A New Era of Oxide Thin-Film Transistors for Large-Sized AMOLED Displays

In order for large-sized AMOLED displays to achieve widespread adoption, manufacturers must find a way to mass produce them at affordable prices. However, scaling-up of production lines causes several technological challenges. This article delves into the critical issue of the TFT backplane, which is crucial for the success of AMOLEDs.

by Jae Kyeong Jeong, Hyun-Joong Chung, Yeon-Gon Mo, and Hye Dong Kim

AMONG existing display technologies, active-matrix organic light-emitting diodes (AMOLEDs) provide the best potential solution to achieve the "ultimate display" due to their fast motion-picture response time, vivid color, high contrast, and super-slim light-weight nature.[1,2] In 2007, Samsung SDI launched the first mass production of small-sized AMOLEDs for cell-phone and MP4 displays.

The display market is now burgeoning for mid- to large-sized applications, such as notebook PCs (NPCs), monitors, and televisions, which accounts for the majority of the flat-panel-display market. Samsung SDI's recent exhibition of 14- and 31-in. full-HD television prototypes[3] and Sony's commercialization of qFHD 11-in. TV (XEL-1) clearly show that the era of AMOLED TV is indeed nearby. Whereas the market is projected to reach 54 million units by 2011,[4] a number of hurdles in technology must be overcome for the mass production of mid–to–large-sized AMOLED panels.

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The biggest impediment to widespread adoption of AMOLED NPCs and TVs is finding a way to produce them in mass quantities at affordable prices. The best strategy for this purpose is to increase the motherglass size at least up to Gen 5.5 (1300 × 1500 mm), which corresponds to the most cost-effective backplane size for NPCs. However, the scaling-up of the production line causes several technological challenges. In this article, we focus on the current status and critical issue of the thin-film-transistor (TFT) backplane, which is one of the most crucial technologies for the success of AMOLEDs.

Amorphous-silicon (a-Si) TFT technology is well-established, a proven technology in the liquid-crystal-display (LCD) industry. This technology offers good scalability (up to Gen 8) and a low-cost process because it does not require the crystallization and ion-doping processes. In addition, its amorphous nature ensures excellent uniformity of device performance, including mobility and threshold voltage. However, the mobility of a-Si TFTs is quite low (~1 cm^2/V-sec), which may not be enough to drive large-sized high-resolution AMOLED displays. Furthermore, the device instability has been a concern for a long time. For example, the threshold voltage of an a-Si TFT seriously shifts under constant current stress due to either the charge trapping into the underlying gate dielectric or the weak bonding break-up of silicon and hydrogen in a-Si thin film, leading to image burnout or serious image sticking (*e.g.*, short lifetime) in AMOLED displays. This is why a-Si TFTs are rarely used as backplanes for AMOLED displays.

On the other hand, low-temperature polycrystalline-Si (LTPS) TFTs have high mobility and excellent stability, unlike that of a-Si TFTs. The key processes in fabricating LTPS TFTs are the crystallization methods that convert a-Si into polycrystalline-Si: non-laser crystallization and laser annealing. Among non-laser crystallization, the simplest method is solid-phase crystallization (SPC). But SPC requires annealing at 600ºC for tens of hours, which makes it unsuitable for use on large-area glass substrates. Other non-laser methods employ metal seeds for crystallization, which may result in a large current leakage in the channel area.

Among the laser methods available, excimer-laser annealing (ELA) has been the most widely used because of the resulting excellent crystallinity, fast crystallization speed, and high mobility. In addition, ELA is already been employed in mass-production, thus well-developed apparatuses are commercially available. However, ELA suffers from

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a narrow process window, as well as high initial investment and maintenance costs. Moreover, the limitations in laser-beam length and laser-beam instability are a major obstacle in the use of ELA on large-sized glass: the largest equipment available is applicable to Gen 4 (a motherglass size of 730 × 920 mm). Finally, all LTPS TFTs, including the ELA technique, suffer from non-uniformity issues because of the existence of grain boundaries, which require the use of a complicated compensation unit pixel circuit such as a 5 transistor + 2 capacitor pixel circuit, leading to a loss in device yield.

Therefore, an obvious question arises: Is there any new TFT that has both high mobility and excellent uniformity at the same time that is suitable for large-sized AMOLED displays? Amorphous-oxide TFTs can be an attractive alternative solution to this question. Amorphous-oxide semiconductors (AOS) provide unique properties that combine the advantages of a-Si and LTPS TFTs. For example, amorphous-oxide TFTs are free from the non-uniformity of mobility and threshold voltage, yet exhibit large carrier mobility (~10 cm^2/V-sec) and excellent subthreshold gate swing (down to 0.20 V/dec). Moreover, the channel layer can be fabricated by using a simple sputtering process. Therefore, large-sized fabrication can easily be implemented up to Gen 8 sizes without using expensive laser apparatus. The process is essentially the same as that for a-Si TFTs so that existing production lines can be used without significant changes. In addition, oxide TFTs can be deposited at room temperature, which in principle makes possible the mass production of AMOLEDs on flexible plastic substrates or cheap soda-lime glass. The technological comparisons among a-Si, poly-Si, and oxide TFT are summarized in Table 1.

A Brief History of Oxide TFTs

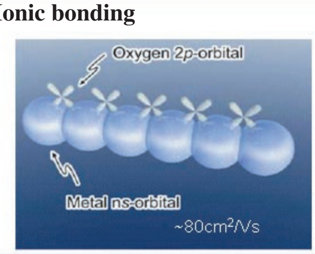
In 2003, the first paper describing high-performance transistors (mobility, ~80 cm^2/V-sec) by using single-crystalline InGaZnO material (from Professor Hideo Hosono's group) was reported in *Science*.[5] However, the high-temperature deposition (700°C) of InGaZnO using pulsed laser deposition (PLD) and annealing at 1400°C prohibited its practical usage as the channel layer of a TFT backplane for AMOLED displays. A subsequent paper in *Nature* in 2004 discussed the concept of amorphous InGaZnO in order to reduce the fabrication temperature (room temperature) by using a PLD technique.[6] These two papers created significant worldwide interest in AMOLED technology, both in industry and academia because of the potential for high mobility, excellent uniformity in device parameters, and good scalability to large substrate size.

Let's look at the origin of high mobility even in the amorphous state. Table 2 shows the orbital structure of the crystalline and amorphous state for indium gallium zinc oxide (IGZO) and solid silicon, respectively. The conduction band of IGZO material is closely related to the In 5s orbital, which has an isotropic property. Interestingly, the spherical symmetry of the 5s orbital makes the structural disordering no longer critical. So even though the phase is transformed into the amorphous state, the a-IGZO semiconductor still has good mobility (>10 cm^2/V-sec). This is drastically different than that for a silicon

Table 1: Comparison of TFT technologies including a-Si, poly-Si, and oxide TFTs

	a-Si TFT	poly-Si TFT	Oxide TFT
Generation	8G	4G	8G
Semiconductor	Amorphous Si	Polycrystalline Si	Amorphous IGZO
TFT uniformity	Good	Poor	Good
Channel mobility	1cm^2/Vs	~100 cm^2/Vs	10 ~ 40 cm^2/Vs
TFT for OLED	4~5	5~11	4~5
Pixel circuit	Complex (> 4T)	Complex (> 4T)	Simple (2T + 1C)
Cost/Yield	Low/high	High/low	Low/high
Stability (ΔV_{th}, 100 khr)	>5V	< 0.5V	NA
Circuit Integration	NO	YES	YES
Pixel TFT	NMOS	PMOS (CMOS)	NMOS

Table 2: The schematic orbital structure of the conduction-band minimum in a silicon semiconductor and in a ionic oxide semi-conductor.[6]

<table>
<tr><th></th><th>InGaZnO</th><th>Si</th></tr>
<tr><td>Crystalline phase</td><td>• Ionic bonding

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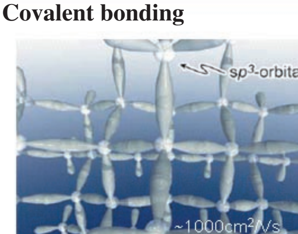
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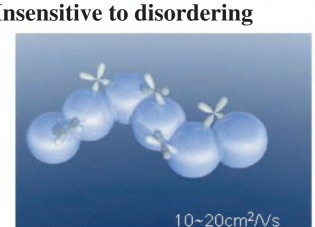
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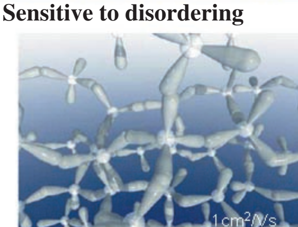
</td></tr>
</table>

H. Hosono et al., J. Non-Crystalline Solids 203, 334 (1996).

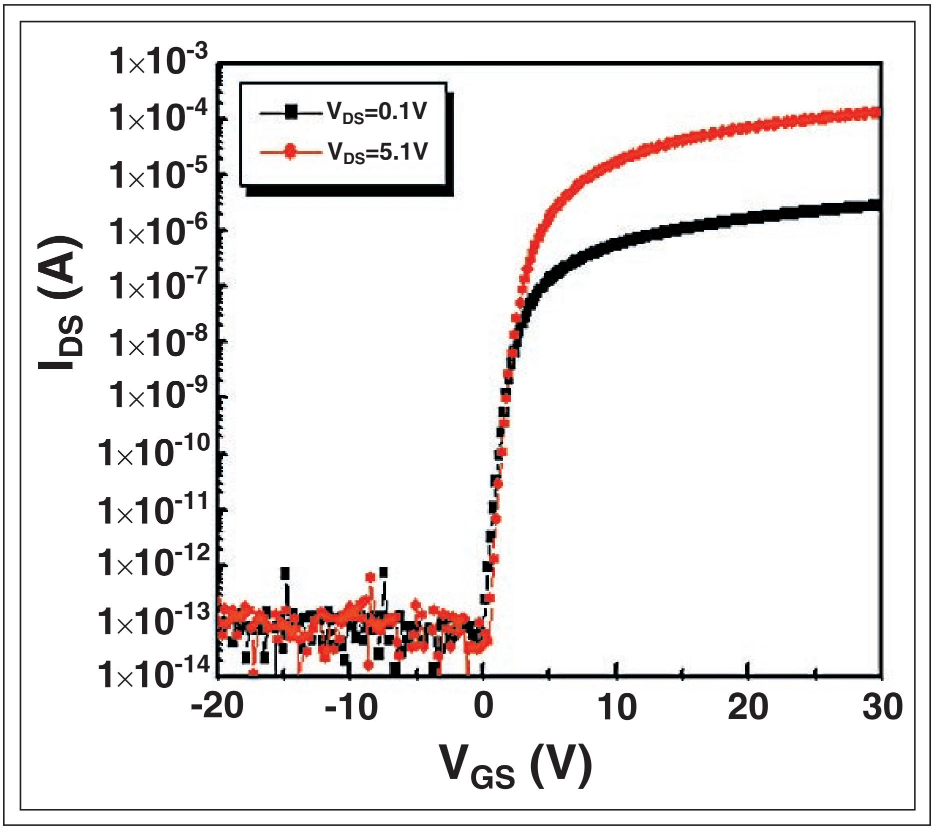

Fig. 1: The panel image of a 12.1-in. WXGA AMOLED driven by oxide TFTs.

semiconductor, in which the mobility drop is significant (from 1000 to 1 cm^2/V-sec) when the phase transforms from the crystalline state to the amorphous state.[6]

In 2006, Canon demonstrated that a high-performance transistor (mobility, > 10 cm^2/V-sec; gate swing, 0.2 V/decade) can be achieved by using RF sputtering with the capability of using large-area deposition rather than PLD.[7] Major panel makers such as LG and Samsung began performing R&D on oxide TFTs for AMOLEDs in 2006. The first AMOLED display was released by LG Electronics in 2007.[8] The fabricated InGaZnO transistor having a top-gate structure exhibited good device performance. This prototype of a full-color 3.5-in. QCIF+ AMOLED demonstrated the possibility of being used as a backplane for an OLED device.

This year at SID's Display Week 2008, Samsung SDI showcased a full-color 12.1-in. AMOLED prototype (Fig. 1) that used InGaZnO TFTs; this is the world's largest AMOLED panel among any oxide TFT-driven OLED display.[9] The WXGA high-resolution (1280 × RGB × 765) is compatible with TFT-LCDs that are currently commercially available for notebook PCs. In addition, even though a 2 transistor + 1 capacitor pixel circuit was implemented, a "random-mura-free" high-quality display was demonstrated, due to the excellent short-range uniformity of the threshold voltage of oxide TFTs.

Performance of Oxide TFT

Initially, an a-IGZO field-effect transistor fabricated on a flexible substrate had a mobility of 8.3 cm^2/V-sec and an $I_{on/off}$ ratio of 10^3.[6] Since 2004, the device performance of oxide TFTs has rapidly improved. The transistor performance reported in the literature includes field-effect mobilities between 1 and 53 cm^2/V-sec and $I_{on/off}$ ratios ranging from 10^4 to 10^8. However, most of the previously reported TFTs have rather large channel lengths and widths (>50 μm) because the shadow mask or lift-off techniques were mainly used to pattern the gate electrode, channel, and source/drain electrodes. Full array fabrication of oxide TFTs applicable for high-resolution AMOLED displays has been attempted by a few major companies, including Samsung SDI, LG, and Toppan, Inc. Figure 2 shows the representative transfer curve of our IGZO TFT with W/L = 25/10 μm, which was taken from a full-array-panel device rather than the individual test device without a suitable passivation layer. We adopted a bottom-gate structure with an etch stop layer. The high field-effect mobility of 17 cm^2/V-sec, an excellent gate swing of 0.28 V/decade, and a good $I_{on/off}$ ratio of 10^9 was achieved; these are state-of-the-art characteristics for any oxide TFT. We believe that these specifications of oxide TFTs are good enough to drive high-resolution and large-area AMOLED panels.

The most difficult aspect of fabricating high-quality AMOLED displays is the presence of "mura" caused by TFT non-uniformities. These non-uniformities are caused by localized differences in TFT properties, which ultimately result in the variation in current levels supplied to the individual subpixels throughout the display. Therefore, another important figure of merit is the short- and long-range uniformity of device performance. The short-range uniformity of oxide TFTs is surprising – the representative standard deviations of threshold voltage is less than 0.01 V. The simple calculation predicts the non-uniformity in luminance to be less than 2%. This result suggests that an ultra-simple pixel circuit such as a 2 transistor + 1 capacitor pixel circuit can be used for the design of AMOLED displays, which will have a very positive impact on the device yield and cost.

Issues and Outlook

In order to impact the TV market, AMOLED TVs must be competitively priced with identically sized AMLCD and PDP TVs. Moreover, the following specification should be met: a lifetime > 100,000 hours, a color gamut > 90%, a peak luminance > 400 nits, a contrast ratio > 100,000:1, and no image burn-in (> 500 hours).

The first issues that must be resolved include the attainment of a TFT threshold voltage change of less than 0.2 V for the lifetime of the display; the elimination of fine mura; and a brightness uniformity of more than 80%. In particular, the instability of the threshold voltage should be improved by the proper choice of passivation material and

Items	Specification
Diagonal size	12.1 inch
No. of pixels	$1280 \times$ RGB $\times 768$
Sub pixel pitch	$69 \times 207\ \mu m^2$
Resolution	123 ppi
Panel size	$283 \times 181\ mm^2$
Pixel element	2Tr 1Cap
Gray	256 gray
Scan driver	Integration
Color coordinate	White (0.31, 0.31) Red (0.67, 0.33) Green (0.29, 0.64) Blue (0.15, 0.11)

Fig. 2: *The representative transfer characteristics of IGZO TFT.*

careful optimization of robust IGZO compositions. Of course, a new oxide semiconductor and compatible gate dielectric should be developed in parallel, which allows for better stability than the combination of IGZO semiconductor and a SiNx dielectric. In addition, to be cost competitive, AMOLEDs must maintain a production yield similar to that of AMLCDs, and the TFT backplane should be produced by using a process consisting of four or five photo-masking steps.

Secondly, OLED patterning technology capable of large-area motherglass size (greater than Gen 5) and high resolution (> 200 ppi) also must be developed. To date, the fine-metal shadow mask (FMM) has been the only commercialized patterning method used in the color primaries of OLEDs. However, an FMM has an intrinsic limit of mechanical bending (~ Gen 4) when the size is increased. To circumvent the problem, a sequential pattern formation can be implemented, but the method has weaknesses in uniformity and tact time. Ink-jet printing of soluble OLED material,[5] color filters on white OLEDs,[6] and laser-induced thermal transfer are strong candidates to replace FMM.

Finally, encapsulation is another important issue for large-sized displays. Encapsulation is necessary in order to prevent the degradation of OLEDs caused by the attack of the oxygen and moisture in the atmosphere. Because HDTVs require at least 50,000 hours of lifetime, the development of a simple but reliable encapsulation method is unquestionably important.

Resolving the aforementioned issues will guarantee the era of AMOLED adoption for use in notebook PCs and HDTVs.

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