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An overview of materials issues in resistive random access memory

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Abstract

Resistive random access memory (RRAM) is a very promising next generation non-volatile RAM, with quite significant advantages over the widely used silicon-based Flash memories. For RRAM, material with switchable resistance, working as the storage medium, is the most important part for the performance of the memory. In this review, as a start, some general hints for the materials selection are proposed. Then most recent studies on this emerging memory from the perspective of materials science are summarized: various materials with resistance switch (RS) behavior and the underlying mechanisms are introduced; as a complementary to the previous review articles, here the increasingly important role of computational materials science in the research of RRAM is presented and highlighted. By incorporating the framework of high-throughput calculation and multi-scale simulations, design process of new RRAM could be accelerated and more cost-effective.

Keywords: Resistive random access memory (RRAM); Material selection; Mechanism; Computational material science

1. Introduction

With the rapid advances of electronic technology and devices, higher-speed and denser memories are required [1]. Non-volatile memory (NVM) is a type of memory mainly for relatively long-term storage, and no external power supply is necessary to maintain the stored information. Nowadays, the NVM market is dominated by the silicon-based Flash. However, there are a few drawbacks for Flash, including scaling issue, relatively slow operation speed, and high voltage for program/erase operations [2]. Even though the three-dimensional crossbar structure may solve the low-density issue of Flash temporarily [3], the market demands next-generation NVM that has overall advantages over Flash. In general, next-generation NVM should exhibit outstanding properties including high density, excellent scalability, low power consumption, and low cost. Resistive random access memory (RRAM) is one of the promising candidates that fulfill the requirements of next-generation NVM. Additionally, RRAM has simple metal/insulator/metal sandwich structure (Fig. 1(a)) [4] and good complementary metal-oxide-semiconductor (CMOS) compatibility, which are vital for its practical applications and mass productions. As implied by the name, RRAM is the memory using the switch of resistance under electric field to record information, where the high and low resistance states correspond to the logic 0 and 1, respectively. The key component of the memory is the insulating resistance switch (RS) layer, as shown in Fig. 1(a), while it should be pointed out that in some cases the top/bottom electrodes can also be involved in the RS process. In RRAM, the transition from high resistance state (HRS) to low resistance state (LRS) is normally called "set", while the reversed transition is named "reset". Two switching modes exist in RRAM, unipolar and bipolar; for unipolar mode, the switching is independent on the polarity of the applied voltage, while for

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bipolar switching, opposite polarity of voltage is required, as shown in Fig. 1(b).

The academic and industrial research topics on RRAM cover quite a wide range: materials problem, RS mechanism, manufacture, integration, and even other function beyond the data storage, as reviewed previously [1−15]. In this review article, we concentrate on the materials science issue including the material selection and the corresponding RS mechanisms. To avoid the overlapping with other previous reviews, we mainly focus on the very latest research results. Also the promising role of computational materials science in the design of new RRAM is highlighted here. Correspondingly, the structure of this paper is organized as follows: first, some general hints for materials selection for RRAM; second, the materials that have been investigated for RRAM are summarized; third, the RS mechanisms are shown; finally, the importance of computational materials science for the development of RRAM is discussed.

2. Some hints for materials selection for RRAM

As for a specific material, the high and low resistance state (logic 0 and 1) should correspond to its two structures that are different at least in the electronic/atomic or even nano-/micro-scale. The two structures, denoted as Struc.0 and Struc.1 in Fig. 2, may have different energy. In essence, the resistance switch is simply a transition between two structures (or two phases, in some cases) of the material in the presence of electric field, while the striking feature for RRAM application compared to normal phase transition is that the involved two structures should have distinct resistance contrast. The structural transition (resistance switch) process is illustrated in Fig. 2. As an appropriate materials for RRAM, the values of "D", "E_{set}", "E_{reset}", "E_{diff}" and "R" should be quite small, which can lead to the high endurance, low power consumption and high operation speed of the device. However, the too small "E_{set}" and "E_{reset}" may impair the retention of the memory. Here, we tried to present a clear connection between performance of the device and the property of the material, and make it easier for the material scientists to participate in the optimization of RRAM. However, it should be noticed that these parameters are actually correlated and not totally independent, for example, a large "E_{diff}" may mean that "E_{set}" is much smaller than "E_{reset}". Anyway, Fig. 2 should provide very general hints to find advanced materials for RRAM, and these hints may strengthen the potential contribution of computation materials science as will be discussed later.

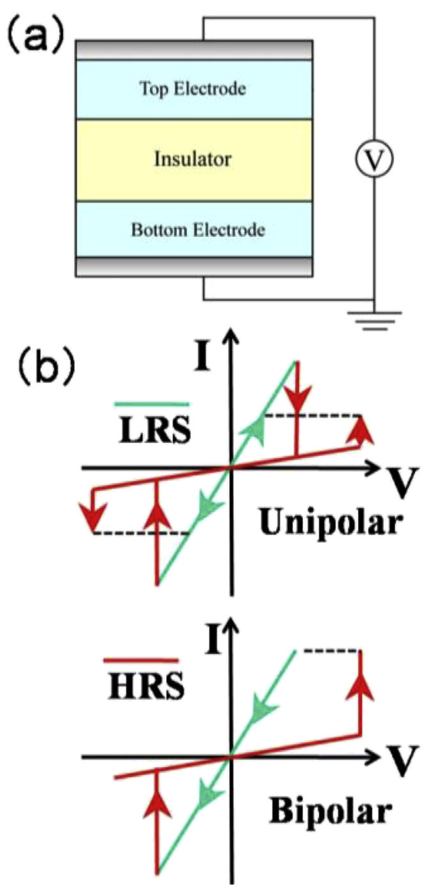

Fig. 1. (a) Sandwich structure of RRAM devices, top/bottom electrodes are normally metals, (b) Typical I−V curve of unipolar and bipolar switching modes.

3. Materials database

The first experimental observation of RS can be dated back to more than half a century ago. In 1962, Hickmott [16] found a large negative resistance in the current−voltage characteristics of five oxide films including SiO_x, Al_2O_3, Ta_2O_5, ZrO_2 and TiO_2. The urgency to find the replacement of Flash memory boosts the searching for RS phenomena in other materials, especially in the past few decades. A large variety of materials have been found exhibiting the RS behavior, which can be categorized into binary oxides, ternary and more complex

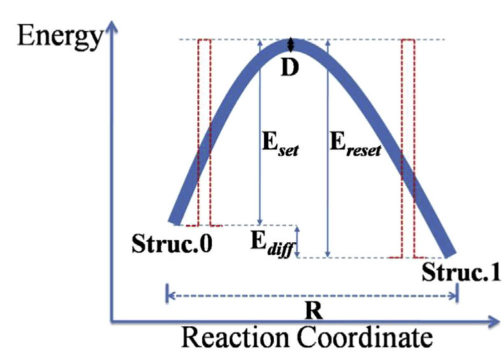

Fig. 2. Illustration of the energy profile of the transition between two structures of the material, as an analogy to the RS process in RRAM. The red column represents the energy needed can be supplied by the electric pulse. Parameter "D" means the reproducibility/stability of the transition path, corresponding to the endurance, uniformity and reliability of RRAM; "E_{set}" is the overall energy needed for Struc.0 to Struc.1 transition, corresponding to voltage and power needed for set process; "E_{reset}" is the overall energy needed for Struc.1 to Struc.0 transition, corresponding to the voltage and power needed for reset process; "E_{set}" and "E_{reset}" are also related to the retention of RRAM; "E_{diff}" is the energy difference of the two states, corresponding to the relative retention of the devices; "R" (reaction coordinate) is the displacements of any electrons/ions involved in the RS process, corresponding to the operation time.