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Effects of Oxygen Injection Rates on a-IGZO Thin-film Transistors with Oxygen Plasma Treatment

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***Abstract*—In this study, investigate the influence of oxygen plasma treatment on the oxide channel layer of amorphous indium gallium zinc oxide (a-IGZO) thin-film transistors based on the amount of oxygen gas injected. The a-IGZO channel layer thin-film transistors (TFTs) were fabricated with plasma treatment of zero, three, six, or nine standard cubic centimeters per minute (sccm) of oxygen gas injection into the a-IGZO channel layer using gun-type plasma cells from a molecular beam epitaxy system after the post-annealing process. In this experiment, oxygen plasma treatment on the a-IGZO channel layer improved the electrical and surface-area performance. Of all the treatment conditions, the a-IGZO channel layer TFT treated with plasma from an injection of 6 sccm of oxygen gas showed excellent transfer characteristics. They include saturation mobility of 14.4 cm^2/Vs, a threshold voltage of 4.5 V, an on/off current ratio of 1.1×10^8, and an inverse subthreshold slope of 0.7 V/dec. Surface morphology analyses confirmed that increases in the oxygen gas injection rate decreased. A dynamic inverter test was conducted by configuring the logic circuit for the a-IGZO channel layer TFT, which verified the possibility for future application of the backplane device in active-driven displays.**

***Index Terms*—IGZO thin-film, transistor, MIM structure, oxygen plasma**

I. INTRODUCTION

With the recent growth in information technology, next-generation semiconductors in the steadily growing semiconductor market require high performance and reduced power consumption. For displays (one of the key components in electronic devices), the market is increasingly demanding higher resolution and larger sizes. Accordingly, recent attention has been given to oxide thin-film transistor (TFT) with high charge mobility and excellent electro-optical uniformity. Oxide TFTs are advantageous in creating screens because of their low temperature processing, high charge mobility, and high reliability, compared to conventional amorphous silicon (a-Si)-based TFTs or low-temperature polycrystalline silicon TFTs [1-5].

To overcome the limitations of existing semiconductor materials, oxide semiconductors having various composition ratios of zinc oxide (ZnO), indium gallium oxide, (S)-4-nitrostyrene oxide, nitrosyl iodide, amorphous indium gallium zinc oxide (a-IGZO), and amorphous indium zinc oxide have been studied for the channel layer in transistors. Notably, a-IGZO has high charge mobility, maintains uniformity across large areas, and has wide band gap energy. Furthermore, a-IGZO is widely used as a material for transparent displays because it is easily deposited at low temperatures through physical vapor deposition and sputtering deposition, and

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additionally has high light transmittance [6-11].

To date, many studies have been conducted on electrical properties and transistor performance, specifically examining various process conditions, such as insulating layer thickness, channel layer thickness, annealing temperature, and surface treatment of the channel layer [5, 12-17]. Recently, studies have been conducted to improve the electrical performance of oxide TFTs through plasma treatment [18-21]. Recent studies have shown that tetrafluoromethane (CF_4) plasma treatment improves performance by reducing contact resistance between the semiconductor channel layer and the electrode, ultimately changing surface morphology [8, 22-26].

In the case of IGZO, studies such as increasing the mobility of transistors through oxygen plasma treatment and controlling internal oxygen vacancy have been conducted [27-30].

Therefore, this study analyzes the effect of surface treatment on the performance of TFTs according to the amount of oxygen injection by applying an oxygen plasma surface treatment with differing amounts of oxygen injection into the a-IGZO channel layer after the post annealing process. A device with a metal-insulator-metal (MIM) structure of a silicon dioxide (SiO_2) insulating layer and an a-IGZO oxide semiconductor between the Si gate electrode and the aluminum (Al) source/drain electrode was fabricated. To observe the change in electrical and surface area characteristics of the a-IGZO channel-layer oxide semiconductor transistor based on oxygen plasma treatment with various amounts of oxygen injection, a semiconductor parameter analyzer, and an atomic force microscope (AFM) were used to identify the surface morphology of the transistor. In addition, the effects of oxygen gas injection on current persistence and stability of a-IGZO channel layer TFTs fabricated with oxygen plasma surface treatment were analyzed. Lastly, a basic logic circuit was constructed, and a dynamic inverter test was conducted to evaluate the applicability of the fabricated device as an active driving backplane display.

II. EXPERIMENT

Fig. 1 shows the structure of the a-IGZO channel layer TFT with the MIM structure. Heavily doped n-type Si

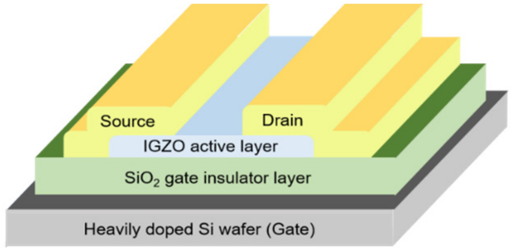

Fig. 1. Schematic representation of the bottom gated a-IGZO TFTs. In the device, Si is used as a gate, SiO_2 is used as a gate-insulator, a-IGZO is used as an active layer (a channel layer of semiconductor), and Al is used as source and drain top electrodes.

wafers were used as substrates and electrodes for gate contacts. A thermal oxidation process applied a 100 nm thick SiO_2 insulating film on the substrate. To remove the organic and inorganic impurities from the surface, a sulfuric acid (H_2SO_4)-hydrogen peroxide (H_2O_2) mixture for cleaning (piranha etch, a.k.a. SPM) was applied for 20 min at a temperature of 60 °C with the H_2SO_4 and H_2O_2 in a 3:1 ratio. The sample was soaked in deionized water, acetone, and an isopropyl alcohol solution, and subsequently dried in a vacuum oven for one hour after 20 min of ultra-sonication.

Afterwards, sputtering was applied using an RF magnetron sputtering system to form an IGZO channel layer on the SiO_2 insulating layer. A 1:1:1 ratio (In_2O_3:Ga_2O_3:ZnO) IGZO having a diameter of three inches was used as the target, and the distance between the target and the substrate was set to 8 cm. To remove impurities in the chamber, the initial vacuum setting in the chamber was 3×10^{-6} torr or less, using a rotary pump and a turbo molecular pump, and 30 standard cubic centimeters per minute (sccm) of argon gas was injected to maintain a vacuum in the chamber at 1.5 × 10-2 torr. The substrate was rotated at 7 rpm for uniform deposition of the thin film, and plasma was generated by applying 150 W of RF power from the RF power generator to deposit a 50 nm a-IGZO channel layer for 6 min 40 s.

After depositing the a-IGZO channel layer through the sputtering process, a post annealing process was performed to planarize the surface by reducing both the crystallization of the a-IGZO channel-layer thin film and any defects present in the thin film. The post annealing process was performed for one hour at a temperature of 350 °C under atmospheric conditions. Then, oxygen plasma surface treatment was applied using a gun-type plasma cell to analyze the surface area and electrical properties of the a-IGZO thin film from differing amounts of oxygen injection. Treatment of the a-IGZO channel layer was accomplished by applying 120 W of RF power from the RF generator for three min. Gun-type plasma cells can provide a locally uniform treatment on the target sample. As the gas collected in the crucible is ionized by the RF power applied through the coil wound around the crucible, it is released toward the crucible nozzle, and changes into a radical state to generate dense plasma. After the surface was treated with oxygen plasma, Al source/drain electrodes with a channel length of 200 µm and width of 2,000 µm were deposited using a DC magnetron sputtering system. To generate vacuum plasma in the chamber, direct current at 150 W was applied for 10 min to deposit a 100 nm Al source/drain electrode.

This study fabricated an a-IGZO channel layer TFT with no oxygen plasma surface treatment after its post annealing as a control, and we further fabricated a-IGZO channel layer TFTs with oxygen plasma surface treatment by injecting oxygen at 3 sccm, 6 sccm, or 9 sccm after the post annealing. Electrical performance and stability of the TFTs were evaluated using a semiconductor parameter analyzer (Keithley 2636, Keithley Instruments LLC) in a dark room at room temperature. To better understand how varying amounts of oxygen plasma surface treatment on the surface of a-IGZO channel layers influenced the surface microstructure of a-IGZO channel layers, AFM (ICON, Bruker Corporation) was used. The current persistence and stability of the fabricated device was analyzed through the retention current stability gate bias stress (GBS) tests using a semiconductor parameter analyzer (Keithley 4200, Keithley Instruments). Finally, an inverter circuit was configured to analyze the switching characteristics of the device to confirm its application to backplane display devices.

III. Results and Discussion

In this study, varying amounts of oxygen injection were used to improve the electrical and surface performance of an a-IGZO channel layer TFT. This was investigated by applying plasma surface treatment to the a-IGZO thin films with differing amounts of oxygen injected at 3 sccm, 6 sccm, or 9 sccm after post annealing in the process of manufacturing a-IGZO channel layer TFTs.

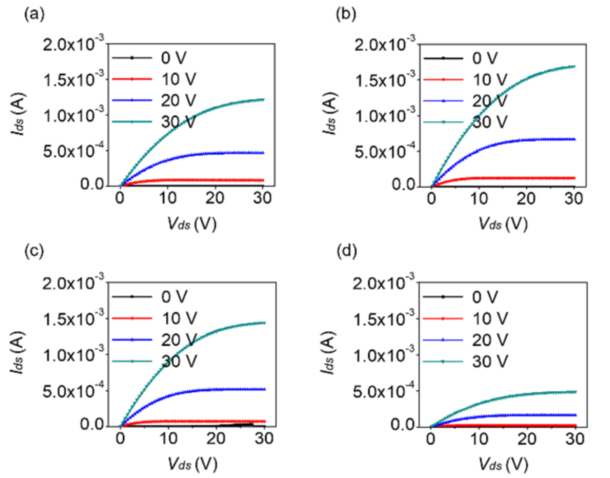

Fig. 2. Output characteristics of I_{ds}-V_{ds} curves at four different V_{gs} levels in TFTs with a-IGZO channel layers treatedwith oxygen plasma with gun-type plasma cell based on the amount of oxygen gas injected (a) as-deposited, (b) at 3 sccm, (c) at 6 sccm, (d) at 9 sccm.

Fig. 2 shows the output characteristic curves of the as-deposited a-IGZO TFT and the a-IGZO TFTs injected with 3 sccm, 6 sccm, and 9 sccm of oxygen for plasma surface treatment. I_{ds} is measured by sweeping 0.5 V increments starting from V_{ds} of 0 V up to 30 V. The gate bias voltage was applied in 10 V increments from 0 V to 30 V. In Fig. 2(b) and (c), which are the output characteristic curves of the a-IGZO TFTs injected with 3 sccm and 6 sccm of oxygen, the output curves are saturated at higher currents. This is due to the decrease in the oxygen vacancy in the a-IGZO channel layer and the decrease in the defects causing trapping, resulting in increased charge mobility and improved leakage current despite the decrease in the free electron concentration.

However, in Fig. 2(d), which is the output characteristic curve of the a-IGZO TFT injected with 9 sccm of oxygen, the output curve is saturated at significantly lower currents, compared to Fig. 2(a) to (c), and there is no difference, even if the gate bias voltage is applied differently. This is due to the considerable reduction of free electron concentration caused by excessive injection of oxygen, leading to a removed oxygen vacancy that is more than necessary in the a-IGZO channel layer, and an increase in surface roughness. Oxygen vacancy in the thin film generally

Table 1. Summary of electrical properties of a-IGZO channel layers treated with oxygen plasma based on the amount of oxygen gas injected, including μ_{sat}, I_{on}/I_{off}, V_{th}, and S/S

Oxygen gas injected (sccm)	μ_{sat} (cm^2/Vs)	I_{on}/I_{off}	V_{th} (V)	S/S (V/dec)	N_{it} (cm^{-2})
as-deposited	10.6	1.3×10^7	2.8	0.9	4.5×10^{12}
3	14.3	1.2×10^9	2.4	0.5	2.2×10^{12}
6	14.4	1.1×10^8	4.5	0.7	3.3×10^{12}
9	9.9	3.6×10^8	8.8	0.6	2.8×10^{12}

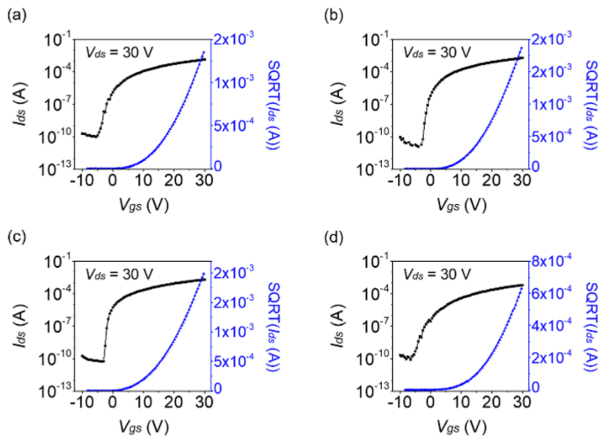

Fig. 3. Transfer characteristics of I_{ds}-V_{gs} curves and square root I_{ds}-V_{gs} with V_{ds} = 30 V in TFTs with a-IGZO channel layers treated with oxygen plasma with gun-type plasma cell based on the amount of oxygen gas injected (a) as-deposited, (b) at 3 sccm, (c) at 6 sccm, (d) at 9 sccm.

acts as a donor of the carrier, and further serves as a trap site to disturb carrier flow. Oxygen vacancy causes trap charges or leakage currents, which greatly affect the reliability of transistors. However, a decrease in oxygen vacancy can lead to reduced charge mobility and increased resistance due to a decrease in carrier density. Therefore, it is important to maintain an appropriate amount of oxygen vacancy for TFT performance [31-38].

Fig. 3 shows the transfer characteristic curves of the as-deposited a-IGZO TFT and the a-IGZO TFTs injected with 3 sccm, 6 sccm, or 9 sccm of oxygen for plasma surface treatment. The graph measures I_{ds} by sweeping 0.5 V increments from 0 V up to 30 V, and shows I_{ds} and square root of I_{ds} values when V_{ds} is fixed at 30 V.

The electrical characteristics of the transistors were extracted based on the transfer characteristic curves, and the results are summarized in Table 1. The a-IGZO channel layer TFTs with oxygen plasma surface treatment demonstrated an increase in charge mobility and current on-off ratios, and furthermore, showed that subthreshold swing (S/S) values improved. In Fig. 3(b) and (c), which are the transfer characteristic curves of the a-IGZO TFTs injected with 3 sccm and 6 sccm of oxygen,

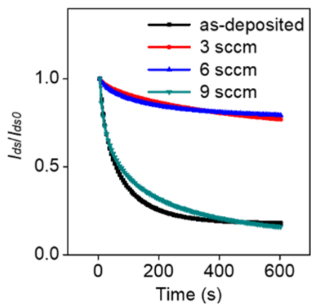

Fig. 4. Retention characteristic curves of TFTs with a-IGZO channel layers treated with oxygen plasma with gun-type plasma cell based on the amount of oxygen gas injected at 0 sccm, 3 sccm, 6 sccm, and 9 sccm when V_{ds} = 30 V, and V_{gs} = 30 V.

the drain off-current is lower than the transfer characteristic curve of the as-deposited a-IGZO TFT in Fig. 3(a). The charge mobility increased by more than 3.7 cm^2/Vs, and the current flashing ratio increased between tenfold and a hundredfold. The subthreshold swing of the transmission curve is more linear, and the on-current voltage shifted positively to near 0 V.

Meanwhile, the improved electrical performance of 6 and 9 sccm sample is related to stable S/S value, the relationship between the S/S and interface trap density (N_{it}) is given in equation.

$$N_{it} = \frac{C_i}{q}\left[\frac{S/S \cdot \log(e)}{k\frac{T}{q}} - 1\right] \quad (1)$$

where q is the electronic charge, k the Boltzmann constant, and T the absolute temperature. The calculated N_{it} values of a-IGZO TFTs from S/S are 4.5×10^{12}, 2.2×10^{12}, 3.3×10^{12} and 2.8×10^{12} cm^{-2}, respectively. (as shown in Table 1) These results demonstrate that the plasma irradiation with suitable oxygen could reduce the N_{it}, which is helpful to reduce the electron capture behavior at trap sites by the channel surface, thereby the electrical performance including mobility is improved.

For the a-IGZO TFT injected with 3 sccm of oxygen gas, the threshold voltage (V_{th}) was significantly lower relative to the control, and the subthreshold swing improved by about half compared to the TFT without plasma treatment. For the a-IGZO TFT injected with 9 sccm of oxygen gas, the overall electrical characteristics of the transistor degraded as shown in the output characteristic results of Fig. 2. The current flashing ratio and the *S/S* value improved, but the charge mobility was reduced, the V_{th} was greatly increased, and the on-current voltage shifted negatively. The charge mobility seemed to decrease due to the decrease in oxygen vacancy, which is likely due to excessive injection of oxygen during the treatment.

Fig. 4 shows the results of the bias test from applying constant voltage to the gate to evaluate the current continuity, stability, and reliability of the as-deposited a-IGZO TFT and the injected a-IGZO TFTs. When V_{gs} and V_{ds} were applied at 30 V each, the retention current stability was measured for about 10 min by dividing the value of I_{ds} by the initial measurement value, I_{ds0}. For the a-IGZO TFT with no oxygen plasma surface treatment, the measured current value decreased sharply over time from the initial value, and after about 10 min, I_{ds} dropped to about 17 % of I_{ds0}. On the other hand, when the a-IGZO TFTs were injected with 3 sccm and 6 sccm of oxygen, the current was maintained at about 80 % of I_{ds0} over time. It seems that oxygen plasma surface treatment removes impurities and defects on the a-IGZO channel layer surface and reduces oxygen vacancy and hydrocarbons to alleviate the reactivity to moisture and oxygen in the atmosphere.

Fig. 5 shows the results of the GBS test to evaluate the applicability and reliability of fabricated a-IGZO channel layer TFTs for display devices. A negative bias voltage stress (NBS) test was conducted to evaluate the turn-off state of the a-IGZO channel layer TFTs injected with oxygen plasma surface treatment. The NBS test measured the transfer characteristic curves when −20 V was applied to V_{gs} for 100 s, 200 s, and 300 s. Then, V_{gs} was swept from −20 V to 20 V at 0.5 V increments. Analyzing the change in I_{ds} over time when bias voltage was applied to V_{gs}, we found the transfer characteristic curve shifted negatively. This result is exaggerated as the time for applying negative bias voltage is extended. The

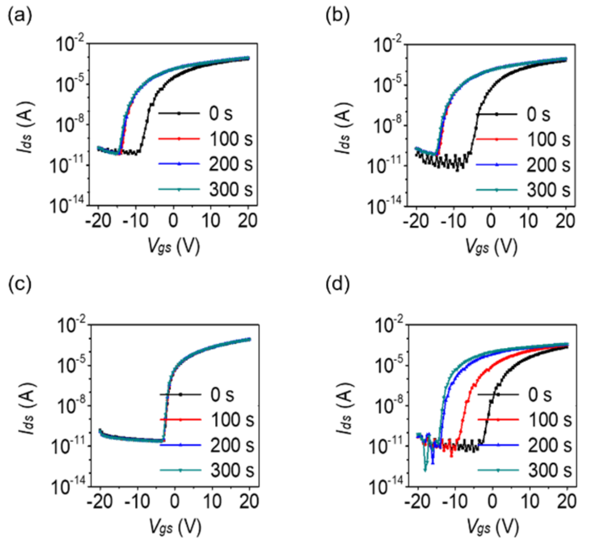

Fig. 5. NBS stability of TFTs with a-IGZO channel layers treated with oxygen plasma with gun-type plasma cell based on the amount of oxygen gas injected (a) as-deposited, (b) at 3 sccm, (c) at 6 sccm, (d) at 9 sccm. The stressing conditions were V_{gs} = −20 V.

results demonstrate that I_{ds} for V_{gs} is constant, despite the decrease in V_{th}, and the slope of the transmission characteristic curve is also constant. This seems to be a phenomenon caused by the movement of the positive holes in the a-IGZO channel layer toward the gate due to the negative voltage across the gate. In the a-IGZO TFT injected with 3 sccm of oxygen, the characteristic curve strongly shifted in the negative direction after applying a negative bias voltage. For the a-IGZO TFT injected with 6 sccm of oxygen, the negative shift was attenuated, compared to TFTs under other conditions.

Fig. 6 shows the results of AFM measurements (size: 2 μm × 2 μm) of the surface morphology of the as-deposited a-IGZO channel layer and the injected a-IGZO channel layers to analyze the effect of plasma surface treatment on the a-IGZO channel layer. Furthermore, the change in root mean square (RMS) value based on the amount of oxygen injection is shown in Fig. 6(e). As the amount of injected oxygen increased, the step difference of the surface of the a-IGZO channel layer decreased. Fig. 6(c) shows the measurement image of the a-IGZO channel layer injected with 6 sccm of oxygen, with the smallest RMS value and surface curvature.

However, when the a-IGZO channel layer was injected with 9 sccm of oxygen, as shown in Fig. 6(d), the step difference on the surface was reduced due to the oxygen

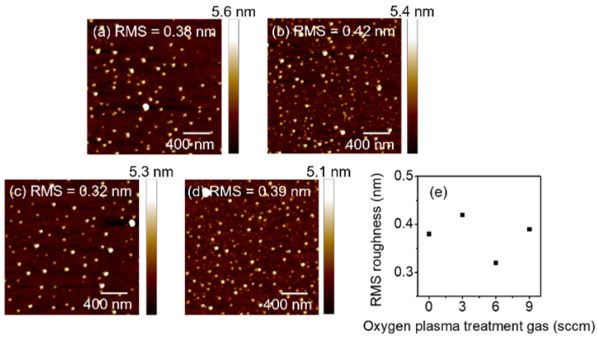

Fig. 6. AFM images on 2 µm × 2 µm a-IGZO channel layers treated with oxygen plasma with gun-type plasma cell based on the amount of oxygen gas injected (a) as-deposited, (b) at 3 sccm, (c) at 6 sccm, (d) at 9 sccm, (e) The change in RMS value depending on the amount of oxygen gas injected.

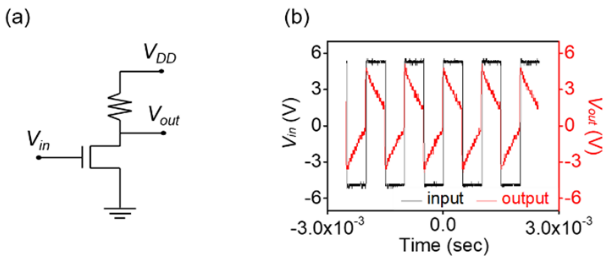

Fig. 7. Dynamic inverter test results from configuring the logic circuit for an a-IGZO channel layer TFT treated with oxygen plasma in which 6 sccm of oxygen gas was injected (a) schematic diagrams, V_{DD} = 5 V, and V_{in} = −5 to 5 V, (b) when input frequency = 1 kHz, V_{DD} = 5 V, and V_{pp} = 10 V.

plasma, but the RMS value increased. Larger RMS values indicate that the roughness of the surface increases. Increase in surface roughness causes trap charges that impede the movement of electrons. When trap charges occur, leakage current is induced, which is the main cause of reduced charge mobility in the transistor [39-41].

Therefore, as the amount of oxygen injected during the oxygen plasma surface treatment increases, the step difference on the surface of the a-IGZO channel layer decreases. Accordingly, the greater the amount of oxygen injected, the better the electrical performance of the transistor. However, when too much oxygen is injected, the surface roughness of the a-IGZO channel layer can be increased, causing current leakage, which will subsequently lower the charge mobility. Accordingly, the a-IGZO channel layer TFT injected with 6 sccm of oxygen performed best, indicating that the optimal amount of oxygen injection is 6 sccm.

Fig. 7(a) shows a logic circuit constructed using the a-IGZO channel layer TFT injected with 6 sccm oxygen. The circuit is composed of a power supply, an oscilloscope, and a function generator. The load resistance of the circuit was 1 MΩ, and V_{DD} was 5 V. When input voltage (V_{in}) was 0 V, the gate was short-circuited so that current flowed to the output voltage (V_{out}), resulting in 5 V output at V_{out}. When Vin was 5 V, the gate was open so that current flowed to ground, resulting in 0 V at V_{out}. Fig. 7(b) shows the results of the dynamic test after a resistive load inverter configuration using the same a-IGZO channel layer TFT. V_{in} was applied in the range −5 V to 5 V with a frequency of 1 kHz, and V_{out} over time was measured. We determined that the gate was open, and inverting occurred properly at about 4.5 V. Based on these findings, we suggest oxygen plasma surface treatment is applicable to creating a backplane device for active driving displays in the future.

IV. CONCLUSIONS

For this paper, a-IGZO TFTs were fabricated by applying plasma surface treatment on the channel layer at 3 sccm, 6 sccm, or 9 sccm of oxygen injected using the gun-type plasma cell of a gun-type plasma cell after post annealing. We then analyzed the electrical and surface performance using a semiconductor parameter analyzer and AFM to investigate the effect of plasma surface treatment on the a-IGZO channel layer TFTs based on the amount of oxygen injection. We determined that an a-IGZO channel layer TFT injected with 6 sccm of oxygen possesses an excellent charge mobility and current flashing ratio, as well as high current persistence and stability. Surface analyses confirmed that as the amount of oxygen injection increases, the step difference on the surface of the a-IGZO channel layer decreases. Electrical and surface performance analyses demonstrate that a logic circuit composed of an a-IGZO channel layer TFT injected with 6 sccm of oxygen leads to proper inversion at 4.5 V. As a result, applicability as a backplane device for active driving displays is confirmed.

This paper confirmed that the plasma surface treatment effect increases in accordance with the amount of oxygen injected. However, excessive oxygen injection interferes with the charge mobility inside the a-IGZO channel layer, resulting in current leakage. In conclusion, oxygen vacancy in the a-IGZO channel layer is controlled to an appropriate density by optimal amounts of oxygen injected during oxygen plasma surface treatment. This optimized condition was found to remove surface impurities and defects, to enhance electrical performance, to reduce surface roughness, and it ensures reliability and stability.

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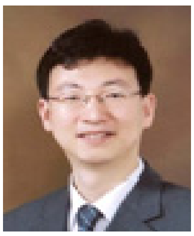

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