Self-rectifying resistive switching characteristics in Cu/IGZO/Si structure

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Abstract: In this paper, we investigate the resistive switching and self-rectifying characteristics of proposed RRAM. We fabricate RRAMs using Cu as the top electrode (TE) and heavily doped *p*-type silicon as the bottom electrode (BE), and amorphous indium gallium zinc oxide (α-IGZO) film as the switching layer. The bilayer film that consists of oxygen-deficient and oxygen-rich α-IGZO, and the monolayer film of oxygen deficient α-IGZO are fabricated by controlling oxygen concentration. Proposed RRAM cells show the typical hysteresis *I*–*V* curve including set and reset operation under the DC sweep mode. Furthermore, self-rectifying phenomenon is observed.

1. Introduction

Resistive random-access memory (RRAM) is expected as one of the next generation non-volatile memory devices, because of its several advantages such as simple structure, excellent scalability, and fast, low power operation [1-3]. Various materials have been studied as an RRAM switching layer. The examples showing the resistive switching phenomenon are praseodymium calcium manganese oxide (PCMO), TiO_2, and indium gallium zinc oxide (IGZO) [4-7]. It has been reported that the switching mechanism of oxide-based RRAMs considerably depends on their oxygen concentration, because the field enhanced migration of oxygen dominantly controls the local resistivity making the layer be more metallic or insulating [8], [9].

In this work, we focus on IGZO as a switching layer, and fabricate RRAM cells with metal-insulator-silicon (MIS) structure using amorphous IGZO switching layer. Process condition split for different oxygen concentration to confirm the role of oxygen vacancies in IGZO resistive switching. In the fabrication process, oxygen vacancies act as donors in IGZO, thus the mobility and conductivity of oxygen deficient layer are greater than oxygen rich layer [10].

We fabricated two kinds of RRAM cells, with oxygen deficient monolayer IGZO film and with bilayer film including both oxygen deficient and oxygen rich IGZO layers, deposited in order. DC sweep measurement of those cells yields typical hysteresis *I*–*V* curves of resistive switching. Also we observed the self-rectifying phenomenon in the cells. The current rectifying ratio between the forward and reverse currents in positive voltage range and negative voltage range respectively, is more than 10 in both monolayer and bilayer cells. Those self-rectifying phenomenon is a remarkable results in resistive switching device to solve the sneak current problem of RRAM crossbar array. To prevent unwanted leakage current in RRAM array structure, an additional rectifying device is needed, resulting in worse scalability. Self-rectifying RRAM does not require an additional device, so that it can have enhanced scalability and can be used in a massive crossbar array [11].

2. Device Fabrication

Proposed RRAM cell is composed of Cu/IGZO/Si stack. The cells are fabricated by sequencially processed implantation and layer depositions on intrinsic *p*-type bare wafer (Fig. 1). We use Cu as the top electrode (TE), and heavily doped *p*-type silicon as the bottom electrode (BE). BE is doped with 20 keV, 5×10^{15} cm^{-2} BF_2^+. Amorphous IGZO film was sputtered on BE. Sputtering condition was controlled by argon and oxygen gas flow rate. Oxygen deficient IGZO monolayer film with thickness of 80 nm was deposited with the flow rate of 20 sccm argon, and 0 sccm oxygen. For the bilayer film, oxygen deficient and oxygen rich IGZO layers were deposited 40 nm each, in order. Cu top electrode was evaporated on the switching layer, with the thickness of 100 nm (Fig. 2). The oxygen rich layer was sputtered with oxygen gas flow rate of 3 sccm. The total gas flow rate of argon and oxygen was maintained as 20 sccm, thus, the conditions of argon 20 sccm and oxygen 0 sccm for the monolayer film, argon 17 sccm and oxygen 3 sccm for the bilayer film were applied. A shadow mask containing circular patterns with the diameter of 100 μm and the pitch of 500 μm (Fig. 3) was used for TE patterning.

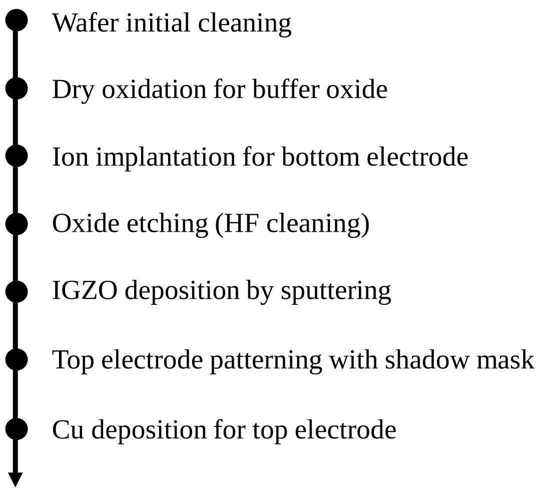

Figure 1. Fabrication process of proposed RRAM cells.

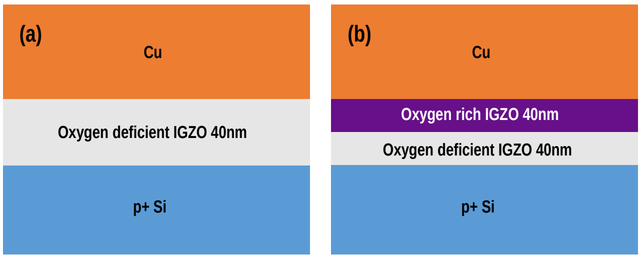

Figure 2. Schematic diagrams of fabricated RRAM cells using (a) oxygen deficient IGZO monolayer film and (b) oxygen deficient and oxygen rich IGZO bilayer film.

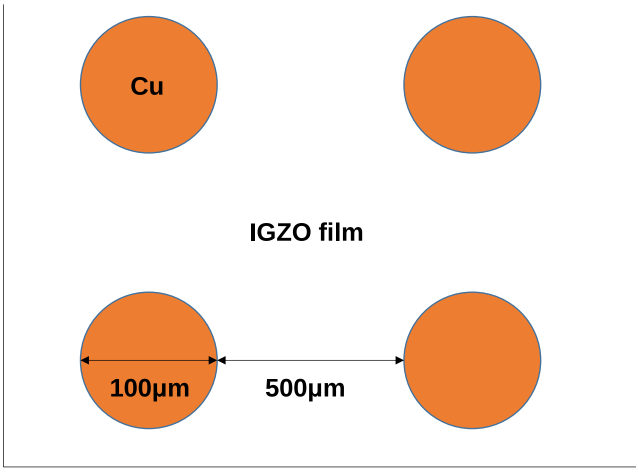

Figure 3. Top view of patterned cells.

3. Results and Discussions

DC sweep measurement was performed with the fabricated RRAM cells. Ground voltage was applied to the BE, and DC sweeping voltage is applied to the TE with the range of covering the set and reset voltage. The set voltage is defined as the point where the transition from high-resistance state (HRS) to low-resistance state (LRS) occurs, and the reset voltage is where the transition from LRS to HRS occurs. A cell with oxygen deficient IGZO monolayer film shows the reproducible results of set operation in negative voltage region, and reset in positive voltage region (Fig. 3). A cell with bilayer film also shows the reproducible set operation in positive voltage region, and reset in negative voltage region (Fig. 4).

Self-rectification occurs in both cells, but the difference of the current level is more remarkable in the bilayer film than in the monolayer film. Interestingly, rectifying direction of monolayer cells and bilayer cells are different. In monolayer cells, forward current flows from BE to TE when TE is negatively biased. In contrast, forward current of bilayer cells flows from TE to BE when TE is positively biased. It implies that the dominant junction which occurs rectifying phenomenon in monolayer cells and bilayer cells are different.

When a negative voltage is applied to the TE of the cells with oxygen deficient IGZO monolayer film, oxygen ions migrate toward the BE, due to electric field. In general, amorphous oxide semiconductor becomes more metallic when oxygen ions are emitted from the lattice by the electric field, generating more oxygen vacancies [12]. Set operation of monolayer cells occur when a negative voltage is applied to the TE. As a result of applied bias voltage, oxygen rich region is temporally formed near the BE because of electric field-induced oxygen migration. Consequently, oxygen deficient layer near the TE becomes more metallic so the resistance of this region is decreased inducing the transition from HRS to LRS for the whole cell. On the other hand, when a positive voltage is applied to the TE of the LRS cell, the reverse migration of oxygen ions toward the TE occurs. This operation makes the cell turn back to HRS.

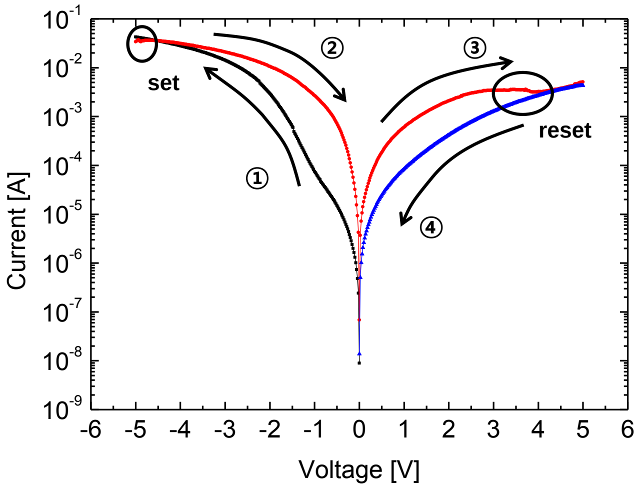

Figure 3. Typical *I*–*V* curve of a monolayer cell.

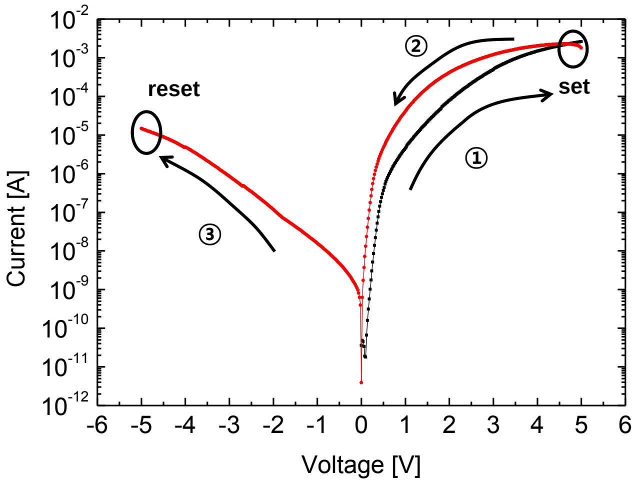

Figure 4. Typical *I*–*V* curve of a bilayer cell.

Like a diode, rectifying phenomenon was also observed. LRS current ratio at the read voltage level (±1 V) is about 10, and HRS current ratio at the same voltage is about 1. Thus, we can find out that rectifying occurs in LRS. It turns out that amorphous IGZO is an n-type semiconductor [13], so it forms the weak rectifying n-p junction with the p-type silicon of BE (Fig. 5). So nevertheless the conductance of the cell is increased due to the transition from HRS to LRS, the interface of n-type IGZO and p-type BE silicon forms rectifying junction and suppresses LRS current when the positive voltage is applied to the TE.

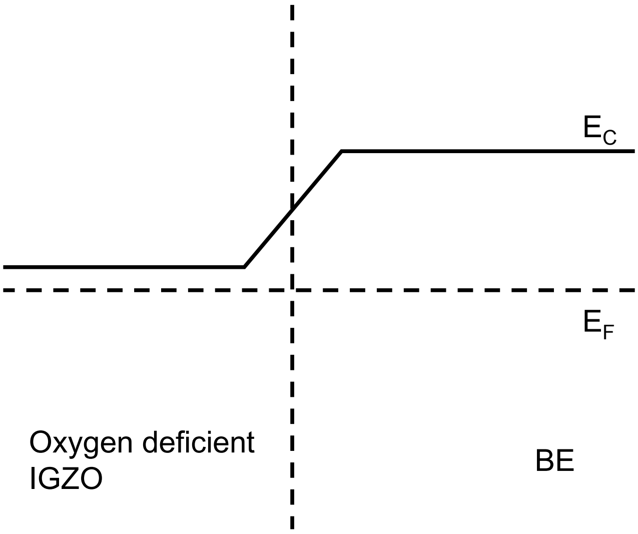

Figure 5. Conduction band diagram at the interface of oxygen deficient IGZO layer and BE.

Oxygen deficient and oxygen rich IGZO bilayer film also shows the hysteresis curve of resistive switching operation and the rectifying phenomenon. When a positive voltage is applied to the TE, the electric field pulls oxygen ions toward the TE. Thus, the conduction front at the interface of oxygen rich layer and oxygen deficient layer approaches to the TE and metallic region becomes wider, so the conductance of the whole cell is increased. By this process, gradual transition from HRS to LRS takes place during the positive voltage sweep. When a negative voltage is applied to the TE, electric field pushes oxygen ions away from the TE. Consequently, field-induced migration removes oxygen vacancies of the oxygen deficient layer, thus the metallic region of the cell becomes narrow and the conductance of the cell is decreased. In this case, gradual transition from LRS to HRS occurs. But the transition is hidden in the *I–V* curve, because of the strong rectifying properties in the negative voltage region. The current ratio between HRS and LRS is maintained as about 10, during 36 cycles of set-reset operations with the voltage range of ±5 V (Fig. 6).

In the case of bilayer cells, rectifying direction is opposite to that of monolayer film. Moreover, rectifying ratio is dramatically increased by more than 10 times compared to that of monolayer cells. Change of rectifying direction and the stronger rectifying phenomenon is probably due to the fact that the rectifying effect by n-p junction at the BE interface becomes no more dominant in the case of bilayer film, and, instead insulating oxygen rich layer near the TE mainly carries the rectifying phenomenon. Oxygen rich layer has more insulating characteristic than oxygen deficient layer, that is, oxygen rich layer is similar to the intrinsic semiconductor due to annihilation of n-type dopant-like oxygen vacancies by the abundant oxygen gas supply. Consequently, Schottky barrier is formed at the interface of TE and oxygen rich IGZO layer in bilayer cells, whereas the interface of TE and oxygen deficient IGZO layer is more like ohmic contact in monolayer cells (Fig. 7). The Schottky barrier induces the rectification in bilayer cells dominantly, compared to n-p junction based rectification in monolayer cells.

Rectifying direction is also different between the bilayer cells and monolayer cells due to the difference of dominant rectifying junctions. In monolayer cells, n-p junction at the interface of oxygen deficient IGZO layer and BE dominantly leads rectification so the forward current flows from the *p*-type BE to the IGZO layer when TE is negatively biased. In bilayer cells, Shottky junction at the interface of TE and oxygen rich IGZO layer is dominant, so the forward current flows from the TE to the IGZO layer when TE is positively biased..

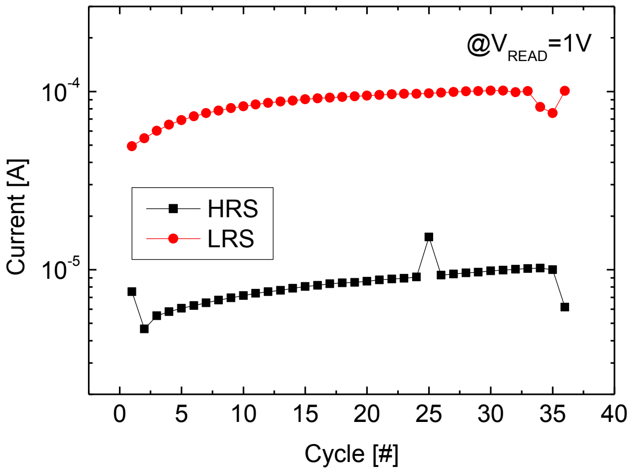

Figure 6. Endurance of a bilayer cell at V_{READ} of 1V.

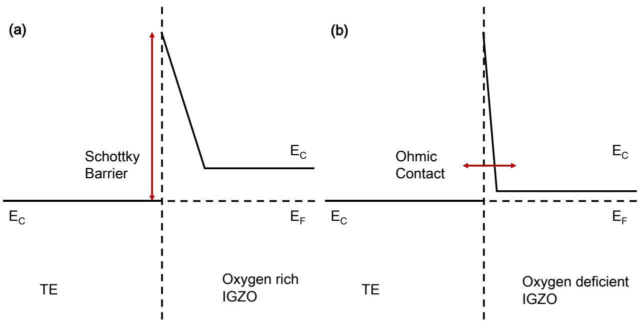

Figure 7. Conduction band diagrams at the interface of (a) TE and oxygen rich IGZO layer and (b) TE and oxygen deficient IGZO layer.

Current rectifying ratios of the bilayer cell is measured at the different read voltages during resistive switching cycles. At 5 read voltages that have the same amplitude and different polarity, the ratios between the forward current (I_F) and the reverse current (I_R) are given as distributions in 36 set-reset operation cycles (Fig. 8). In general, the current rectifying ratios are greater than those of monolayer cells. It implies that the barrier height of Schottky barrier in bilayer cells is higher than the n-p junction barrier in monolayer cells, so the junction resistance of bilayer cells at reverse bias condition is higher than that of monolayer cells.

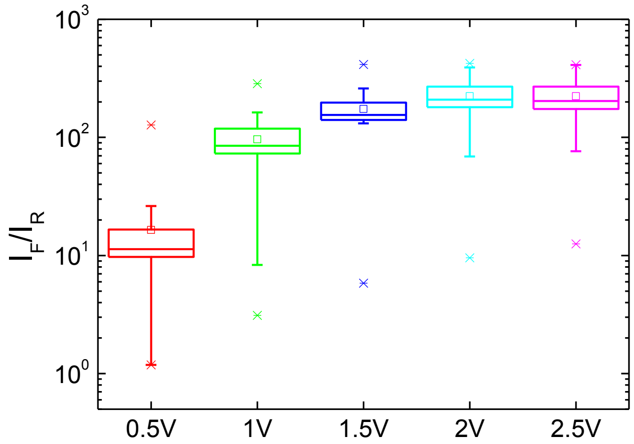

Figure 8. Distributions of rectifying ratio as a function of read voltage.

4. Conclusion

We have proposed the RRAM structure using IGZO switching layer and the silicon BE. Resistive memory using IGZO film shows the resistive switching with self-rectifying characteristics, which is associated with the formation of p-n junction at the BE interface or formation of Schottky barrier between the TE interface and insulating layer by annihilation of oxygen vacancies in the case of monolayer and bilayer, respectively. All the results show that proposed RRAM cells have self-rectifying characteristic that is applicable for massive RRAM crossbar array, and the rectifying ratio of the RRAM with IGZO can be controlled by the oxygen gas flow during the fabrication of oxygen rich layer.

Acknowledgements

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