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Understanding the gradual reset in Pt/Al_2O_3/ Ni RRAM for synaptic applications

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Abstract

In this work, a study has been performed to understand the gradual reset in Al_2O_3 resistive random-access memory (RRAM). Concentration of vacancies created during the forming or set operation is found to play a major role in the reset mechanism. The reset was observed to be gradual when a significantly higher number of vacancies are created in the dielectric during the set event. The vacancy concentration inside the dielectric was increased using a multi-step forming method which resulted in a diffusion-dominated gradual filament dissolution during the reset in Al_2O_3 RRAM. The gradual dissolution of the filament allows one to control the conductance of the dielectric during the reset. RRAM devices with gradual reset show excellent endurance and retention for multi-bit storage. Finally, the conductance modulation characteristics realizing synaptic learning are also confirmed in the RRAM.

Keywords: RRAM, forming, set, reset, synapse, diffusion

(Some figures may appear in colour only in the online journal)

1. Introduction

Neuromorphic computing is expected to emulate brain functions in the near future enabling massive parallel computing and less complex architecture [1]. Current technology designed to emulate the brain function of animals like spiders, cats, and others requires an excessive number of processors, memory, and computation time [2]. These barriers can be overcome with bio-inspired computing [1–6]. Several non-volatile memory candidates such as phase change (random-access memory) RAM (PCRAM) [2], conductive bridge RAM (CBRAM) [3], resistive RAM (RRAM) [4–6] have been proposed as the synapse element, but RRAM is a promising candidate because of its CMOS compatibility and low energy switching properties [4]. RRAM has been reported to have excellent retention and endurance, and can be arranged in the form of a cross-bar array, thereby enabling high-density memory architecture [1].

The RRAM memory operation is achieved with a filament formation in the dielectric with a forming or set operation (low resistance state or LRS), followed by the rupture of the filament for a reset operation (high resistance state or HRS) [1]. During forming or set operation, oxygen ions are moved out of the dielectric leading to the formation of a filament comprising of oxygen vacancies in the dielectric, oxygen ions are stored into the electrode [9]. The dielectric is prevented from going into hard breakdown by setting a compliance current (CC) limit [9]. During reset, oxygen ions from the electrode comes back to the dielectric and fills up those vacancies thereby rupturing the filament. However, all of those vacancies are not replenished during the reset event, and hence the set event starts at higher current level than the forming event [7].

In the bipolar RRAM reset process, two main mechanisms have been proposed as (i) drift of oxygen ions by electric field and (ii) diffusion of oxygen ions caused by concentration gradient of oxygen ions stored in the electrode [10]. It should be noted that the temperature of the dielectric caused by Joule heating also plays a major role in the reset process [9, 10]. The reset in the dielectric has found to be either instantaneous [11], or gradual where the current drops gradually during the reset [5]. One prime requirement of RRAM to be applicable for synaptic applications is the feasibility of gradual reset characteristics [1]. A recent report on reset in HfO_2 RRAM was observed to be dependent on the concentration of oxygen ions stored in the electrode [13]. The reset behavior in the RRAM having less oxygen storage in the electrode was observed to be abrupt whereas the reset behavior with the electrode having an excess of oxygen storage was observed to be gradual [13]. Similarly, a gradual reset was observed in bipolar RRAM [14] and unipolar RRAM [15] where the filament comprised a higher number of vacancies, which in turn stores a higher number of oxygen ions in the electrode. Thus, gradual reset is possibly caused by oxygen ion concentration gradient diffusion-dominating the reset process which ruptures the filament gradually.

Even though some binary oxide RRAMs have been reported showing a gradual reset [4, 5], in many cases these oxides typically show an abrupt reset, thereby eliminating the possibility of realizing synaptic behavior [1, 7, 8]. In this work, we studied the resistive switching properties of Al_2O_3 RRAM to understand the gradual reset. It was observed that a gradual set process comprising a significantly higher number of vacancies in the dielectric while reaching CC leads to a gradual reset behavior. A multi-step forming technique was then employed to confirm the gradual filament dissolution, thereby realizing a gradual reset in Al_2O_3 RRAM with excellent multi-state retention and endurance behavior. This gradual reset behavior was further extended to realize synaptic learning in the RRAM.

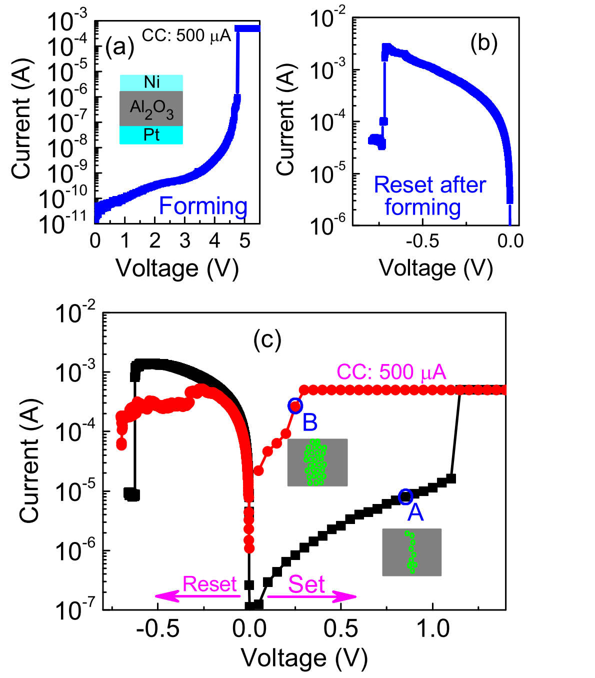

Figure 1. (a) Forming; (b) reset after forming and (c) two kinds of set-reset behavior observed in the RRAM.

2. Experimental

In order to obtain bipolar resistive switching behavior, Al_2O_3 RRAMs were fabricated on Si/SiO2 wafer with Ni and Pt as metal electrodes. 50 nm Ni followed by a 20 nm Pt metal bottom electrode was deposited on a Si/SiO_2 wafer using a UHV-RF sputtering system. A 6.4 nm Al_2O_3 dielectric resistive switching layer was deposited using atomic layer deposition (ALD) technique at 200 °C substrate temperature. 50 nm Ni followed by 70 nm W capping layer serving as the top electrode was deposited using a UHV-RF sputtering system, and patterned with conventional photolithography. All of the devices under measurement have an area of 100 μm × 100 μm, CC was kept at 500 μA during forming and set operation of the RRAM, and memory operations were performed by applying bias to the Pt electrode [20].

3. Results and discussion

Figure 1 shows the forming, reset after forming and set-reset behavior of Pt/Al_2O_3/Ni RRAM. Forming was observed to have an abrupt rise in current before reaching the CC, shown in figure 1(a). The reset after the forming was observed to be abrupt, shown in figure 1(b). Previously, it has been reported that successive set-reset cycles increases the number of vacancies in the dielectric thereby reducing the I_{on}/I_{off} ratio [16, 17]. This is primarily because vacancies created during the set are not completely recovered during reset, leaving behind additional vacancies in the dielectric. A similar trend was observed during set-reset operations in Al_2O_3 RRAMs, two different set-reset behaviors were observed, shown in figure 1(c). These two behaviors can be categorized as case-(A): a set operation where abrupt rise in current leads to reach CC, the corresponding reset was also observed to be abrupt. Whereas in case-(B): a set where gradual rise in current leads to reach CC, and the corresponding reset was also gradual. Forming was observed to be similar to case-(A), and the reset after forming was also similar to case-(A) reset.

It is known that a rise in current during forming or set event leads to generation of vacancies inside the dielectric thereby creating a filament [12]. Considering point A and point B in the set curves before the CC is reached in case of an abrupt set (or case-(A)) and gradual set (or case-(B)) respectively, point A has a lower current at higher voltage signifying fewer vacancies present in the dielectric. The current overshoot (as observed in case-(A)) required a high current for the reset leading to a big gap in the filament that in turn resulted in an abrupt reset with a large resistance window. Whereas in the case of point B, a gradual set, a higher number of vacancies are present in the dielectric resulting in higher current at lower voltage. This indicates that the gradual set leads to the generation of a significantly higher number of oxygen vacancies and hence a higher number of oxygen ions are stored in the Pt electrode in the case of a gradual set as compared to an abrupt set. A higher number of vacancies inside the dielectric is known to create a higher temperature gradient in the dielectric near the filament [12, 21]. Thus oxygen ions can recombine with the vacancies at lower reset currents because of concentration gradient dominated diffusion of oxygen ions in the case of a gradual reset [10]. Hence, the reset in case-(B) was possibly because of a diffusion-dominated filament dissolution where vacancies are ruptured gradually. A recent study also demonstrated a similar result where a higher concentration of oxygen ions stored in the electrode after the set process resulted in a gradual reset [13]. In other words, the higher concentration

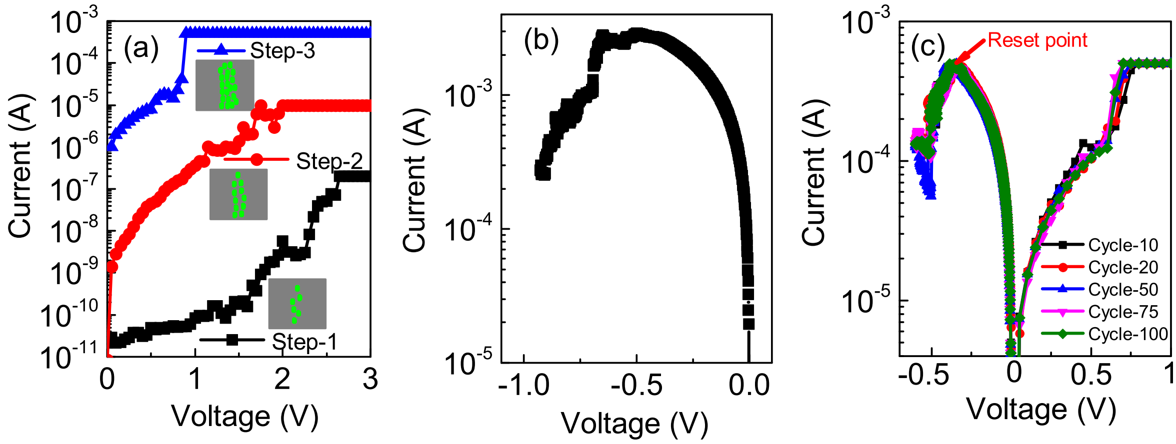

Figure 2. (a) Multi-step forming method used to generate a higher number of oxygen vacancies before reaching CC, (b) corresponding reset after multi-step forming, and (c) dc endurance of the device after multi-step forming (CC was kept at 500 μA during set operations).

of oxygen ions stored in the electrode after the gradual set process caused thermal diffusion of oxygen ions during the reset operation causing a gradual dissolution of the filament. Also note that a gradual reset was observed to occur at a lower current compared to the abrupt reset case.

Better control of the filament diameter (resistance) can be achieved with multi-step forming [14] and multi-step set techniques [18, 19]. To reconfirm the gradual filament dissolution hypothesis, a virgin device was analysed and the forming process was broken into three parts in order to generate a higher number of vacancies in the dielectric before the device reaches the final CC. During forming, CC was kept at 200 nA, 10 μA and 500 μA, respectively, for successive steps, shown in figure 2(a). The forming operation was observed to start at higher current levels with successive forming steps signifying an increase in the concentration of vacancies in the dielectric with each step. Possible vacancy profiles after a successive sweep are also illustrated in figure 2(a). The forming current at step-3 was observed to be similar to set at case-(B) of figure 1(c), which indicates that a higher number of vacancies are present in the dielectric during step-3 of the multi-step forming compared to the abrupt forming of figure 1(a). The corresponding reset after the multi-step forming is shown in figure 2(b), and the reset was also observed to be gradual which ascertains the hypothesis of the concentration gradient dominant diffusion reset mechanism. Successive set-reset endurance cycles after obtaining a gradual reset are shown in figure 2(c). Unlike the abrupt reset case where the I_{on}/I_{off} ratio varies randomly with successive endurance cycles, the gradual reset after vacancy diffusion showed almost no degradation even after 100 dc cycles. The set-reset uniformity was also observed to be greatly improved. This kind of controllable gradual reset is advantageous over an abrupt reset, and are of particular interest to analog memory applications where RRAMs can resemble a multi-bit operation with excellent retention and endurance [19].

Next, the gradual reset characteristics were further used to study the conductance modulation of the Al_2O_3 RRAM for realizing a synaptic element. A set operation was performed initially in the Al_2O_3 RRAM keeping the CC at 500 μA, followed by the reset operation performed with either dc sweep or ac pulse. A read was performed at 0.1 V. Change in the conductance of the dielectric during reset with respect to the reset stop voltage during dc reset and pulse time during ac reset are shown in figure 3(a). Both dc and ac reset were observed to result in dielectric conductance modulation, and the change in conductance of the dielectric was observed as higher in the case of the dc reset using a reset stop voltage compared to the ac reset. The retention characteristics of the multiple memory states obtained by choosing a different dc reset stop voltage is shown in figure 3(b). Excellent retention was observed in the Al_2O_3 RRAM for four different memory states achieved with the set and dc gradual reset operation. Interestingly, Al_2O_3 RRAM showed a higher conductance change compared to HfO_2 RRAM which is an advantage in realising the synaptic memory [22].

Finally, the synaptic operation was carried out in the RRAM where the conductance of the dielectric was changed gradually using ac pulses. The primary requirement of a synaptic circuit used in neuromorphic system is to detect very small changes in the resistance of the memory, and it has been reported that a smart synaptic system should detect a 1% change in resistance per synaptic activity [4]. The controllable resistance or conductance change in RRAM can be achieved by gradually varying the CC during the set and gradually increasing the pulse voltage during the reset. Figure 4 shows the conductance change in Al_2O_3 RRAM with 60 steps of set and 70 steps of reset. During the set of the device, the CC was varied from 100 μA to 500 μA keeping the pulse voltage fixed at +1.5 V, 5 ms, whereas during the reset, the pulse voltage was varied gradually from −0.4 V to −0.58 V; a read was performed at 0.1 V. A controllable conduction change was observed in the RRAM which confirms the applicability of using Al_2O_3 RRAM as a synaptic memory after obtaining the gradual reset.

4. Conclusions

A higher number of vacancies created during the forming or set event results in a diffusion-dominated gradual filament

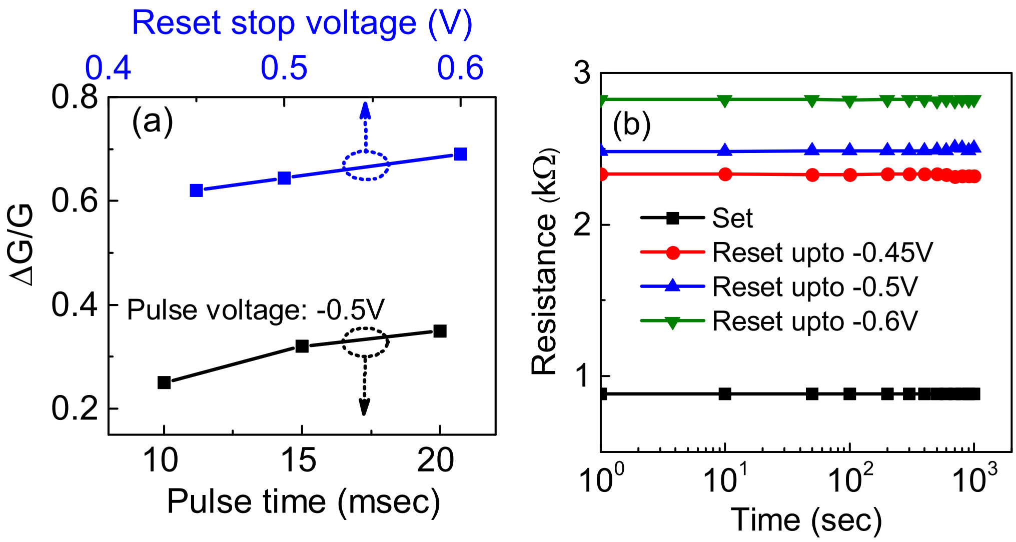

Figure 3. (a) Conductance change in Al_2O_3 RRAM during reset with respect to the reset stop voltage and reset pulse time; (b) retention characteristics of the multi-state of the Al_2O_3 RRAM.

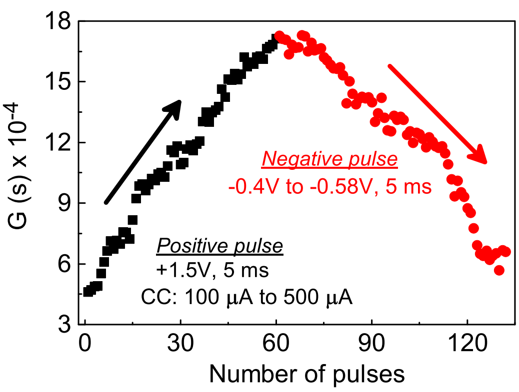

Figure 4. Synaptic learning in Al_2O_3 RRAM with 60 steps of set and 70 steps of reset, read was performed at 0.1 V.

dissolution process during the reset. In order to generate a higher number of vacancies in the dielectric, the forming step was broken into three parts which resulted in a gradual reset in Al_2O_3 RRAMs. Such a gradual reset resulted in multi-bit analog memory characteristics in the Al_2O_3 RRAM. The devices also showed no degradation in the gradual reset characteristics after 100 dc endurance cycles. The property of controllable conductance change was observed in Al_2O_3 RRAM using dc and ac reset techniques. which were further used to demonstrate synaptic learning behavior in the Al_2O_3 RRAM. Hence, by generating a higher number of vacancies inside the dielectric during the forming or set process, Al_2O_3 RRAM was demonstrated to have gradual reset characteristics suitable for multi-bit analog memory and neuromorphic computation applications.

Acknowledgments

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