1
Comparison between the properties of various recent non-volatile memory devices.

	DRAM	PCRAM	RRAM	MRAM	FRAM
Non-Volatile	No	Yes	Yes	Yes	Yes
Technology node	3x nm	4x nm	5x nm	130 nm	180 nm
Granularity	Small	Small	Small	Small	Large
Software	Easy	Easy	Easy	Easy	Easy
Write Operation Voltage (V)	2.5	3	3	1.8	0.6
Write Time	< 10 ns	50 ns	< 5 ns	< 100 ns	20 ns
Erase Time	< 10 ns	120 ns	< 5 ns	< 100 ns	20 ns
Read Time	< 10 ns	< 60 ns	< 10 ns	< 20 ns	20 ns
Endurance	> 3E16	1E15	1E12	> 3E16	1E14

trends. We have chosen interesting material high –k HfO_2 and review it in more detail. Besides, we discussed future outlook for RRAM and its emerging applications for reconfigurable logic and neuromorphic computing.

2. Operation principle of RRAM

Generally speaking, there are two types of resistive switching memory. One type is based on the conductive filaments (CF) of oxygen vacancies (Vo); the other type is based on the CF of metal atoms, which is also called conductive-bridge RAM (CBRAM). CBRAM relies on the fast-diffusive Ag or Cu ions migration into the oxide (or chalcogenide) to form a conductive bridge [15,16]. Fig. 1 shows the schematic diagrams of the transition metal oxide (TMO) resistive memory device with its switching I-V curves [17]. We first introduce some basic concepts and terminologies about metal–oxide RRAM. The operation principle of RRAM is based on the reversible resistive switching (RS) between at least two stable resistance states, the high resistance state (HRS) and low resistance state (LRS), which occurs in TMO in simple metal-insulator-metal (MIM) configurations as shown in Fig. 1. There exist two types of the switching memory associated with the electrical polarity requisite for the switching properties. In general, the operation which changes the resistance of the device from high resistance state (HRS) to low resistance state (LRS) is called SET process, while the opposite process is defined as RESET. The specific resistance state (HRS or LRS) can be retained after the electric stress is cancelled, which indicates the nonvolatile nature of RRAM. Usually for the fresh samples in their initial resistance state, a voltage larger than the set voltage is needed to trigger on the resistive switching behaviors for the subsequent cycles. This is called the forming process or electroforming. Based on the relationship of electrical polarity between SET and RESET processes, the resistive switching behaviors can be divided into two modes: unipolar and bipolar as shown in Fig. 1. In the unipolar RRAM, the switching direction does not depend on the polarity of the applied voltage but depends on the amplitude of the applied voltage as indicated in Fig. 1b. The device switches from HRS to LRS occurs under the same voltage polarity as the switching from LRS to HRS. If the unipolar switching can symmetrically occurs at both positive and negative voltages, it is referred to the nonpolar switching behavior. In the bipolar RRAM, switching direction depends on the polarity of applied voltage as shown in Fig. 1c. Thus, writing and erasing occur under the different polarity. For the each switching mode, in order to avoid the permanent dielectric breakdown in the set process, it is recommended to enforce to set compliance, which is usually provided by the memory cell transistor, series resistor or semiconductor parameter analyzer. To read the data from the memory cell, a small voltage is applied that does not affect the memory cell to detect whether the cell is in LRS or HRS.

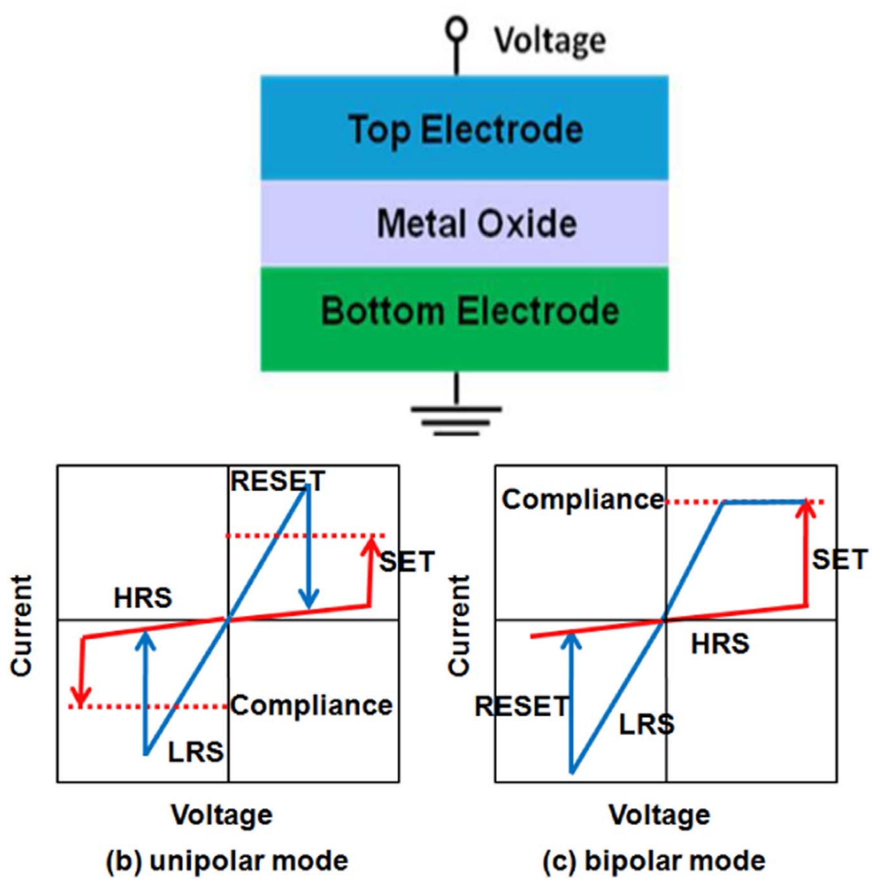

Fig. 1. (a) Schematic of metal-insulator-metal structure for oxide RRAM, and schematic of metal oxide memory's I-V curves, showing two modes of operation: (b) unipolar and (c) bipolar [17].