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To cite this article: Jiazhen Sheng, Hyun-Jun Jeong, Ki-Lim Han, TaeHyun Hong & Jin-Seong Park (2017) Review of recent advances in flexible oxide semiconductor thin-film transistors, Journal of Information Display, 18:4, 159-172, DOI: 10.1080/15980316.2017.1385544

To link to this article: https://doi.org/10.1080/15980316.2017.1385544
INVITED PAPER

Review of recent advances in flexible oxide semiconductor thin-film transistors

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ABSTRACT

This paper describes the recent advances in flexible oxide thin-film transistors (TFTs), one of the rapidly emerging technologies for the next-generation display applications. First, the paper focuses on the effect of the buffer layer over the plastic substrate, which significantly influences the electrical performance and stability of oxide TFTs. Then oxide semiconductor TFTs fabricated through atomic layer deposition among the various oxide semiconductor fabrication methods were reviewed due to their potential as high-performance flexible TFTs. Finally, the mechanical fatigue behaviors of the TFTs were investigated, including the various mechanical factors, such as the bending radius, cycles, and stress directions. Structural solutions for the TFT were also introduced, such as TFT design modification and the use of the neutral plane concept, to improve the mechanical durability.

1. Introduction

Since recently, the flat panel display has been used in small- and mid-sized mobile devices like smartphones and PCs (personal computers). Large-size panels have also been demanded to have some specifications, like high resolution, light weight, low power consumption, durability, thinness, and a variety of designs. Specifically, due to the display market requirement, it has been predicted that the next-generation innovation could be the flexible and thin paper-like display, which can be folded or rolled from a large screen size to a small form factor [1]. Among the various display modes, the organic light-emitting diode (OLED) has been considered the superior choice for the flexible display due to its outstanding advantages, such as the fact that it has no cell gap problem, has lower power consumption, and has a good form factor for ultra-slimness. Besides, self-luminescent OLED displays are available for folding/rolling mechanics utilizing a flexible substrate [2]. Many studies have been conducted on semiconductor materials and processes that are suitable for flexible substrates. It has been a great challenge to come up with a low-temperature process and a flexible substrate. In the meantime, efforts should be made to ensure the maintenance of reliable device performances, such as mobility and on–off current modulation, contact resistance, and mechanical flexibility [3,4].

The TFTs that have mostly been demonstrated in the commercial display market for a few decades are amorphous silicon (a-Si) and polycrystalline silicon (poly-Si) TFTs [5,6], and numerous organic and inorganic materials have also been extensively explored [7,8]. The a-Si TFTs on a flexible substrate, however, are still limited because of their low mobility (\(<1\text{ cm}^2/\text{Vs}\)) and inferior bias stability [4,9–11]. The poly-Si TFTs have shown the problems of a high-process temperature (\(>450^\circ\text{C}\), dopant activation step) and an expensive crystallization process, eclipsing their outstanding advantages of high mobility (\(>80\text{ cm}^2/\text{Vs}\)) and excellent TFT stability [12,13]. As a result, oxide semiconductor TFTs have gained significant attention of late due to their great potentials, such as their reasonable mobility (\(>10\text{ cm}^2/\text{Vs}\)), low process temperature, and good transparency in the visible-light region [2].

Several issues still need to be addressed, however, before the flexible display based on oxide semiconductors can be realized, issues relating to the semiconductor material, deposition method, and buffer layer with low permeability [14]. Interestingly, since 2008, many researches have been reported to demonstrate flexible oxide semiconductor TFTs. Table 1 summarizes the existing flexible oxide semiconductor TFTs. The amorphous In-Ga-Zn-O (a-IGZO) TFTs have been most actively investigated, and relevant researches on In-Zn-O (IZO)
Table 1. Summary of oxide semiconductor flexible TFTs.

| Year | Substrate | Active layer | Method     | Mobility (cm²/Vs) | Strain/radius | Bending cycle | Ref. |
|------|-----------|--------------|------------|------------------|---------------|---------------|------|
| 2008 | Polyimide | a-IGZO       | sputter    | 10               | 5mm (tens./comp.) |               | [15] |
| 2009 | Polyimide | a-IGZO       | sputter    | 15.1             | 6.35%         | 100           | [16] |
| 2010 | PI        | ZnO          | solution   | 0.35             | 0.3% (tens./comp.) | 2500          | [17] |
| 2011 | Kapton E  | a-IGZO       | sputter    | 9.5              | 5mm           | 1000          | [18] |
| 2012 | PI        | a-IGZO       | sputter    | 14.5             | 3mm           | 2000          | [19] |
| 2012 | PI        | IZO          | solution   | 7.5              | 7mm           |               | [21] |
| 2014 | PI        | IGZO         | solution   | 5.1              | 10mm          | 320           | [22] |
| 2014 | PEN       | IGZO         | sputter    | 5.51             | 1.50%         | 100           | [23] |
| 2014 | PEN       | IGZO         | sputter    | 11.2             | 20mm          | 100,000       | [25] |
| 2014 | PI        | IGZO         | sputter    | 14.88            | 15mm          | 10,000        | [26] |
| 2015 | PEN       | IGZO         | sputter    | 15.5             | 3mm           | 10000         | [27] |
| 2015 | PEN       | IGZO         | sputter    | 15.5             | 3.3mm         | 10000         | [14] |
| 2016 | PI        | IZO          | ALD        | 42.1             | 2mm           | 5000          | [28] |
| 2016 | PI        | InOx         | ALD        | 9.7              | 5mm           | 10000         | [29] |
| 2016 | PET       | IZO          | sputter    | 40.1             | 7.5mm         | 5000          | [30] |
| 2016 | PI        | InOx         | ALD        | 15               | 5mm (0.4% tens.) | 10000         | [31] |
| 2016 | PI        | In2O3        | solution   | 7.12             | 1mm           | 5000          | [32] |
| 2016 | PI        | a-IGZO       | sputter    | 23               | 0.25mm        | 20000         | [33] |
| 2017 | PI        | a-IGZO       | sputter    | 76.8             | 1mm           | 5000          | [34] |
| 2017 | PI        | a-IGZO       | sputter    | 12.5             | 2mm           |               | [35] |

[36], Zn-Sn-O (ZTO) [37], and In-Sn-Zn-O (ITZO) [38], among others, have been conducted for improving their mobility and stability. Since 2008, most researchers have used polyimide (PI) or polyethylene naphthalate (PEN) polymers as flexible substrates. In terms of the highest stress conditions, a 0.25 mm bending strain or radius [33] and 100,000 repeated bending cycles were reported as the results of a test [39]. Based on the previous reports, although the sputter method is still an important method of depositing an oxide semiconductor layer, alternative deposition methods such as solution and atomic layer deposition (ALD) also show significant device performances (51 cm²/Vs [solution]) [22] and 42.1 cm²/Vs [ALD], respectively) [28].

Since very recently, the use of the ALD process as an alternative thin-film process for flexible device applications has considerably increased because it has accurate thickness control as well as excellent conformity and uniformity even on three-dimensional structures [40]. Moreover, the multi-component film growth, such as that of the binary/ternary semiconductor materials Al₂O₃/ZnO (AZO), ZnO/SnOₓ (ZTO), and In₂O₃/ZnO (IZO), can be reproducible and highly controllable even on large substrates, with the self-limiting reaction of ALD offering great benefits to many materials [41].

In this paper, an overview of the recent issues and advances with regard to the flexible oxide semiconductor TFTs will be given. In the first chapter, the buffer layer and structure on a flexible substrate will be discussed because it is the first consideration in flexible TFT fabrication. That is, the selection of the buffer structure and material plays a very important role in the device performances. In the second chapter, the emerging ALD process and material for active layer engineering will be discussed. The potentials of reliable and repeatable ALD methods for high-mobility and high-stability TFTs will be shown. In the third chapter, the degree of flexibility of flexible TFTs will be evaluated. Finally, in the last chapter, emerging applications like the flexible/stretchable display and sensor array for bio-healthcare will be discussed.

2. Issues regarding the flexible oxide semiconductor TFTs

2.1. Materials and structure of the buffer layer

The conventional buffer layer fabrication process on a glass substrate is losing attention due to the high water vapor transmission rate (WVTR) of carrier glass. Additionally, as organic-based flexible substrates have a poor WVTR [42–44], the buffer layer shows a very important role in TFT stable operation. Among the various insulating materials, silicon oxide (SiO₂), silicon nitride (SiNₓ), and aluminum oxide (Al₂O₃) are universally used for the flexible substrate buffer layer [16,26,45–47]. SiO₂ and SiNₓ are fabricated through the plasma-enhanced chemical vapor deposition (PECVD) process and are already being used for the a-Si and oxide TFT passivation layers, and SiNₓ is preferable in terms of the water encapsulation property because it has a higher WVTR than SiO₂. The PECVD process for SiNₓ, however, has an extremely high hydrogen (H₂) concentration (∼25%) [48,49] and hydrogen diffusion, which may degrade the TFT performance. As for Al₂O₃, it is usually fabricated through ALD and has a low H₂ concentration with a high WVTR compared...
to the silicon-based thin films [50,51], which are widely used for OLED encapsulation.

In this study, a-IGZO TFTs were fabricated on PI substrates with different buffer materials and stack structures [26]. Top-gate and bottom-contact a-IGZO TFTs were fabricated as shown in Figure 1(a). All the fabrication processes were the same, without buffer layers. The fabricated a-IGZO TFTs were SiNx 50 nm (device A), SiNx 50 nm/Al2O3 10 nm (device B), SiNx 50 nm/Al2O3 100 nm (device C), and SiO2 50 nm (device D). As shown in Figure 1(b), the transfer characteristics were very different, with different buffer materials and thicknesses. Device A exhibited very poor transfer performances (as shown in Table 2, saturation mobility = 3.31 cm²/Vs; threshold voltage = −23.93 V; and subthreshold voltage = 0.76 V/decade) compared to the other devices. It was supposed that the SiNx buffer layer had a higher H₂ concentration, which resulted in device characteristics degradation by the H₂ that penetrated when the TFT fabrication processes were proceeded with. In terms of the Al2O3 thickness, device B showed a higher subthreshold voltage (0.84 V/decade) compared to device C (0.24 V/decade). The increase in the subthreshold voltage after annealing revealed that effective hydrogen passivation did not occur because the Al₂O₃ thickness was not efficient for hydrogen passivation for device B. Additionally, the applied negative bias thermal stress (NBTS, V_G = −20 V; temperature = 60°C; and time = 3000 s) and the threshold and subthreshold voltage shifts are

| Buffer layer/annealing condition | Vth (V) | μsat (cm²/Vs) | SS (V/dec) | WVTR (g/cm²·day) |
|----------------------------------|--------|---------------|-----------|-----------------|
| A (pristine)                     | −23.93 | 3.31          | 0.76      | 0.82            |
| A (250°C)                        | N.D    | N.D           | N.D       | N.D             |
| B (pristine)                     | −0.69  | 13.07         | 0.55      | 0.51            |
| B (250°C)                        | −0.87  | 11.75         | 0.84      | N.D             |
| C (pristine)                     | −0.72  | 14.20         | 0.31      | 0.033           |
| C (250°C)                        | −1.25  | 14.43         | 0.24      | N.D             |
| D (pristine)                     | −0.35  | 14.50         | 0.26      | 1.33            |
| D (250°C)                        | −2.19  | 14.88         | 0.22      | N.D             |

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Figure 1. a-IGZO TFT fabricated on a PI substrate with different buffer materials and stack structures: (a) schematic diagram of a top-gate/bottom-contact a-IGZO TFT; (b) transfer performance of TFTs; (c) threshold and subthreshold voltage shift under NBTS; (d) device DOS of the near-conduction bands with different buffer materials structures (ref. [26]).
shown in Figure 1(c). It was found that device B was seriously degraded compared to device C, due to the defect states in the a-IGZO layer and/or the interface between the a-IGZO and the gate insulator caused by H₂ [52]. On the other hand, in spite of the low WVTR of SiO₂, which resulted in ineffective water vapor passivation, the intermediate variation of the threshold and subthreshold voltages of device D can be attributed to the lower H₂ concentration of the SiO₂ buffer layer compared to the SiNx buffer layer. Nevertheless, the device density of states (DOS) of the near-conduction band (shown in Figure 1(d)) was highest for device B due to the H₂ diffusion effects, and that of device C was lower than those of the other devices that effectively passivated the H₂O and H₂ molecules.

2.2. Fabrication process of the buffer layer

As discussed in the foregoing, ALD Al₂O₃ showed a high WVTR and H₂ passivation compared to the Si-based materials. The fabrication process, however, critically affected the WVTR and H₂ passivation [53]. The TFT transfer characteristics under different buffer fabrication processes (utilizing water and ozone as reactants) are shown in Figure 2(a,b). The TFT performances (as shown in Table 3) of the ozone process showed lower field effect mobility and a higher subthreshold voltage than the water process due to the poor quality of the Al₂O₃ buffer layer. The NBTS (V₆₀ = −20 V; temperature = 60°C; and time = 3000 s) was measured under ambient air (relative humidity, RH = 30%) and ambient vacuum (∼10 mtorr), and the results are shown in Figure 2(c). Ambient vacuum is available for reducing the external ambient environment effects, such as the O₂, H₂O, and H₂ molecules. The NBTS characteristics fabricated by Al₂O₃ (H₂O) showed more stable transfer curves than Al₂O₃ (ozone) under ambient vacuum, and serious device degradation was exhibited under the ambient air, which reveals that the TFTs fabricated on Al₂O₃ (ozone) were easily exposed to the ambient molecules, resulting in transfer characteristics degradation under bias and temperature stress.

Table 3. Key device parameters of flexible a-IGZO TFTs with the average and standard deviation values of five TFTs given (ref. [53]).

| Buffer          | Vth (V) | µsat (cm²/Vs) | SS (V/dec) | ION/IOFF ratio |
|-----------------|---------|---------------|------------|----------------|
| Al₂O₃ (H₂O)    | 0.56 ± 0.08 | 7.15 ± 0.79   | 0.23 ± 0.02 | 1.16 × 10⁹     |
| Al₂O₃ (ozone)  | −0.34 ± 1.26 | 4.73 ± 0.18   | 0.40 ± 0.05 | 2.53 × 10⁸     |

Figure 2. TFT transfer characteristics under different buffer fabrication processes: (a) using water as a reactant; (b) using ozone as a reactant; (c) under NBTS (V₆₀ = −20 V; temperature = 60°C; and time = 3000 s) in ambient air (relative humidity, RH = 30%) and ambient vacuum (∼10 mtorr); (d) X-ray reflectivity analysis for the film density and surface roughness; and (e) device DOS of the near-conduction band for the TFTs with different reactants and measured in RH = 30% and ambient vacuum (ref. [53]).
To determine the reason for the different TFTs’ degradation, X-ray reflectivity analysis of two different buffer layers was carried out to determine the film density and surface roughness (shown in Figure 2(d)). Al₂O₃ (H₂O) showed a higher film density (3.14 g/cm³) and a smoother surface (0.49 nm) than Al₂O₃ (ozone) (2.97 g/cm³ and 1.04 nm, respectively). The low film density of Al₂O₃ (ozone) resulted in its easier penetration by the ambient molecules, and the rough surface contributed to the poor transfer performance as the rough interfaces acted as charge trap sites. As regards the DOS of the two different TFTs, as shown in Figure 2(b), Al₂O₃ (ozone) contained a higher density state than Al₂O₃ (H₂O), and the DOS extracted under the ambient vacuum showed a lower value compared to the ambient air. Thus, the effective passivation or elimination of the external ambient factors plays an essential role in reducing the defect state and in ensuring the stability of the TFT operation.

3. High-Performance TFT

3.1. ALD oxide semiconductors as active layers

To realize flexible TFTs, the devices are required to be fabricated on plastic substrates such as PEN, polyethylene terephthalate (PET), or PI [54]. For the sputter-based oxide TFTs, however, such as IGZO, process temperatures above 300°C are necessary to realize sufficiently reliable oxide TFTs with better performances, but these can degrade the TFT performance results in terms of the coefficient of thermal expansion and temperature capability [55]. Some groups reported a-IGZO TFTs’ field effect mobility based on the sputtering process, such as 7 cm²/Vs by Ok et al. [53], 10 cm²/Vs by Jeong et al. [35], and 7 cm²/Vs by Bak et al. [56], which is not sufficient for the high-resolution active-matrix organic light-emitting diode (AMOLED) display.

ALD is a technique based on self-limiting deposition realized by exposing the substrate to two or more separated gaseous reactant pulses. The general growth process of ALD is shown in Figure 3(a), where there are sequential alternating pulses of gaseous chemical precursors that react with the substrate, which were called ‘half-reactions’. During each half-reaction, the precursor that was pulsed into the chamber within a certain time fully reacts with the substrate surface. Then there will be no more than one monolayer at the reaction surface due to the self-limiting process. Subsequently, inert carrier gas is purged into the chamber to remove the reaction by-products. The process of cycling half-reactions by pulse and purge then forms layers of the desired material [59].

Based on the growth mechanism of ALD, considering the growth of high-quality inorganic films at temperatures that can be withstood by plastic substrates, ALD is at present the most appropriate deposition method.

A number of reports about oxide TFTs based on ALD were recently published, which showed the comparable performance of such TFTs to those fabricated using the sputter or solution methods, such as the 20 cm²/Vs-ZnO

Figure 3. (a) ALD growth mechanism; (b) homogeneous laminated active layer; (c) bilayer; and (d) gradient active layer by ALD for oxide semiconductor TFTs (refs. [28,57,58]).
TFT by Lin et al. [60], the 13.4 cm²/Vs-ZnHfO TFT by Nayak et al. [61], the 6 cm²/Vs-AZO TFT by Chung et al. [62], etc. [57,58,63]. To improve the performance of the TFT, some groups came up with post-annealed TFTs like a 21.3 cm²/Vs TFT fabricated via O₂ annealing at 400°C by Geng et al. [64], a 30.2 cm²/Vs TFT fabricated via O₂ annealing at 350°C by Ahn et al. [65], etc. [66,67]. Such high process temperature does not meet the low process temperature requirement for the flexible TFT, which may play an essential role in the next-generation display.

### 3.2. Optimization of the active layer structure

Based on the advancement of ALD, active layer structure promotion was reported by some groups. The homogeneous laminated active layer is the most widely researched on, where the concept of ‘supercycle’ was introduced. Each supercycle consists of several subcycles for each element; for example, the IZO active layer is deposited with IZO supercycles containing one ZnO cycle and one In₂O₃ cycle [28] (shown in Figure 3(b)). Thus, the composition of the deposited thin film can be effectively adjusted based on the number of subcycles, which contributes to the mobility optimization. On the other hand, the ALD process is a more appropriate approach for fabricating bilayer-channel structures that include a very thin front channel layer, commonly thinner than 5 nm, compared to the structures fabricated via sputtering. The bilayer-channel structure has superior TFT mobility and stability compared to the monolayer-channel structure due to the possibility of a high charge trap density and high carrier concentrations for both the front and back channels [68,69]. Figure 3(c) shows ZnO-based bilayer-channel TFTs consisting of ZnO and AZO layers with different Al compositions and stacking sequences. The use of AZO thin layers as front channels reduced the charge trap density at the gate dielectric/channel interface and the backchannel effect on the channel surface, resulting in more stable TFTs under gate bias stress. In addition, by controlling the composition of Al, the crystallization, which can affect the mobility and stability, was adjusted through the ALD process [58]. A similar approach for the TFT performance by ALD was reported, as shown in Figure 3(d), where step-composition gradient channels in oxide-based TFTs were deposited, and their effects on the performances and electrical stability of the TFT devices were investigated [57]. By utilizing ALD, the Al step-composition gradient channel was deposited, which led to the alignment of the conduction band offset within the channel layers for higher mobility and stability.

### 3.3. Optimization of the device performances

The previous researches on the ALD-processed flexible TFT revealed its potential for application to the flexible display technology. Figure 4(a) shows the bottom-gate/top-contact TFTs based on IZO channels fabricated on a PI substrate through ALD at different growth temperatures. With regard to the effect and growth temperature mechanism of the IZO channel layer, it was found that the IZO channel layer growth increased until 200°C, and exhibited better transfer performance (saturation mobility = 42.3 cm²/Vs; threshold voltage = 0.7 V; subthreshold voltage = 0.29 V/decade; and hysteresis = 0.21 V) compared to that at 150 and

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**Figure 4.** High-performance ALD-processed flexible oxide TFT with an active layer as (a) IZO researched on in terms of its growth temperature dependence (ref. [28]; copyright 2016, American Chemical Society); (b) ZnO TFT with various passivation layers (ref. [60]; copyright 2015, American Chemical Society); and (c) InO with N₂O plasma post-treatment (ref. [29]; copyright 2016, American Chemical Society).
175°C due to the highest carrier concentration with increased oxygen vacancy [28]. The effect of the ALD growth passivation layer on the ALD-processed flexible TFT, as shown in Figure 4(b), was also reported [60]. The defect formation mechanism that occurred during the ALD-passivation process on the ALD-processed ZnO channel was investigated, and the ALD-passivation-induced defects were resolved by minimizing the oxygen extraction tendency of the metal–organic precursor of the ALD-passivation process, resulting in plastics-based ZnO TFTs with excellent device characteristics and stability (field effect mobility > 20 cm²/Vs, with nearly intact characteristics after bias stressing for 10,800 s). The ALD-processed flexible TFT was also available for post-treatment, as shown in Figure 4(c) [29]. The performance of the ALD In₂O₃ TFT was affected by the N₂O plasma treatment time. When the N₂O plasma treatment time was increased from 600 to 2400 s, the In₂O₃ positive shift and the mobility decreased, which can be explained by the oxidation at the surface of the active layer. The plasma treatment at the In₂O₃ channel induced oxygen deficiency decrease, and the carrier concentration dropped as the N₂O plasma treatment time increased.

4. Mechanical evaluation for flexible TFTs

4.1. Mechanical test platform for flexible TFTs

The bending test systems reported in the previous papers can be roughly classified into two types according to the bending methods used. The type where the flexible substrate is wrapped around a rigid jig [70] is shown in Figure 5(a), where both tensile and compressive stresses with a controllable radius can be realized by changing the shape of the rigid jig. The electrical measurements are processed using probe tips [71] (shown in Figure 5(b)), which is found at the contact point between the flexible devices, and where the probe tips are worse than those in the compressive-stress jig.

When performing the repetitive bending test for flexible TFTs, the bending machine is required for cycling and radius adjustment. Various types of bending machines based on different bending concepts are shown in Figure 5(c). The machine in the first image [18] contains a movable plate for adjusting the radius of the carrier substrate covered by flexible devices, while the machines in the second and third images are named ‘sliding machine’. The test concept of the first sliding machine is cycling the flexible devices by pulling the carrier substrate repeatedly around the jigs, or radius adjustment. As for the second sliding machine, its design concept is based on the two pieces of moving slide glasses maintaining a certain distance that is equal to the radius of sliding.

4.2. Degradation of the device performances under mechanical stresses

Considering the effects of the mechanical stress is important for flexible devices, which are sensitive to mechanical stress due to their dimensional shape transformation. A number of papers have presented the TFT characteristics under mechanical stress [26, 29, 33, 35, 39, 61, 64, 72–78], and they reported that when a critical strain or bending cycles were applied to TFTs, their performances were degraded [29, 35, 39, 64, 75, 77, 78].

Figure 5. Measurement platform for bending characteristics of flexible TFTs: (a) bending test with a rigid jig (© 2017, Elsevier B.V); (b) measurement with bended substrates (© 2017, Elsevier B.V); and (c) various forms of banding machines.
In this study, a-IGZO TFTs were fabricated on flexible PI substrates to investigate the effect of the strain on the flexible IGZO TFTs, as shown in Figure 6(a) [35]. As the radius of the jig was decreased, the strain of the TFTs increased (from 0.19% to 0.93%). Figure 6(b) and Table 4 show the transfer curves and parameter changes under different strains, where the field effect mobility and subthreshold voltage were degraded when the strain was increased from 0.19% to 0.93%. The contact resistance of the two transistors was increased from 19.0 to 29.6 Ω cm, which affected the TFT performance. The NBTS with mechanical stress under a different strain and ambient environment is shown in Figure 6(c). It was found that the threshold voltage exhibited serious degradation (–6.49 V for the ambient air and –0.97 V for the ambient vacuum, with strain = 0.93%) under a large strain, which was supposed to be attributed to the effect of the formation of a micro-crack in the buffer and/or gate insulator thin films that are easily penetrated by the external molecules. The difference in the threshold voltage shifts in a different ambient environment was explained by the smaller amounts of oxygen and/or water molecules that exist in the ambient vacuum and that penetrate the TFTs compared to the ambient air.

In terms of the effect of the bending cycles and bending direction on the flexible transistor performance, the In$_2$O$_3$ TFTs for a bending axis along the channel width (for case I), and the channel length (for case II), are shown in Figure 7 (Figure 7(a) as schematics) [29]. In both cases, a fixed bending radius ($r = 5$ mm) was applied, and the transfer characteristics were recorded after 100, 300, 700, 1500, 3000, and 10,000 bending cycles (as shown in Figure 7(b,c)). For case 1, where the electrical current flow and bending axis were perpendicular, despite the transfer curve’s drastic shift after 3000 bending cycles, the subthreshold voltage shift was minor. In contrast, for case 2, where the electrical current flow and bending axis were parallel, the transfer curves showed a large shift after 700 bending cycles, which was faster than that in case 1. This phenomenon is attributed to the fact that when mechanical stress is applied, the source/drain electrode and active layer interface may act as the stress concentration points, and these points may create charge trapping and/or defects, which may degrade the TFT performance. Figure 7(d) shows the a-IGZO TFT parameters’ shift for different types of stress (tensile/compressive) on the 50 μm PI substrate [77]. For the tensile stress, as the bending radius decreased, the threshold voltage negative shift and saturation mobility decreased. On the other hand, for the compressive stress, the variation tendencies of the TFT parameters were opposite. These phenomena

### Table 4. Transfer characteristics and parameters of flexible IGZO TFTs under different strains (0.19%, 0.38%, and 0.93%) (ref. [56]).

| $\epsilon$  | $V_{th}$ (V) | $\mu_{sat}$ (cm$^2$/Vs) | $SS$ (V/decade) |
|------------|-------------|----------------|-----------------|
| 0.19%      | 0.27 ± (0.09) | 12.35 ± (0.35) | 0.258 ± (0.01) |
| 0.38%      | 0.64 ± (0.47) | 11.3 ± (0.49)  | 0.29 ± (0.02)  |
| 0.93%      | 1.49 ± (0.84) | 9.91 ± (0.51)  | 0.33 ± (0.04)  |
Figure 7. (a) Schematics of bent In$_2$O$_3$ TFTs for a bending axis along the channel width (for case I) and the channel length (for case II); transfer characteristics of In$_2$O$_3$ TFTs under repeated bending cycles, to which a 5 mm bending radius was applied along the (b) channel width and (c) channel length; (d) a-IGZO TFT parameters’ shift for different types of stress (tensile/compressive) on a 50 μm PI substrate (ref. [29]; copyright 2016, American Chemical Society).

Figure 8. Cross-section of a flexible TFT and an applied neutral plane (ref. [76]).
reveal that energy level splitting in the internal semiconductor materials induced a change in the atomic bonding distance [79] and resulted in TFT parameter changes by changing the fermi-level energy level.

4.3. Optimization of the TFT structure for the reduction of the mechanical stress by the neutral layer

In the previous chapter, it was shown that mechanical stress can significantly degrade the TFT performance and can be a major obstacle to adopting mass production. To reduce the mechanical stress effects, two main approaches are available.

First, applying an additional layer (neutral layer) on top of the flexible devices [33, 76, 80, 81] was reported by several researches. Figure 8(a) shows the cross-section of a flexible TFT with a neutral plane applied. Strain ($\varepsilon$) is applied with the following equation:

$$
\varepsilon = \frac{\Delta L}{L} = \frac{(r + d/2)\theta - r\theta}{r\theta} = \frac{d}{2r},
$$

where $r$ is the bending radius, $d$ is the film thickness, and $\theta$ is the bending angle.

A neutral plane is usually formed in the middle of films without any additional layer ($r\theta = L$). In this approach, a neutral plane is deposited at the top of the TFT device. The TFT transfer parameters after the bending cycles with a neutral plane exhibited little difference from the initial ones. In addition, an AMOLED panel was bended up to 10,000 cycles at $R = 5$ mm, without any panel image degradation, defect, dark spot, or bright spot [76], which means that the neutral layer successfully played a stress release role in the mechanical transformation.

Second, with regard to the optimization of the TFT structure through mechanical stress reduction [64], the conventional materials used for the TFT components are vulnerable to strain, and most of them are non-organic materials. In this study, however, the TFTs with an optimized structure [82] (as shown in Figure 9(a)) showed stable performance under strain compared to those with a non-optimized structure (as shown in Figure 9(b)).

Figure 9. Initial (without bending) transfer characteristics and those after 1000 bending cycles for the (a) non-structure-optimized TFTs and (b) structure-optimized TFTs. Optical image of the TFT after repeated (1000 times) 90-degree bending for the (c) non-structure-optimized TFTs and (d) structure-optimized TFTs by reducing the metal (reprinted with permission from IEEE Publishers Ltd.: [AM-FPD] [82]; copyright 2015).
Without structure optimization, the transfer curve was not operated due to the crack formation in the TFT active layer, as shown in Figure 9(c). The reduction of the gate electrode area, however, decreased the number of cracks formed in the TFT (Figure 9(d)).

5. Current development of the oxide TFT: flexible and stretchable display and sensor arrays for health care

To realize a design-free, body-embedded display, the biomedical health flexible display, stretchable display, and sensor array are actively being analyzed and researched on. In addition, oxide semiconductors are candidate materials because of their superior electrical performance for adopting high-end applications. In this chapter, a practical oxide semiconductor research case for a flexible and stretchable display and a sensor array for health care are introduced.

Flexible and stretchable displays are the next-generation bendable and foldable displays and are the final forms of the future display. Researches on flexible and stretchable displays are based on a unit device and investigate the degradation mechanism, lowering the temperature and developing a robust device under a higher strain. Some companies have produced prototypes of the flexible display and have exhibited these in conferences. For example, a 7.8-inch prototype AMOLED display was exhibited by AU Optronics Corporation [83]. A prototype of the stretchable display was also exhibited, using a pre-stretched substrate [84]. The electrical performance of stretchable oxide TFTs were not changed under ∼12% strain, but the transfer characteristics of oxide TFTs were not implemented over 30% strain.

The biosensors on the flexible array are also important because they make real-time monitoring possible by adopting the human body. Various types of biosensor have been investigated [85], and the active-matrix-based sensor array is the key technology for transforming various types of signals into electrical signals, and for analyzing signals. For example, Figure 10 shows a glucose-biosensor embedded on IGZO TFTs, whose transfer characteristics were changed by changing concentration of glucose.

6. Summary

In this paper, the results of a current study on flexible oxide TFTs for the next-generation flexible display are reported. The buffer layer deposited on the flexible substrate showed a necessity for planarization and lower water permeability. The performance of the TFT that was stacked over the buffer layer was influenced by the material of the buffer layer, and the previous research also showed that hydrogen diffusion may be the main reason for the changes in the device characteristics and stability. Considering the process temperature and performance, oxide TFTs with channel layers processed via ALD are more attractive than sputter-based oxide TFTs as they have high mobility and can thus drive high-resolution flexible displays. Mechanical stress degrades the performance of oxide TFTs, which can be explained by the micro-crack generation. Additionally, TFTs may contain a stress concentration point under the bending stress that creates charge trapping states and defects. To reduce the degradation of TFTs, structural optimization was proposed in this study, such as dimensional shape modification and utilization of a neutral plane.

Disclosure statement

No potential conflict of interest was reported by the authors.

Figure 10. (a) Schematic illustration of experimental apparatus for IGZO-FET sensor under electrochemical test. (b) Transfer characteristics of GOx/IGZO TFTs with different glucose concentration (© 2016, American Chemical Society).
Funding

This research was supported by [grant numbers 10051403, 10052020, and 10052027] from MOTIE (Ministry of Trade Industry and Energy Korea) and KDRC (Korea Display Research Corporation).

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