1. Introduction

In 2004, amorphous oxide semiconductors (AOSs) were reported as a promising active layer material for the next generation thin film transistors (TFTs)\(^1\). Since then, many achievements have been reported by laboratories and companies. Several companies have successfully mass-produced display devices with AOSs, notably In-Ga-Zn-O (IGZO). Mass production of the IGZO-LCDs was started in 2012\(^2\). So far, many products like smartphone, PC, and TV using IGZO TFT-based display panels have been introduced by several companies.

IGZO TFT has some advantage over conventional TFTs. The mobility is 10 times higher than a-Si TFT. This is an advantage in drive speed and high resolution. Another is the low leakage-current at off state, which is 1/1000 smaller than a-Si TFTs, and necessary for low frequency and low power consumption devices. IGZO TFT shows good threshold voltage (V\(_{th}\)) uniformity in a large substrate for glass size generation 8 (G8) \([2,160 \times 2,400 \text{ mm}^2]\). Which is very important for mass production of large-sized displays. On the other hand, there are some issues of back channel etch IGZO TFT, such as, parasitic capacitance and the reliability. To operate the current-driven displays in high frequency, it is important to reduce parasitic capacitance in the TFTs. Therefore, a top gate structure is needed. Using a top gate structure, the capacitance between source and gate electrodes can be reduced. It is also advantageous over the back channel etch process as the process damage by source/drain dry etching is less. Besides, these, it is possible to increase the TFT’s on current by thinning the gate insulator.

Reliability is also an important issue for oxide TFTs. Especially for the current-driven displays, characteristics degradation directly affects brightness. During stresses, defect states can be easily generated in the IGZO subgap, and/or in the GI/IGZO interface\(^3\). High quality GI/IGZO interface can be formed by a top gate structure.

Because of those advantages, top gate structure TFT has been studied intensively in many development institutions\(^3,4,5\). High mobility is a key property to realize the display devices with high potential\(^5\). TFTs with high mobility can be operated at low voltage, and can reduce the power consumption. In addition, reduction of TFT size is possible to realize high resolution and narrow bezel displays. For small to medium size display backplane, low temperature poly silicon (LTPS) is the most popular
material for high mobility TFTs, but is not suitable for large area and low power consumption displays. Therefore, we need to improve the mobility of IGZO TFT up to that of the LTPS TFT.

We established mass-production of back channel etch type IGZO TFT in 2012. We call this technical generation "IGZO3" which means the 3rd generation of IGZO. Since IGZO3, we have improved the mobility by 1.5 times and evolve the generation, like IGZO3, IGZO4, IGZO5, and now IGZO6 is being developed. The high mobility IGZO6 TFT can be used not only for OLED but also for other self-luminous devices like mini/µLED displays for high brightness.

IGZO TFTs are also suitable for automotive display backplane. Inside the vehicle, environment, especially temperature, frequently changes to vary the TFT characteristics. Since, the same screen is often displayed, image sticking can easily occur. Therefore, real-time compensation by current reading is necessary. Compensation of $V_{th}$ is possible with elapsed time by internal compensation. By adding camera compensation to this, initial luminance compensation is possible. On the other hand, external compensation can read the current value after the lapse of time, and it is possible to compensate the current value after aging. In addition, by adopting the external compensation, it is possible to reduce the circuit that reads the current value in the pixel, so the number of TFTs can be reduced. Therefore, we will have the design and process flexibility, as well as high yield.

Figure 1 shows the external and internal compensation for IGZO and LTPS TFT, respectively. Table 1 summarized a comparison between internal, internal plus external, and IGZO TFT with external compensation. IGZO TFT is suitable for external compensation because of its excellent off state characteristic. The off-state leakage current causes noise during external compensation and making it difficult to perform highly accurate compensation. High mobility IGZO TFTs with a top gate structure show high on current, low parasitic capacitance and low off-state leakage current. Therefore, adopting a high mobility top gate IGZO TFT in the external compensation would enable to develop a narrow bezel display with low power consumption and image sticking free performance.

In this paper, top gate IGZO TFTs with high mobility are successfully manufactured for automotive OLED display panels. The IGZO TFT shows high mobility with enhanced threshold voltage. It is also shown that the reliability under positive bias temperature (PBT), negative bias temperature (NBT) and negative bias temperature illumination (NBTI) stress tests is high enough to widely adopt the IGZO TFTs in mass-production. Finally, we fabricated a prototype 12.3” ultrawide OLED display with high brightness uniformity.

2. Experiment

2.1 TFT structure

Top gate IGZO TFTs were fabricated on a polyimide (PI) or glass substrate, as shown in Fig. 2. A silicon-based dielectric base coat layer was deposited using plasma-enhanced chemical vapor deposition (PECVD). The IGZO film was sputtered as an active layer and patterned with photolithography and wet etching. Top gate insulator (TGI) and top gate electrode (TGE) were deposited on the...
IGZO channel by PECVD and sputter, respectively. The TFT properties are strongly influenced by the top gate metal work-function, thus optimization of the gate material is also an important factor for controlling the \( V_{th} \). Herein, 300-nm-thick titanium/aluminum/titanium films were used as the gate electrode.

After patterning and dry etching of both the TGI and TGE, an interlayer dielectric (ILD) was deposited. For top gate IGZO TFT, a conductive region (\( n^+ \) IGZO) is needed to form electrical contact between the active channel and electrode. After opening the contact holes by photolithography and dry etching, stacked titanium/aluminum/titanium films were deposited as the Source/Drain electrodes (SE). Considering the TFT's characteristics and reliability, the silicon-based passivation layer was chosen carefully. During the fabrication processes, several annealing steps were also applied to activate the TFTs. The channel length (\( L \)) and width (\( W \)) of the TFTs were 7.5 and 10 \( \mu m \), respectively. Note here, all the process parameters are selected to satisfy the mass-production. Figure 3 shows a scanning electron microscope (SEM) image of the top gate IGZO TFTs. This image shows that the TFTs was manufactured without serious problems such as over etching of the channel region, or poor coverage of the dielectric interlayer.

For Hall measurements, 100-nm-thick IGZO film was deposited on the glass substrate.

### 2.2 Process optimization

To enhance the mobility, we have engineered the IGZO process and evolve the IGZO generation, like IGZO3, IGZO4, IGZO5, and IGZO6. Although the basic TFT structure was same, the channel, gate insulator and interlayer were modified for every generation. Figure 4 shows the Hall mobilities of the IGZO films formed by different processes generation as a function of the carrier concentration. Every time the generation of the IGZO process evolves, the hall mobility increases. From IGZO3 to IGZO6 the hall mobility becomes 10 cm\(^2\)/Vs to 50 cm\(^2\)/Vs. However, the electron carrier concentration also rises in orders of magnitude, which is similar to the previous reports of high mobility AOSs\(^1\). For n-type semiconductor the threshold voltage is related to the carrier concentration. We found that, if the carrier concentration is over 20\(^{th}\) order, an enhancement mode TFT becomes very difficult to obtain. From this point of view, we have controlled the carrier concentration of the new high mobility IGZO process (IGZO6) below 10\(^{20}\) cm\(^{-3}\) and realized the Hall mobility of 50 cm\(^2\)/Vs.

Several process optimizations are needed to fabricate good quality top gate IGZO TFTs for mass production. Obtaining the enhancement mode TFTs with good uniformity is a challenge. First, we optimized the channel, GI, and interlayer process to control the \( V_{th} \). The arrangement of the process was based on the Microwave photoconductivity decay (\( \mu \)-PCD) method\(^8\). From the \( \mu \)-PCD peak reflectivity, the defect states of the IGZO film can be evaluated after every processing step.

Figure 5 (a) and (b) shows the \( \mu \)-PCD mapping of the substrates for the (a) conventional and (b) optimized process. Transfer characteristic of 13 TFTs fabricated through the (a) conventional and (b) optimized process.
microwave peak reflectivity over the substrates for the conventional and optimized processes, respectively. The conventional process shows an average peak reflectivity of 1166 mV with a uniformity of 56.7%, whereas the optimized process shows an average peak reflectivity of 2334 mV with a uniformity of 16.4%. As a result, TFTs in the same mother glass (MG) became uniform. Figure 5(c) and (d) depict 13 TFTs characteristics on a generation 4.5 (G4.5) [730 × 920 mm] substrate at various places, for the conventional and optimized process, respectively. The TFTs formed by the optimized process shows good uniformity compared to those by the conventional process.

In order to suppress appearance of the depletion mode, oxygen vacancies in the IGZO channel need to be reduced. Threshold voltage can be positively shifted by adding oxygen in the IGZO film during the fabrication process. However, the on current and mobility would decrease significantly. Moreover, excess oxygen atoms create weakly bonded –OH and Vth shifts under the stress 3). Previously, it was reported that the reliability could be improved by increasing hydrogen concentration into the TGI 4). However, diffused H in the IGZO channel also acts as a shallow donor and increases the carrier density. Therefore, we have introduced a process to supply balanced oxygen and hydrogen in the TGI and the IGZO channel as shown in the Fig. 6 (a) and (b).

In this work, the gate insulator and interlayer were deposited by plasma enhanced chemical vapor deposition (PECVD), which contain hydrogen. Those H can be easily diffused to the IGZO. Oxygen can also be supplied by varies PECVD carrier gas. We have balanced the hydrogen and oxygen ratio by choosing suitable source and carrier gas. GI and ILD film deposition temperature and post fabrication annealing also effect the hydrogen and oxygen contain in the IGZO. By introducing oxygen to some extent and balancing hydrogen the Vth becomes around 0 V, and high mobility and high reliability were obtained at the same time.

### 3. Results

#### 3.1 TFT performance

The transfer characteristic of the TFTs were measured by Agilent B1500A semiconductor analyzer at room temperature in dark. The field effect mobility (µEF) was calculated by the following equation 3):

\[
\mu_{EF} = \frac{g_m L}{W C_{OX} V_D}
\]

where \(g_m\) is the transconductance obtained by \(g_m = \frac{dI_D}{dV_g}\).

The Vth of the IGZO TFTs remains in enhancement mode and almost similar to the other TFTs formed by all the process generations, as shown in Fig. 7. Table 2 lists the values of the mobility, threshold voltage and hysteresis of the TFTs with different IGZO process generations. All the TFTs shows good performance with very small hysteresis and high uniformity. Despite very minimal

![Figure 6](image)

**Figure 6.** (a) Schematic diagram of Hydrogen and Oxygen balance in the IGZO channel (b) Transfer characteristics of the TFTs, before and after process optimization.

| Table 2. Electrical characteristics of the TFTs. |
|-----------------------------------------------|
| IGZO3 | IGZO4 | IGZO5 | IGZO6 |
| \(\mu_{EF} \ [cm^2/Vs]\) | 7 | 12 | 18 | 32 |
| \(V_{th} \ [V]\) | 0.5 | 0.3 | 0.5 | 0.4 |
| \(V_{th} \ [\sigma]\) | 0.13 | 0.12 | 0.10 | 0.15 |
| Hysteresis \(\ [V]\) | 0.05 | 0.04 | 0.08 | 0.08 |

![Figure 7](image)

**Figure 7.** Transfer characteristics of IGZO TFTs with IGZO3, IGZO4, IGZO5, IGZO6 process.
low off-state current, the on current gradually increased with the IGZO process generation evolved. As a result, the mobility for IGZO3, IGZO4, IGZO5, and IGZO6 become 7, 12, 18, and 32 cm²/Vs, correspondingly.

In general, the oxygen vacancy could supply the electron and enhance the mobility. However, the IGZO6 exhibited positive $V_{th}$ with high on current. The channel lengths of the TFTs with different IGZO process generations are almost equal to one another. Therefore, the oxygen vacancy was successfully compensated by balancing the oxygen and hydrogen, which would be the origin of the high mobility obtained by the IGZO6 process.

3.2 TFT’s Bias Stress Reliability

Figure 8 (a) summarized the $V_{th}$ shift under positive and negative bias temperature (PBT and NBT) stresses for the TFTs with different IGZO process generations. A gate voltage stress of +30 V or −30 V was applied for 3, 600 s at a stress temperature of 60°C. Under the PBT stress the positive $V_{th}$ shift increases from 0.2 V to 0.35 V for the IGZO6 device. Under the NBT stress, the negative $V_{th}$ shift of the IGZO6 is −0.35 V, which is reasonable for high mobility TFTs. The NBTI test shown in the Fig. 8 (b) was conducted as similar condition of the NBT with a white light illumination of 10,000 lux. The negative $V_{th}$ shift under the NBT stress trends to gradual increase with the IGZO TFT’s mobility enhancement.

Compared with the LCDs, the TFT in the OLED display is less affected by the light, thus the NBTI degradation value of the high mobility TFT would not impact the mass-production. Nevertheless, the PBT and NBT shift for IGZO6 are +0.35 and −0.36 V, and the NBTI shift is below 1 V, which are small enough to use in OLED display devices.

3.3 Ultrawide flexible OLED display Bias Stress Reliability

We demonstrate a 12.3” ultrawide flexible OLED display, using top emission OLED structure and a high-mobility top-gate IGZO TFT backplane as shown in Fig. 9. The display having narrow bezels can be bended at a curvature radius of R=5 mm. The specifications of the display are listed in Table 3. The prototype display showed an excellent brightness uniformity. The device can be operated under high temperature of 85°C to low temperature of −30°C. The display was tested also under stress at a temperature and humidity of 60°C and 90%, respectively for a long time. The device and backplane remain working in good condition even after 1,000 hours.

4. Summary

In summary, we developed high-mobility top-gate IGZO TFTs and successfully adopted them in a flexible OLED display panel. The mobility of TFTs reaches as high as 32 cm²/Vs and showed the threshold voltage of 0.4 V with excellent uniformity. We checked the reliability under the PBT, NBT and NBTI stress tests. IGZO6 TFTs shows a slight change of $V_{th}$ within ±1.0V.

| OLED | Top emission |
|------|--------------|
| Size | 12.3’ Ultrawide |
| Resolution | 1920 x 720 x RGB (167ppi) |
| Brightness | 600 cd/m² |
| Substrate | Polyimide |
under these stress tests which is no critical shifts. These $V_{th}$ shift of the TFTs under the stress are small enough to use in the OLED panel. A prototype 12.3” ultrawide OLED display module for automotive applications is demonstrated. The prototype display showed an excellent brightness uniformity even after bending. The device and backplane also show good reliability. Therefore, TFTs using high mobility IGZO6 process are suitable for automotive OLED display panels.

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