# Improved Reliability of a-IGZO Thin Film Transistor through Organic/Inorganic Passivation Layer

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## ABSTRACT

*The electrical characteristics and reliability of an amorphous indium gallium zinc oxide thin film transistor (a-IGZO TFT) was improved two materials, organic and inorganic, as a passivation layer in a stacked structure. it can reduce defect state and acts as an excellent barrier against adsorption/desorption of atmospheric molecules.*

## 1 Introduction

The progress toward practical applications of large-area flexible electronics such as information displays, wearable and ultra-light devices requires the development of high-performance electronic materials. a-IGZO has a high $I_{on}/I_{off}$ ratio due to a lower leakage current compared to a-Si and LTPS, beside it has a high mobility that is about 10 times faster than a-Si, so it is suitable for high resolution. In addition, the number of process steps is less than LTPS. Furthermore, a separate crystallization process is not required, and a solution process is possible in a-IGZO TFTs. Therefore, low-cost manufacturing is possible. Also, low-temperature process is possible at 150 ~ 350 ℃ [1, 2]. Although the a-IGZO TFTs exhibit excellent characteristics, such as high mobility, steep sub-threshold swing (S.S), and ultra-low off current, they also suffer from instability issues under illumination and electrical stresses. To solve these reliability and stability issues of oxide thin film transistors, a passivation layer of organic and inorganic hybrid structure was introduced. By using CYTOP, a hydrophobic organic material that has an excellent role as a barrier against moisture, and $AlO_x$, an inorganic material that has an excellent role in defending molecules in the atmosphere compared to organic substances, it can control the ambient effect on the backchannel layer. In addition, each material affects the characteristics of the devices, thereby improving the device characteristics and stability.

In this paper, a solution-processed passivation layer was fabricated with stacked structure with organic and inorganic materials and introduced into an a-IGZO TFT. When these two materials are fabricated in a stacked structure, the advantages of the two excellent barrier functions can be combined, thereby more effectively improving the reliability and stability of the device. Furthermore, it can reduce the oxygen related defect states like vacancies ($V_o$) and interstitials ($O_i$) by each material. As a result, it was possible to improve the stability and we confirmed reliability with positive bias stress (PBS) test [3, 4].

## 2 Experiment

### 2.1 Precursor solution synthesis

A 0.1 M IGZO solution was prepared by dissolving indium (III) nitrate hydrate (In $(NO_3)_3$ $xH_2O$)), gallium nitrate hydrate ($GaN_3O_9$ $xH_2O$), and zinc acetate dehydrate (($C_2H_3O_2)_2$ $Zn_2H_2O$) in 2-metoxyehanol at a molar ratio of 7:1:2. The solution was mixed at 75 °C for 11 hours and 30 minutes. For inorganic substances, 0.1 M $AlO_x$ was dissolved in 2-methoxyethanol and mixed at 75 °C for 11 hours and 30 minutes to prepare a solution.In the case of organic materials, 3 wt% of CYTOP solution was used. The solution was mixed at room temperature for 11 hours and 30 minutes.

### 2.2 Device fabrication

The heavily doped P-type silicon with thermal oxidized $SiO_2$ wafer washed with acetone and isopropyl alcohol. The prepared IGZO solution was deposited to a thickness of 10 nm by spin-coated at 4000 RPM for 30 seconds on the wafer, followed by UV-$O_3$ treatment for 2 hours, and annealed at 350 ℃ for 3 hours and 15 minutes. After that, the a-IGZO channel layer was patterned by a photo process and wet etched. To fabricate top-contact a-IGZO TFTs, the upper electrode was deposited with aluminum using a thermal evaporator. The solution-processed passivation layer was introduced with organic and inorganic materials with double stacked structure on a-IGZO TFT. In the case of organic materials, a 3 wt% of CYTOP solution was spin-coated on the a-IGZO TFT. After that, heat treatment was performed at 350 °C for 1 hour. For inorganic substances, 0.1 M $AlO_x$ solution was spin-coated on the a-IGZO TFT device and heat treatment was performed at 350 °C for 1 hour.

### 2.3 Measurement

All device properties were measured using an Agilent 4145B semiconductor parameter analyzer. To confirm the stability, positive bias stress (PBS) test was performed.

## 3 Results Discussion

### 3.1 Electrical properties according to passivation layer conditions

Fig. 1 shows the electrical characteristics obtained from solution-processed a-IGZO with various materials and structures as a passivation layer. The black line in Fig. 1 indicates a-IGZO TFT without passivation layer. To confirm that the changes in device characteristics are not caused by annealing condition, it was additionally post-annealed at 350 ℃ for 1 hour in the air to unifying the post-annealing temperature and time with other passivation layer process conditions.

It is well known that oxygen vacancy ($V_o$) acts as a shallow donor and weakly bonded oxygen acts as an electron trapping center. In addition, it is important to reduce $V_o$ in a-IGZO TFT because the solution-processed a-IGZO has a higher ratio of $V_o$ than vacuum process.

When CYTOP, $AlO_x$ and CYTOP, $AlO_x$ double-layer structure passivation layer was deposited, great reduction of Subthreshold swing (S.S) was observed in all of them. When $N_{it}$ (Interface trap state density) is calculated through Equation (1), where k is the Boltzmann's constant, T is the temperature, and $C_{ox}$, is the capacitance of $SiO_2$.

$$N_{it} \quad = \left[\left(\frac{S.S}{ln10}\right)\left(\frac{q}{kT}\right) - 1\right]\left(\frac{C_{ox}}{q}\right) \qquad (1)$$

The interface trap state density was $6.71\times10^{11}$ for the device without passivation. It decreased to $1.46\times10^{11}$ ($\pm0.2\times10^{11}$) after adding CYTOP, $AlO_x$ and CYTOP, $AlO_x$ double layer structure passivation layer. This result indicates that the material of the passivation layer can reduce Interface trap state.

Another big difference among the parameter values is the threshold voltage. It is well known that $V_o$ acts as a shallow donor and weakly bonded oxygen acts as an electron trapping center. CYTOP is an organic material containing fluorine (F). When CYTOP is used as a passivation layer, F, which has a similar ionic radius to oxygen in the CYTOP, diffuses into the interface between the channel layer and the gate insulator, thereby reducing oxygen vacancy or weakly bound oxygen. As can be seen from Equations (2) and (3), the ionic radii of F and O are very similar, it can reduce $V_o$, which acts as a shallow donor and reduce the carrier concentration. It can also substitute oxygen and provides free electron.

$$V_o^2 + 2e^- + F^- \leftrightarrow F_o + e^- \qquad (2)$$

$$O_o^x + F^- \leftrightarrow F_o + e^- \qquad (3)$$

Due to these two mechanisms of F in a-IGZO, as a result, defects are reduced due to reduced oxygen vacancy in the a-IGZO, which is consistent with the results of reduced S.S.

In the case of a device passivated with $AlO_x$, S.S was significantly reduced. This result expected that $AlO_x$ passivation can reduce defects because of high reactivity of aluminum [5, 6]. Besides, $Al^{3+}$ (0.53 Å) having a similar ionic radius with $Ga^{3+}$ (0.62 Å), it can reduce structure disorder. Besides, it can reduce metal-vacancy or weakly bonded oxygen, known as defect states [6-11].

Finally, when a- IGZO TFT was passivated by CYTOP and $AlO_x$ with double stacked structure, since the CYTOP passivation layer is deposited on the ultra-thin $AlO_x$ layer of about 8 nm, it is expected that fluorine will diffuse to the a-IGZO through $AlO_x$ passivation layer. From this result, $V_o$ is reduced in a-IGZO TFT which is act as a defect state by F. Because of the difference in ionic radius, Al can also reduce oxygen vacancy, but it is less effective than F. Therefore, it is expected that oxygen vacancy decreased when CYTOP was deposited on the $AlO_x$ layer. As a result, it can reduce oxygen related defect states like vacancies ($V_o$) and weakly bound oxygen more effectively.

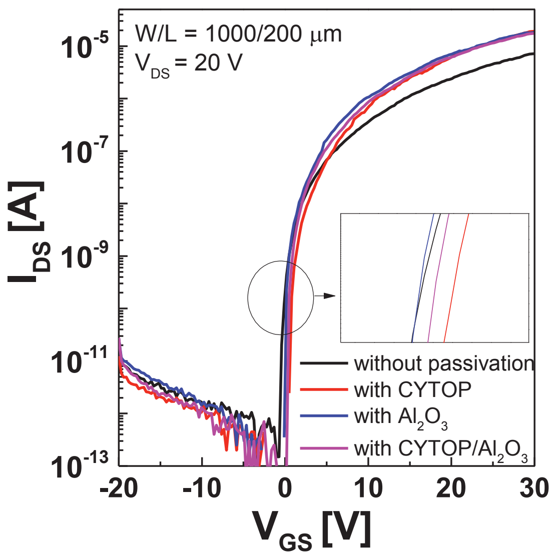


**Fig. 1 I-V characteristics of a-IGZO TFT without passivation (black), with CYTOP passivation (red), $AlO_x$ passivation (blue) and CYTOP, $AlO_x$ stacked structure passivation (magenta)**

**Table. 1 The average value of the parameters for each condition of different materials and structures of the passivation layer**

| Average value | Mobility ($cm^2$/V·s) | $V_{th}$ (V) | S.S (V/dec) |
|---|---|---|---|
| without passivation | 0.82 | 8.11 | 0.51 |
| with CYTOP | 0.96 | 6.07 | 0.15 |
| with $AlO_x$ | 0.79 | 3.56 | 0.14 |
| with CYTOP/$AlO_x$ | 0.75 | 3.88 | 0.13 |

### 3.2 Positive bias stress (PBS) test of a-IGZO TFT according to various passivation structure

The oxygen and water molecules in the ambient are known to affect the characteristics of devices. These molecules adsorb/desorb on the back-channel region and thus may play an important role during the stress bias of the oxide transistor [5]. Huge positive $V_{th}$ shift in a-IGZO TFT without passivation resulted from the increased negatively charged-oxygen adsorption and charge trapping at the dielectric/channel layer [3, 12].

The positive gate voltage stress of 20 V was biased in a- IGZO TFT and Fig. 2 shows the amount of change in threshold voltage shift according to the stress time for each device. As PBS test result, when CYTOP, an organic material and $AlO_x$, an inorganic material, were stacked as passivation layers, it not only reducing defect states in a-IGZO, acts as a great barrier against oxygen and moisture in the atmosphere than when each material is stacked one layer at a time.

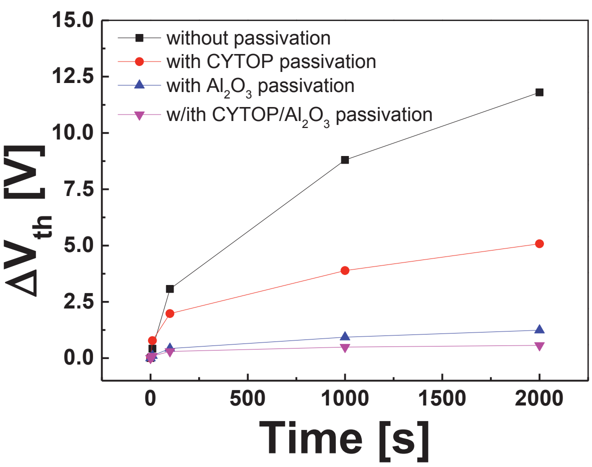


**Fig. 2 Positive bias stress test ($V_{GS}$: 20 V) results of IGZO TFT without passivation (black), with CYTOP passivation (red), $AlO_x$ passivation (blue) and CYTOP, $AlO_x$ stacked structure passivation (magenta)**

## 4 Conclusions

Herein, it was confirmed that the case of a device passivated by CYTOP and $AlO_x$ double stacked structure, it can be most effectively reduced the oxygen related defect states like vacancies ($V_o$) and weakly bound oxygen, as well as plays a role as an excellent barrier against oxygen and moisture. PBS test was performed to confirm reliability and stability. In the PBS test, huge positive $V_{th}$ shift in a-IGZO TFT without passivation was greatly reduced in a device passivated by CYTOP and $AlO_x$ double stacked structure, resulted from the increased negatively charged-oxygen adsorption and charge trapping at the dielectric/channel layer. As a result, it can reduce defect state and acts as an excellent barrier against adsorption/desorption of atmospheric molecules.

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