

## Improving the electrical performance of resistive switching memory using doping technology

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In this paper, improvements of resistive random access memory (RRAM) using doping technology are summarized and analyzed. Based on a Cu/ZrO<sub>2</sub>/Pt device, three doping technologies with Ti ions, Cu, and Cu nanocrystal, respectively, are adopted in the experiments. Compared to an undoped device, improvements focus on four points: eliminating the electroforming process, reducing operation voltage, improving electrical uniformity, and increasing device yield. In addition, thermal stability of the high resistance state and better retention are also achieved by the doping technology. We demonstrate that doping technology is an effective way of improving the electrical performance of RRAM.

**non-volatile memory, resistive random access memory (RRAM), doping technology**

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How far floating gate based memory can extend and what the further direction of next generation memory is, are two research questions that have attracted extensive attention and concern. To solve the shortcomings of conventional memories, several new emerging memories, including magnetic random access memory (MRAM), ferroelectric random access memory (FRAM), phase-change random access memory (PRAM), and resistance random access memory (RRAM), have been studied as candidates for future memories [1]. Of these candidates, RRAM devices based on binary metal oxide (BMO) have received considerable research attention because of their advantages of simple device structure, high density, excellent scalability, fast switching speed, low energy consumption, and compatibility with CMOS technology [2].

In general, RRAM has a sandwich structure of metal-insulator-metal. The “metal” here denotes a material with

good electrical conductivity [3], where Cu, Ag, Pt, Ti, and TiN are the materials most frequently used as electrodes in this capacitor-like structure [4–8]. Several BMO materials such as ZrO<sub>2</sub> [9], HfO<sub>2</sub> [4,8], TiO<sub>x</sub> [10], ZnO<sub>2</sub> [5], NiO [11], CeO<sub>x</sub> [12], Ta<sub>2</sub>O<sub>5</sub> [13], CuO<sub>x</sub> [14], and WO<sub>x</sub> [15] have been reported as the insulator layer in RRAM. Under an appropriate electric stimulus, the resistance of the insulator layer can be switched between a high resistance state (HRS) and a low resistance state (LRS). The memory effect is realized by the different resistance states. Although the mechanisms responsible for the resistive switching behaviors in different materials are still being debated intensely, the critical role of defects and impurities in resistive switching has been recognized. Unfortunately, the intrinsic defects (i.e., dislocation, grain boundary, ions, or vacancy) in BMO films are inhomogeneously and nonuniformly distributed and difficult to control. RRAM devices with pure BMO films often exhibit unfavorable memory performance, i.e., low device yield, high operation voltage, low uniformity, and poor device stability,

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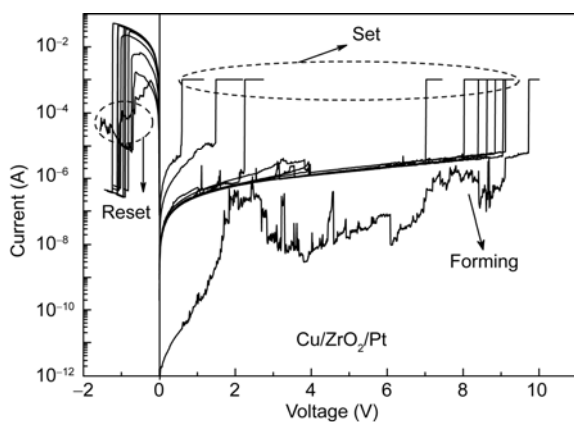
which hampers their application in industry [16].

Several research groups have adopted doping technology as an effective method for solving above problems. It has been demonstrated that the performance of BMO-based RRAM devices can be greatly improved by intentionally introducing homogenous impurities in the BMO films [16–24]. In this paper, we discuss the effect of doping technology on the resistive switching characteristics of RRAM devices. Undoped Cu/ZrO<sub>2</sub>/Pt devices are fabricated for comparison, while three types of doping technology including Ti, Cu, and Cu nanocrystal (NC) in the Cu/ZrO<sub>2</sub>/Pt are referred to in our discussion.

Ti impurities are doped in the ZrO<sub>2</sub> films using the ion implantation method, while the Cu and Cu NC impurities are introduced using a thermal diffusion method. The detailed fabrication processes of the Cu/ZrO<sub>2</sub>:Ti/Pt, Cu/ZrO<sub>2</sub>:Cu/Pt, and Cu/ZrO<sub>2</sub>:Cu NC/Pt devices have been described, respectively, in our previous papers [17,23,24]. The control samples (Cu/ZrO<sub>2</sub>/Pt) without doping impurities are simultaneously fabricated to investigate the impact of doping impurities on the resistive switching behavior. The electrical parameters for these devices are measured with the Keithley 4200 semiconductor characterization system and Agilent 81110A pulse pattern generator. For the electrical measurements, the bias polarity is defined with reference to the bottom Pt electrode.

## 1 Characteristics of undoped-BMO-based RRAM devices

Figure 1 shows 10 cycles of the current-voltage (*I-V*) curves of the Cu/ZrO<sub>2</sub>/Pt device under DC voltage sweep. As can be seen from this figure, the resistive switching characteristics of the undoped RRAM device exhibit two weaknesses. (i) An electroforming process with a high voltage (~10 V) is needed to trigger resistive switching behaviors. In this process, a 1 mA current compliance is used to prevent the



**Figure 1** Reproducibility of the resistive switching (10 cycles) of the Cu/ZrO<sub>2</sub>/Pt device under DC voltage sweep. Here, the cell size is 100 μm × 100 μm and the ZrO<sub>2</sub> thickness is 70 nm.

BMO films from hard breakdown. (ii) A wide distribution of the resistive switching parameter is shown in the undoped RRAM devices. The  $V_{\text{Set}}$  and  $V_{\text{Reset}}$  are, respectively, the threshold voltages from the HRS to the LRS, and vice versa. For the undoped Cu/ZrO<sub>2</sub>/Pt device, the distributions of  $V_{\text{Set}}$  and  $R_{\text{HRS}}$  have wide ranges. A high electroforming voltage and poor electrical uniformity are also observed in other undoped-BMO-based RRAM devices, such as TiN/HfO<sub>2</sub>/Pt, Pt/TiO<sub>2</sub>/Pt, and Pt/NiO/Pt [25–27].

Additionally, low device yield is also observed in the undoped-BMO-based RRAM devices. For example, only about 40% of the cells of the Cu/ZrO<sub>2</sub>/Pt devices show the repetitive resistive switching phenomenon. For real application, these weaknesses of undoped-BMO-based RRAM devices must be well controlled.

## 2 Improving resistive switching performance with doping technology

Before discussing the doping effect, we first address the conceivable resistive switching mechanism in BMO-based RRAM. Recent studies have shown that the resistive switching behavior in a BMO-based RRAM device is mainly dominated by the formation/rupture of the conductive filaments inside the BMO layer [18]. The conductive filament is formed by the percolation of defects, such as the migration of metal ions or oxygen vacancies [3]. These defects may come from decomposition of the function materials themselves or diffusion from the electrode materials. However, the generation of these defects in pure BMO films requires a higher voltage. The quality of the films degrades easily under high electrical stimulus, resulting in the poor resistive switching characteristics mentioned above. According to the analysis, if reasonable defects can be introduced into the proper positions in BMO films, high voltage may no longer be necessary and the resistive switching performance can be improved.

### 2.1 Eliminating the electroforming process and reducing operation voltage

The electroforming operation can induce enough defects (i.e., charge traps, movable ions, or vacancies) in BMO films because of the high electrical voltage. The process is similar to soft-breakdown in an oxide [28]. Under high electrical fields, the induced defects form a local conducting filament between the bottom and top electrodes, resulting in a change in the resistive switching from the HRS to the LRS. However, the high voltage not only degrades the materials reliability, but also complicates the RRAM circuit's design. Thus, the excessive voltage required is undesirable.

By doping proper impurities, the electroforming process can be eliminated and the operation voltage can also be reduced. The *I-V* curve of the Ti doped ZrO<sub>2</sub> device is shown

in Figure 2, where the required voltage of the first Set operation is equal to that of the following Set process. Furthermore, the maximum operation voltage of the Cu/ZrO<sub>2</sub>/Pt is reduced from 10 to 3 V by doping Ti impurities. It is worth to note that the Cu/ZrO<sub>2</sub>:Cu/Pt and Cu/ZrO<sub>2</sub>:Cu NC/Pt devices exhibit a similar phenomenon [17,23]. The doping induced forming-free phenomenon has also been observed in other BMO-based RRAMs by other researchers. For example, Gao et al. [28] reported that the average forming voltage of the TiN/HfO<sub>2</sub>/Pt device decreased from 7.82 to 2.71 V by doping Al in the HfO<sub>2</sub> films.

Figure 3(a) and (b) shows the typical *I-V* characteristics of the Cu/ZrO<sub>2</sub>:Cu/Pt and Cu/ZrO<sub>2</sub>:Cu NC/Pt devices, respectively. Both devices exhibit unique nonpolar resistive switching behavior (the Set and Reset operation can be achieved under negative and positive voltages). Different from the Cu/ZrO<sub>2</sub>:Cu/Pt device, the Cu/ZrO<sub>2</sub>:Cu NC/Pt device exhibits a lower positive Set voltage (the  $V_{\text{Set}}$  decreased from ~3 to ~1 V). The difference between the two devices can be attributed to the different doping processes. The Cu NC doping process not only supplies more metal ions, but also enhances the electrical field around the Cu NC located within the ZrO<sub>2</sub> matrix. The strengthening electrical field can accelerate the migration velocity of Cu ions and reduce the required voltage to form the conductive filaments [25].

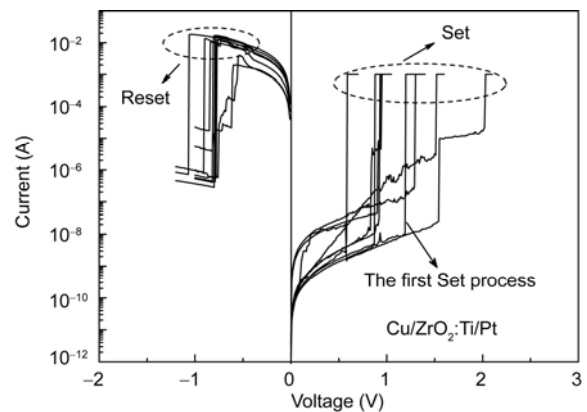
## 2.2 Improving electrical uniformity

In general, large variations in switching voltages and resistance states are shown in undoped-BMO-based RRAM devices, as can be seen in Figure 1. The poor uniformity not only reduces the stability of the device, but also enhances the complexity of the peripheral circuit for read/write operations. In general, the nonuniformity of the switching parameters is related to the random nature of the nucleation/growth of the conductive filament (CF) [3]. This makes it difficult to form the CF along the same path in repetitive

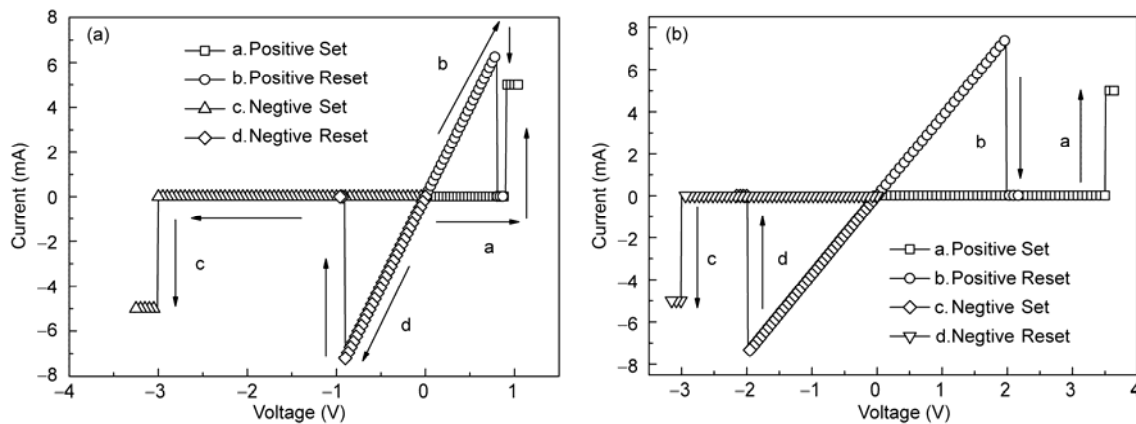
switching cycles.

Compared to the Cu/ZrO<sub>2</sub>/Pt device, the Ti doped device shows a more stable Set process, as shown in Figure 2. Further evidence verifying this conclusion is given by the statistical data. As shown in Figure 4, the average values of  $V_{\text{Set}}$  and  $V_{\text{Reset}}$  for the Cu/ZrO<sub>2</sub>:Ti/Pt device are 1.43 and -0.66 V, respectively, which are lower than the values for the Cu/ZrO<sub>2</sub>/Pt device (5.31 and -0.94 V, respectively). Furthermore, the standard deviation of  $V_{\text{Set}}$  is reduced from 3.45 to 0.78 V after doping Ti ions. This indicates that the dispersion of  $V_{\text{Set}}$  for the Cu/ZrO<sub>2</sub>:Ti/Pt device is obviously reduced when compared with the Cu/ZrO<sub>2</sub>/Pt device. The resistance states in 50 cycles of the Cu/ZrO<sub>2</sub>/Pt and Cu/ZrO<sub>2</sub>:Ti/Pt devices are shown in Figure 5. After doping Ti ions, the fluctuation in  $R_{\text{HRS}}$  is reduced from 10<sup>4</sup> to 10 times. This proves that the  $R_{\text{HRS}}$  of the Cu/ZrO<sub>2</sub>:Ti/Pt device is more stable than that of the Cu/ZrO<sub>2</sub>/Pt device. In addition, the Cu/ZrO<sub>2</sub>:Cu/Pt and Cu/ZrO<sub>2</sub>:Cu NC/Pt devices also show tight distribution of the resistive switching parameters [17,23].

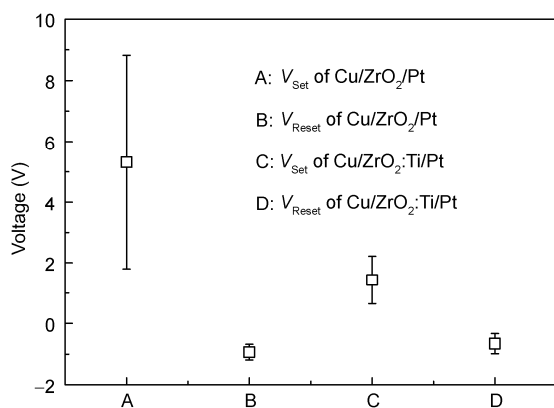
Previously, improvement in the electrical uniformity of



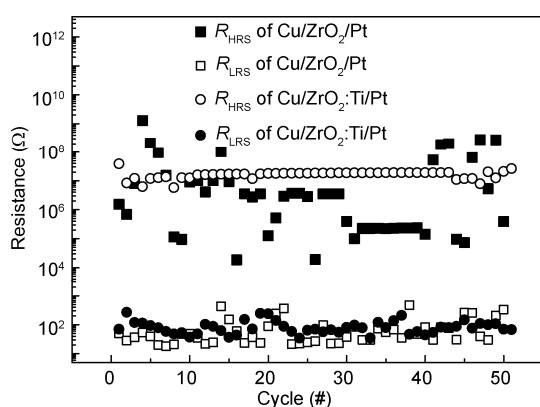
**Figure 2** Reproducibility of the resistive switching (10 cycles) of the Cu/ZrO<sub>2</sub>:Ti/Pt device under DC voltage sweep. The cell size is 100  $\mu\text{m} \times 100 \mu\text{m}$  and the ZrO<sub>2</sub>-thickness is 70 nm.



**Figure 3** (a) Typical asymmetric nonpolar *I-V* switching behavior of the Cu/ZrO<sub>2</sub>:Cu NC/Pt device, and (b) typical symmetric nonpolar *I-V* switching behavior of the Cu/ZrO<sub>2</sub>:Cu/Pt device. The cell size of both devices is 3  $\mu\text{m} \times 3 \mu\text{m}$  and the thickness of ZrO<sub>2</sub> is 40 nm.



**Figure 4** Variations in operating voltage in Cu/ZrO<sub>2</sub>/Pt and Cu/ZrO<sub>2</sub>:Ti/Pt devices.



**Figure 5** Distribution of  $R_{\text{HRS}}$  and  $R_{\text{LRS}}$  in the Cu/ZrO<sub>2</sub>/Pt and Cu/ZrO<sub>2</sub>:Ti/Pt devices.

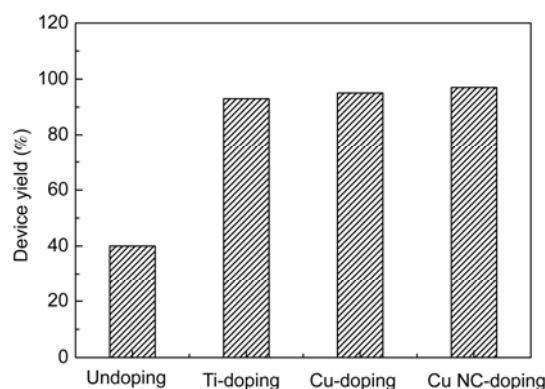
impurities doping in RRAM device has been demonstrated by a variety of studies [17–30]. However, why doping impurities improve the electrical uniformity of the RRAM device is still unclear. A general hypothesis is stated as follows: the conductive filaments are easily formed/ruptured near the impurities doped location. This reduces the randomness of the CF formation/rupture process and improves the uniformity of the resistive switching properties. In our recent work [18], we obtained high resolution transmission electron microscopy images of conductive filaments in the Ag/ZrO<sub>2</sub>/Cu NC/Pt device. These images show that the growth location and orientation of CFs can be well controlled by the Cu NC dopant. According to the electrical field simulation, the Cu NC plays a critical role in enhancing the local electrical field. During the Set process, more metal ions converge around the Cu NC location under a higher local voltage. So the CF grows easily at the location of the NC. Thus, CFs are easily formed, ruptured, and reformed along the same paths in repetitive switching cycles, resulting in a substantial improvement in the electrical uniformity. For other types of doping impurities, further research is needed to investigate the underlying physical mechanism.

### 2.3 Increasing device yield

For actual application, device yield (percentage of working cells) is a critical parameter in the memory array. Unfortunately, low device yields are frequently shown in undoped-BMO-based RRAM devices [16,24]. There are two possible reasons for this. One is the electroforming operation, which is needed to activate the resistive switching behavior in undoped devices. During the forming process, the local region of the BMO film may be broken down under high voltage. Another is the randomness of the intrinsic defects in the undoped BMO film. A large variation in the intrinsic defects leads to unstable resistive switching behavior. By using homogeneous and uniform doping, the defects in the BMO film can be well controlled and the device yield is also improved. As can be seen from Figure 6, the device yield of the Cu/ZrO<sub>2</sub>/Pt device is greatly improved by doping Ti, Cu, and Cu NC. After using doping technology, the device yield of RRAM devices increases to almost 100%. Similar results were also reported by Lee et al. [29] in the Al doped ZnO, Cu doped MoO<sub>x</sub> and Cu doped Al<sub>2</sub>O<sub>3</sub> devices.

### 2.4 Improving other memory performance

Other important memory characteristics of undoped RRAM devices may also be modulated by doping impurities. Recently, Jung et al. demonstrated that Li-doping NiO could improve the thermal stability of the HRS. The Li doped device showed a much better retention property and stable Set/Reset operation [31]. Recently, Wang et al. reported that the retention characteristics of both resistive states in the CuO<sub>x</sub>-based RRAM can be significantly improved by doping Si impurities. Based on a first principles calculation, they suggested that the activation energy of Cu vacancy migration in Cu<sub>x</sub>Si<sub>y</sub>O increased more than that in Cu<sub>x</sub>O, resulting in the good retention characteristics [32]. In our previous work, we demonstrated that the storage window (defined as the ratio of  $R_{\text{HRS}}/R_{\text{LRS}}$ ) of the ZrO<sub>2</sub> film can



**Figure 6** Device yield of the Cu/ZrO<sub>2</sub>/Pt, Cu/ZrO<sub>2</sub>:Ti/Pt, Cu/ZrO<sub>2</sub>:Cu/Pt, and Cu/ZrO<sub>2</sub>:Cu NC/Pt devices.

**Table 1** Resistive switching characteristics of the undoped and doped devices

Device structure	Yield (%)	Forming process	$V_{Set}$ (V)	$V_{Reset}$ (V)	$R_{HRS}/R_{LRS}$ ratio	Retention (s)	Switching polarity
Cu/ZrO <sub>2</sub> /Pt	<40	Yes	0.5–10	–0.5– –1.5	>10 <sup>4</sup>	–	Bipolar
Cu/ZrO <sub>2</sub> :Cu/Pt [9]	~100	No	2.1–3.6	0.8–1.5	~10 <sup>6</sup>	>10 <sup>4</sup>	Nonpolar
Cu/ZrO <sub>2</sub> :Au/Pt [33]	~100	No	2–5	0.5–1.2	>10 <sup>4</sup>	>10 <sup>6</sup>	Nonpolar
Cu/ZrO <sub>2</sub> :Ti/Pt [24]	~100	No	1–4	–0.5– –1.5	>10 <sup>4</sup>	>10 <sup>7</sup>	Bipolar
Au/ZrO <sub>2</sub> :Au/Pt [16]	~5	–	–	–	–	–	Bipolar
Au/ZrO <sub>2</sub> :Au NC /Pt	~75	–	–	–	51	1000	Bipolar
TiN/ZrO <sub>2</sub> /Pt [28] <sup>a)</sup>	–	Yes	–	–	100	–	Bipolar
TiN/ZrO <sub>2</sub> :Al/Pt [28] <sup>a)</sup>	–	No	0.5–1.5	–0.6– –0.8	100	–	Bipolar
TiN/HfO <sub>2</sub> /Pt [25] <sup>a)</sup>	–	–	0.7–2.7	–0.9– –1.5	~3	–	Bipolar
TiN/HfO <sub>2</sub> :Gd/Pt [25]	–	–	0.8–1.0	–0.6– –0.9	~30	10 <sup>4</sup>	Bipolar
Pt/TiO <sub>2</sub> /Pt [33] <sup>a)</sup>	–	–	0.25–1.75	–0.25– –0.5	5	1000	Bipolar
Pt/TiO <sub>2</sub> :Pt NC/Pt <sup>a)</sup>	–	–	0.5–1.0	–0.5– –0.75	2	10 <sup>4</sup>	Bipolar
Cu/NiO <sub>x</sub> /Pt [34] <sup>a)</sup>	–	Yes	–2.6– –8.6	–1– –1.8	1000	–	Unipolar
Cu/Cu:NiO <sub>x</sub> /Pt <sup>a)</sup>	–	No	–2.1– –3	–0.6– –1	>10	–	Unipolar
W/ZrO <sub>2</sub> /Pt [35] <sup>a)</sup>	25	–	–	–	–	–	Unipolar
W/ZrO <sub>2</sub> :Ag/Pt <sup>a)</sup>	85	Yes	–	–	10	–	Unipolar

a) Some data are taken from figures in references.

be greatly enhanced by implanting Zr ions [20].

### 3 Conclusion

The resistive switching characteristics of various devices using doping technology are summarized and shown in Table 1. Compared to an undoped device, the change induced by doping can be observed clearly. In summary, doping technology is an effective method for modulating and improving RRAM's performance. Generally, the doped BMO films exhibit many more preferred memory properties, including a free-electroforming process, low operation voltage, good electrical uniformity, and high device yield. To effectively improve the performance of the RRAM device by doping, more work needs to be done in understanding the physical mechanism and the inherent laws.

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