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High performance and electrical characterization of write-once-read-many-times memory devices base on IGZO thin film with O_2 plasma treatment

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Abstract

Write-once-read-many (WORM) devices were demonstrated based on indium gallium zinc oxide (IGZO) thin film with O_2 plasma treatment. The treated Al/IGZO/Al device exhibited a high ON/OFF resistance ratio, long retention time of more than 10 years as predicted and fast writing speed in the order of μs.

1. Introduction

Write-once-read-many-times (WORM) memory devices have attracted much interest due to the rapid, permanent archival storage application of video images and noneditable database.[1] WORM memory devices based on organic materials, organic/inorganic materials, and/or containing nanocrystals have been studied in recent years. Many researchers have discussed that the resistivity switching phenomenon in the metal oxides (e.g. TiO_2, NiO_x, $SrTiO_3$ and so on) due to the oxygen vacancy migration and electric field-induced joule heating. Amorphous indium gallium zinc oxide (a-IGZO) is one of attractive oxide semiconductors due to its high transparency, good uniformity and low temperature process.[2] It provides the opportunity to fabricate the devices on the flexible substrate. The switching behaviors in IGZO thin film based on selected electrodes have also been reported.[3] However, no report is available on WORM memory devices employing a-IGZO as active material. In this report, an Al/a-IGZO/Al WORM memory device has been fabricated. The electrical characteristics and carrier transport mechanism of device with O_2 plasma treatment was investigated.

2. Experimental Details

The WORM devices were fabricated as follow. A 200 nm thick Al layer was deposited on a p-type, (100)-oriented Si wafer as bottom electrode by electron-beam evaporation. Subsequently, 200 nm IGZO film was deposited onto the Al thin film by RF magnetron sputtering of an IGZO target with mole ratio = 1:1:1 in a mixed Ar/O_2 ambient at a flow rate ratio of 30/1. During the sputtering, the RF power was 100W and the sputtering pressure was 3 mtorr. The deposited IGZO thin films were then subjected to an O_2 plasma treatment. Finally, the top Al electrode was deposited by e-beam evaporation and patterned into circuit pads using shadow mask (Fig. 1). For the comparison purpose, the WORM devices without O_2 plasma treatment were also fabricated. The electrical characteristics of the devices were carried out with a Keithley 4200 semiconductor characterization system at room temperature.

3. Results and Discussion

A. I-V Characteristics

Figure 2 shows the current-voltage (I-V) curves for the Al/IGZO/Al devices which were measured by sweeping the voltage from 0 to 9 V and then back to 0 V. For the O_2 plasma treated devices, the device is initially in high-resistance state (OFF state) at the order of 10^{-7}. The current is drastically increased at a critical voltage of about 7.8V as shown in Fig. 2(a). The device current then remains at 10^{-3} A which is in the high-conductivity state (ON state). This state transition from OFF state to ON state is a writing process for the memory device and the ON state will not return to the OFF state in the subsequent positive or negative voltage sweeps. This irreversible transition from OFF to ON state is very promising for the WORM device application. On the other hand, it is observed that the I-V characteristics of the Al/IGZO/Al devices without O_2 plasma treatment on IGZO thin film do not show the large current transition. The maximum ON/OFF ratio of the as-deposited devices is on the order of 10 compare to the treated devices which is approximately 10^4. Obviously, the O_2 plasma plays an important role of enhancement in the current transition.

B. WORM Memory effect characteristics

Figure 3(a) shows the current measured at 3 V as function of the writing voltage for the fixed writing time of 1 μs. The current is 200 nA at initial high resistance state when writing voltage is less than 5 V. The current drastically increase to 0.1 mA after writing at 7V, and further increase 1 mA with the writing voltage at 20V. Fig. 3(b) shows the current as a function of the writing time for the fixed writing voltage of 15 V. As shown in Fig. 3(b), the current increases to the order of 10^{-4} and 10^{-3} after writing to the state for the writing time of 0.1 μs and 1 μs, respectively. This result indicates that the treated device can switch from OFF state to ON state at even a short writing pulse of 1 μs. Fig. 4 shows the data-retention characteristics of the WORM devices for the ON state and the OFF state currents as the function of time at room temperature. The OFF state current measurement is firstly carried out on the device with 10^5 cycles of 3V pulses. Each pulse is set up at 0.5 s duration with 0.5 s interval. The current is measured at specific times. Subsequently, a 15 V with 1 μs pulse was then applied to switch the device from OFF state to ON state. The ON state current measurement is carried out at a same voltage with 10^5 times pulses. It is observed that there is no significant degradation in the ON and OFF state currents after 10^5 cycles reading. This means that the WORM device has a good retention performance. It is predicted that the data retention can be retained up to 10 years with ON/OFF ratio of more than 10^4 after 10^8 times reading. The degradation of the current is attributed to the charge release from the oxygen vacancies which is caused by reading operation.

C. Carrier transport mechanism

In order to understand the carrier transport mechanism of the O_2 plasma treated device, the I-V characteristics of the ON and OFF states were studied as shown in Fig. 5. For the OFF state, the I-V curve could be well fitted with slope of 1.06 by using Ohmic process at low voltage. The current conduction is dominated by the thermally generated electrons, resulting in an Ohmic behavior. With the increasing positive voltage, the I-V curve for the device with O_2 plasma immersion could be described by Schottky emission model as shown in the inset of Fig. 5a). When V > 1V, the Schottky emission becomes the dominant current conduction process.[4] It is clear that the current conduction at high field transfer from trap-fill process to schottky emission process upon the O_2 plasma immersion. For the On state as shown in Fig. 5b), the I-V characteristics for treated device show a straight line from 0 to 9 V with slop of 1.07, the current is a perfect Ohmic conduction current. It is believed that the conductive filament will be formed due to the oxygen migration under high voltage bias. After the conductive filament formed, the device will switch from OFF state to ON state. This transition is the transfer from electron injection limited current to Ohmic conduction current. The device in the ON state will not return to OFF turn as the positive or negative bias will not break the conductive filament.

4. Summary

We have shown a WORM memory device based on a-IGZO thin film by O_2 plasma treatment. The ON/OFF ratio for the device with O_2 plasma treatment is much larger than the device without treatment. The treated device exhibited a good performance and indicated that it is promising to utilize a-IGZO for the WORM memory devices.

References [1] Nature ,vol. 426, no. 6963, pp. 166–169, Nov. 2003; [2] Adv. Mater.11(2010) 044305; [3] C. H. Kim., 97 (6), 062109 (2010); [4] Z Liu, ECS Solid State Letters 1 (1), Q4-Q7 (2012)

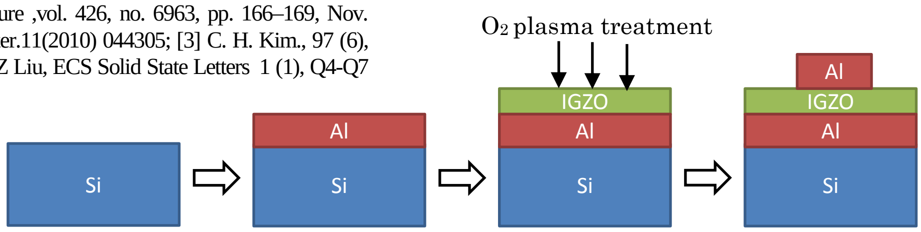

Fig. 1. Schematic illustrations of the WORM device process. An 200nm Al and 50nm IGZO film are grown via e-beam and subsequently subjected to O_2 plasma anneal, followed by 200nm Al top electrode via e-beam.

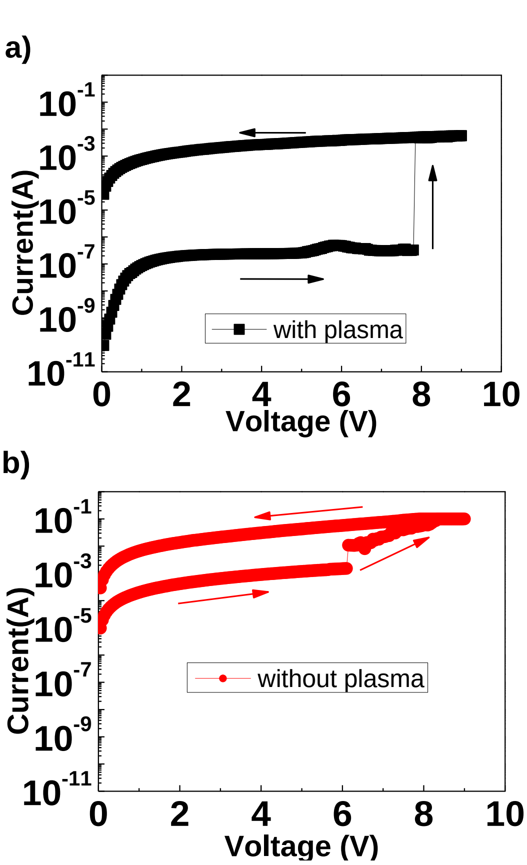

Fig. 2 Typical I-V characteristics of Al/IGZO/Al devices with and without O_2 plasma immersion by sweeping the voltage from 0 V to 9 V and then back to 0 V on a semi-logarithmic scale.

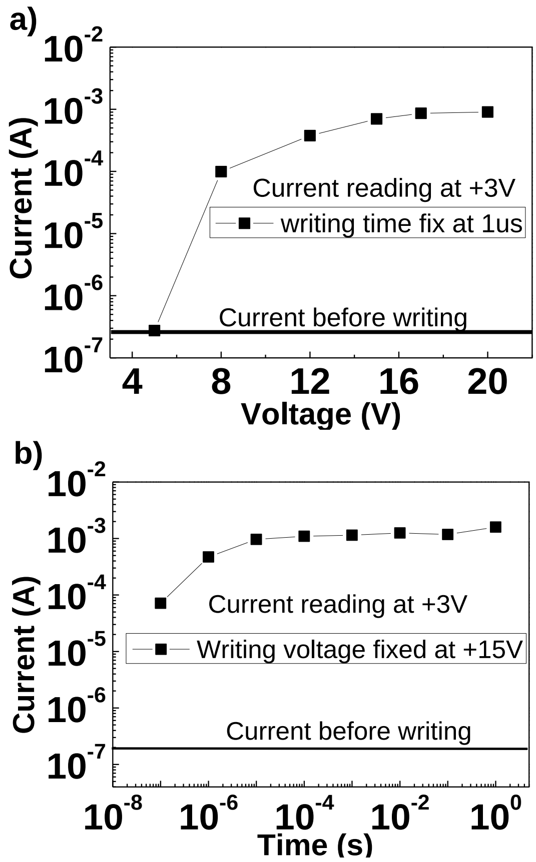

Fig. 3 Current measured at + 3 V as a function of either a) the writing voltage for the fixed writing time of 1 μs or b) the writing time for the fixed writing voltage of + 15 V.

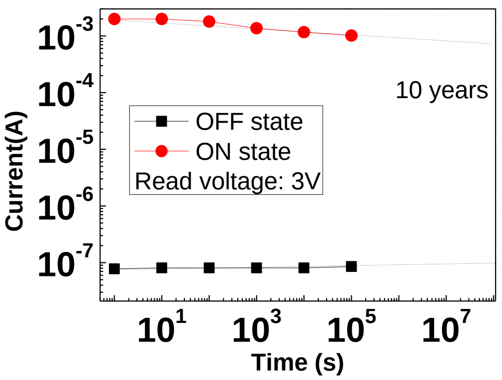

Fig. 4 Retention characteristic of the OFF- and ON-state of fabricated device read at + 3V

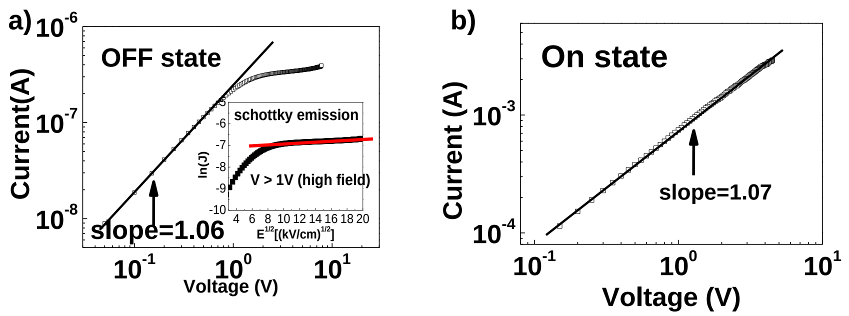

Fig. 5 a) Experimental and fitted I-V curves of the Al/IGZO/Al WORM devices in the OFF state. The inset shows that schottky emission model is dominant at the high field. b) Experimental and fitted I-V curves of the Al/IGZO/Al WORM devices in the ON state.