High performance and electrical characterization of write-once-read-many-times memory devices base on IGZO thin film with O₂ 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 O₂ 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. TiO₂, NiO, SrTiO₃, 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 memory device has been fabricated. The electrical characteristics and carrier transport mechanism of device with O₂ 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/O₂ 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 O₂ plasma treatment. Subsequently, 200 nm IGZO was deposited by RF magnetron sputtering. Finally, the device was completed by depositing Al layer on a p-type, (100)-oriented Si wafer as top electrode. 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 O₂ plasma treated devices, the device is initially in high-resistance state (OFF state) at the order of 10⁵. 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 10⁸ 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 application. The current conduct at high field transfer from trap-fill process to Schottky emission process upon the O₂ 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 slope of 1.07, the current is a perfect Ohmic conduction current. It is predicted 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 10⁵ times reading. The degradation of the current is attributed to the charge release from the oxygen vacancies which is caused by reading operation.

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 10⁴ and 10⁵ 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 10⁵ 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 same voltage with 10⁵ times pulses. It is observed that there is no significant degradation in the ON and OFF state currents after 10⁵ cycles reading. This means that the WORM device is noneditable database. 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.

C. Carrier transport mechanism
In order to understand the carrier transport mechanism of the O₂ 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 O₂ 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.8 It is clear that the current conduction at high field transfer from trap-fill process to Schottky emission process upon the O₂ 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 slope 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, O₂ plasma treatment. The ON/OFF ratio for the device with O₂ 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.
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 O₂ 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 O₂ 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 +3 V.

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.