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PAPER

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High performance of solution-processed SnO₂ thin-film transistors by promotion of photo-exposure time-dependent carrier transport during the pre-annealing stage

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Abstract

We fabricate high-performance solution-processed SnO₂ thin-film transistors (TFTs) exhibiting improved carrier transport features by exposing the ultraviolet/ozone (UV/O₃) on the SnO₂ film during the pre-annealing stage. The SnO₂ layer is treated with different UV/O₃-exposure times from 0 to 60 minutes before the post-annealing step. As UV/O₃-exposure time increases from 0 to 30 minutes, the M-O-M (M, metal; and O, oxygen) network, mass density, and oxygen vacancies of films are enhanced. In contrast, the M-O-M network and mass density decrease, while the oxygen vacancies rather increase when the UV/O₃-exposure time reaches 60 minutes beyond 30 minutes. The SnO₂ (Sn⁴⁺) phase, thickness, and surface morphology of SnO₂ films are not considerably changed regardless of UV/O₃-exposure time. When the UV/O₃-exposure time is 30 minutes, devices demonstrate superior field-effect mobility (10.1 cm² V⁻¹ s⁻¹) at approximately two times higher than the TFT without UV/O₃-exposure. Furthermore, the SnO₂ TFT with UV/O₃-exposure time for 30 minutes shows improved subthreshold-swing characteristics and a high on/off current ratio. These devices are adequate for use in high-resolution active-matrix LCDs or OLED displays that demand a high field-effect mobility (>10 cm² V⁻¹ s⁻¹) and on/off ratio (>10⁶).

Keywords: SnO₂, photo-exposure time, solution-process, thin-film transistor, high-performance

(Some figures may appear in colour only in the online journal)

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1. Introduction

Metal oxide semiconductor-based thin-film transistors (TFTs) have become important as fundamental devices for next-generation displays because they exhibit not only outstanding electron mobility but also high transparency in the visible light regime compared with conventional silicon (Si)-based TFTs [1–4]. Among the different metal oxides, binary oxide semiconductors including indium(III) oxide (In_2O_3), zinc oxide (ZnO), and tin(IV) oxide (SnO_2) show higher electrical conductivity than the other insulating ionic compounds [5–7]. Many investigators have recently turned to Sn-based oxide TFT because indium (In) is toxic, a rare earth element, and costly [8, 9]. Furthermore, the SnO_2 semiconductor has many advantages such as a wide optical band gap, crystallization at relatively low temperatures, and remarkable charge transport properties via heavy-metal cations with $(n-1)d^{10}ns^0$ ($n \geq 5$) electronic configurations, leading to the impressive electrical performance of SnO_2 TFTs [10–12]. On the other hand, oxide semiconducting materials can be formed into thin-film by both a vacuum process and a solution process [13–16]. From the viewpoint of vacuum-free deposition, the solution process is cost-effective, simple, and applicable to spin-coating, inkjet printing, and meniscus-guided coating, suitable for large-scale production [17–20]. The solution-process inevitably requires a pre-annealing step to evaporate residual solvent on coated films before post-annealing with a relatively high-temperature to develop the active layer [21, 22]. The pre-annealing temperature leads to an endothermic reaction related to the precursor dissociation and subsequent hydrolysis reaction that generates M-OH bonding (M, metal; O, oxygen; and H, hydrogen) which could be converted to M-O-M network bonding through dehydration and alloying reactions during the post-annealing step [21–23]. In this regard, researching pre-annealing treatment is important for improving the electrical performance of oxide TFTs. However, many studies have focused on post-annealing treatments such as high-pressure annealing, ambient gas control, and water vapor annealing [24–26].

In this study, we fabricated high-performance TFTs by controlling ultraviolet/ozone (UV/ O_3)-exposure time on solution-processed SnO_2 films during the pre-annealing stage. The change of molecular structure, crystallinity, and morphological characteristics of solution-processed SnO_2 thin-films with different UV/ O_3 -exposure times from 0 to 60 minutes was systematically investigated. We observed the enhanced physical- and chemical characteristics of SnO_2 films that show increased mass density, M-O-M network, and oxygen vacancies when the UV/ O_3 -exposure time is 30 minutes. In contrast, mass density and M-O-M network decreased, while the oxygen vacancies rather excessively increased when UV/ O_3 -exposure time reached 60 minutes beyond 30 minutes. The crystalline size, thickness, and surface roughness of SnO_2 films were similar regardless of UV/ O_3 treatment. The SnO_2 TFT with UV/ O_3 treated for 30 minutes demonstrated superior electrical properties with the highest field-effect mobility of $10.1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and on/off current ratio of 1.2×10^6 ,

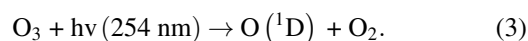
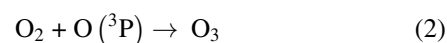
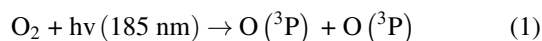
adequate for use in high-resolution active-matrix LCDs or OLED displays [27].

2. Methods

2.1. Fabrication process

A schematic for the fabrication process of a coplanar bottom-gate SnO_2 TFT with UV/ O_3 treatment is depicted in figure 1. A heavily boron-doped p-type Si wafer and thermally grown 100 nm SiO_2 were used as the gate electrode and gate insulator, respectively. For the bottom contact structure, 50 nm thick Au electrodes were deposited on SiO_2 using e-beam evaporation and then patterned by the lift-off method to design an active channel layer with a length of 1 000 μm and width of 100 μm . The Si/ SiO_2 substrate was cleaned by UV/ O_3 for 60 minutes before spin-coating. The solution for the SnO_2 active materials was prepared by dissolving 0.025 M of tin(II) chloride dihydrate ($\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$) in ethanol. The prepared solution was spin-coated at 3000 rpm for 50 s onto a Si/ SiO_2 substrate followed by pre-annealing at 150 °C for 10 minutes to evaporate the residual solvent. In a previous study, SnO_2 films coated with ethanol-based chloride precursor solution dried at 150 °C demonstrated suitable environmental stability with high densification [28].

UV irradiation (25 mW cm^{-2}) was conducted with a low-pressure mercury lamp with two types of light sources (Jaesung engineering, UVC-30). One had a wavelength of 184.9 nm and an energy of 647 kJ mol^{-1} , and the other had a wavelength of 253.7 nm and an energy of 472 kJ mol^{-1} . These two light source energies are larger than the bonding energy of the contaminant organic and hydrogen compounds such as C-C (348 kJ mol^{-1}), C-O (352 kJ mol^{-1}), C-H (413 kJ mol^{-1}), and O-H (463 kJ mol^{-1}). Moreover, these light sources continuously produce O_3 and oxygen free radicals ($\text{O}(^3\text{P})$ and $\text{O}(^1\text{D})$) through the following reactions [29, 30]:



As presented in Equations (1) and (3), Ozone (O_3) and excited singlet atomic oxygen ($\text{O}(^1\text{D})$) are strong oxidants and easily eliminate organic contaminants as volatile byproduct molecules such as CO_2 , H_2O , and O_2 [29]. The UV/ O_3 -exposure time was adjusted at 0, 15, 30, 45, and 60 minutes to explore the effect of UV/ O_3 -exposure on SnO_2 film and obtain the high electrical performance of a SnO_2 TFT. After the pre-annealing stage with UV/ O_3 -exposure, post-annealing was performed at 450 °C for 1 h in a tube furnace with ambient air to remove organic residues, activate metal oxide film, and assist crystallization of SnO_2 . The coated films were mechanically eliminated in advance before measurement of the electrical performance in the SnO_2 TFT for complete

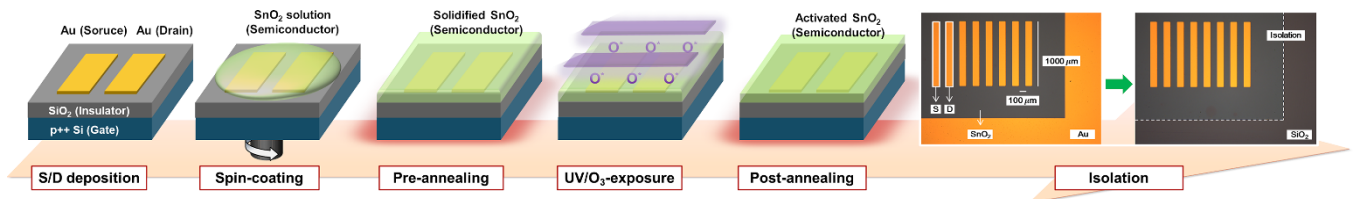


Figure 1. A schematic for the fabrication process of the coplanar-bottom gate UV/O₃-exposed SnO₂ TFT.

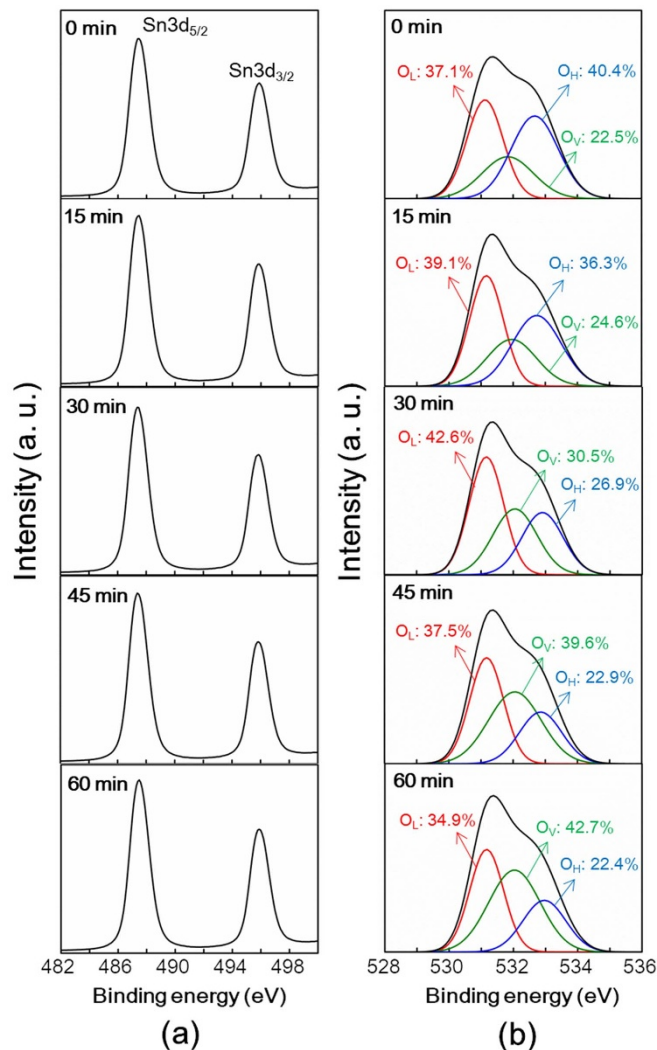


Figure 2. XPS spectra of (a) Sn 3d and (b) O 1s state of SnO₂ films with different UV/O₃-exposure times.

isolation to minimize gate leakage current and fringing effect. The optical images before and after the isolation of the device are shown in figure 1.

2.2. Analysis method

x-ray photoelectron spectroscopy (XPS) (ThermoFisher Scientific, NEXSA) was conducted using a monochromatic Cu K α (1.5418 Å) light source to observe the surface electronic states and chemical compositions of SnO₂ films. The mass density and thickness of the films were investigated with x-ray reflectivity (XRR) (Panalytical, Empyrean) analysis and

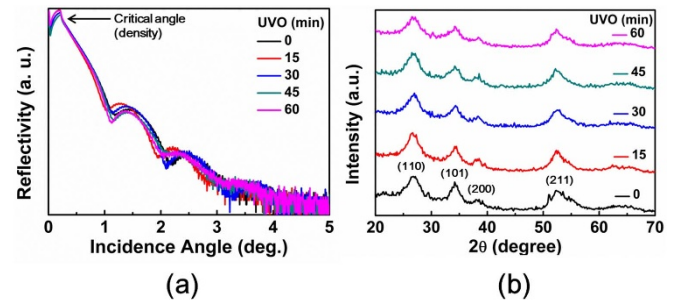


Figure 3. (a) XRR spectra and (b) GIXD patterns of SnO₂ films with different UV/O₃-exposure times.

simulation using commercial software (X'Pert Reflectivity). The crystallization behavior of SnO₂ films was examined using grazing incidence x-ray diffraction (GIXD) (Panalytical, Empyrean). The surface morphology of the films was obtained through atomic force microscopy (AFM) (NX20, Pary Systems) in non-contact mode. The electrical properties of the SnO₂ TFTs were measured using a source measure unit (Keithley 2636B, Tektronix) and a probe station (MSTECH, MST 4000A) under atmospheric pressure in a dark space.

3. Results and discussions

Figures 2(a) and (b) present the XPS spectra of Sn 3d and O 1s peaks of SnO₂ films with different UV/O₃-exposure times. Based on the Sn 3d core level in figure 2(a), the peak positions of Sn3d_{5/2} and Sn3d_{3/2} for all films occurred at 487.4 and 495.8 eV, consistent with the typical SnO₂ (Sn⁴⁺) phase [31, 32]. There was no shift in the binding energy of Sn peaks irrespective of UV/O₃-exposure time, indicating that UV/O₃-exposure on SnO₂ films during the pre-annealing stage did not affect the phase transition between SnO₂ and SnO. The O 1s state is divided into three peaks associated with lattice oxygen (O_L, denoting the M-O-M network for the electron path), oxygen-vacancies (O_V, denoting free carrier concentration), and hydroxyl groups (O_H, denoting the electron trap site) at 531.1, 532.0, and 532.8 eV, using Gaussian fitting as depicted in figure 2(b) [33]. As the UV/O₃-exposure time increase, the O_H ratio decreased and the O_V ratio increased because UV irradiation and the oxidation by both O₃ and oxygen-free radicals contribute to decompose the residual hydrogen compounds and then removed as volatile products. When the UV/O₃-exposure time was 30 minutes, the O_L ratio was highest because of improved the M-O-M network formations and reorganization through reduced carbon-based

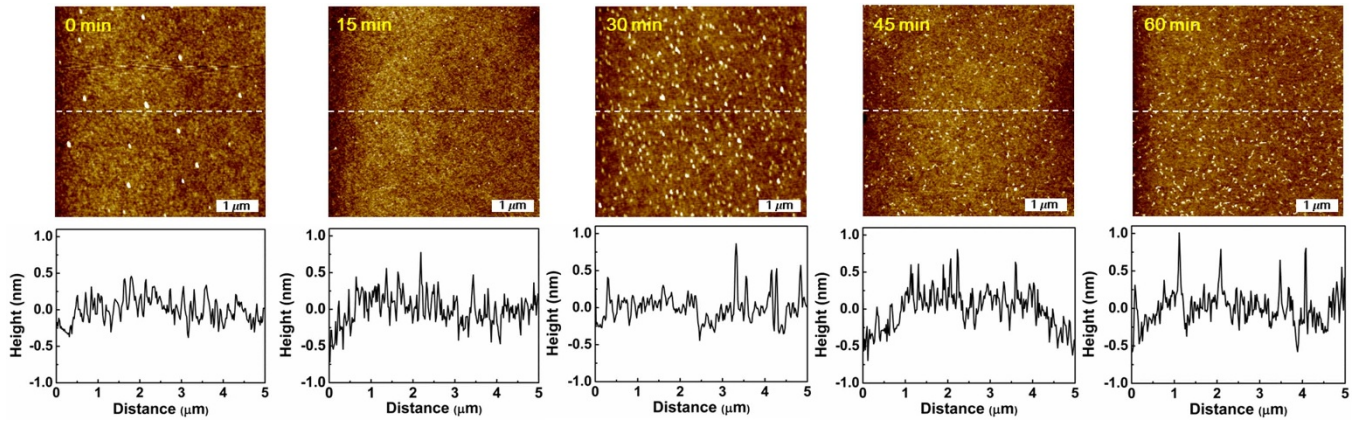


Figure 4. AFM images ($5 \times 5 \mu\text{m}$) and corresponding cross-sectional height profiles of SnO_2 films with different UV/O_3 -exposure times.

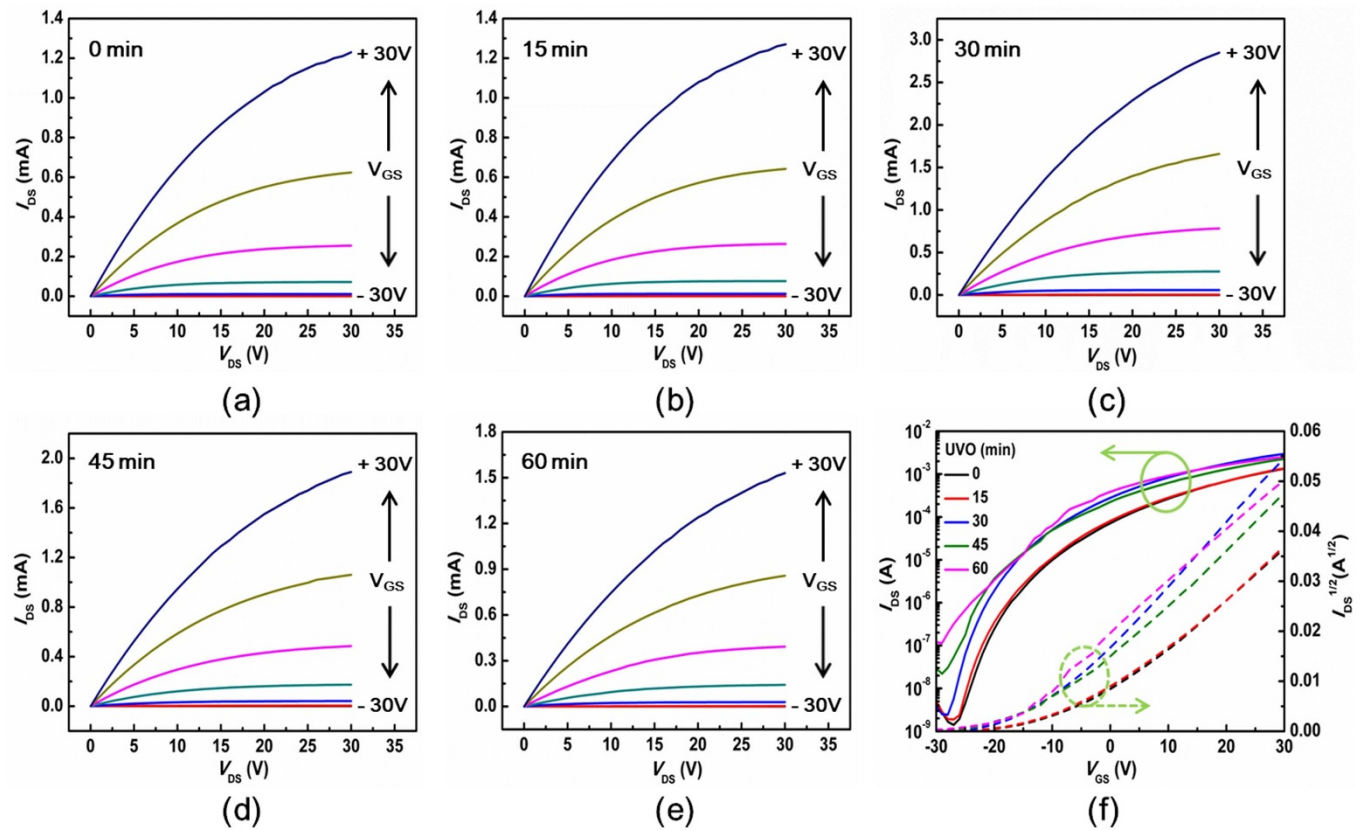


Figure 5. (a)–(e) Output and (f) transfer characteristics of SnO_2 TFTs with different UV/O_3 -exposure times.

content [16]. However, the O_L ratio was reduced by eliminating too many hydrogen compounds which could be involved in formation of the M-O-M network via condensation reactions when the UV/O_3 -exposure time exceeded 30 minutes. Figure 3(a) illustrates the XRR curves of SnO_2 films with different UV/O_3 -exposure times and arrow means the point where the critical angle was determined using X'Pert Reflectivity software. Accordingly, we extracted the critical angle to calculate the mass density of SnO_2 thin-films using following equation:

Table 1. The critical angle, mass density and RMS roughness of the SnO_2 films with different UV/O_3 -exposure times.

UV/O_3 -exposure time (min)	Critical angle (deg)	Mass density (g cm^{-3})	RMS roughness (nm)
0	0.2417	3.17	0.20
15	0.2420	3.18	0.21
30	0.2613	3.71	0.24
45	0.2680	3.90	0.26
60	0.2424	3.19	0.32

Table 2. The electrical properties of the SnO₂ TFTs and their standard deviations with different UV/O₃-exposure times.

UV/O ₃ -exposure time (min)	Field-effect mobility (cm ² V ⁻¹ s ⁻¹)		On/off ratio		Subthreshold swing (V/decade)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
0	5.95	0.43	8.3 × 10 ⁵	1.2 × 10 ⁵	2.53	0.20
15	6.31	0.59	9.4 × 10 ⁵	2.3 × 10 ⁵	2.13	0.21
30	9.81	0.57	1.1 × 10 ⁶	2.2 × 10 ⁵	1.98	0.24
45	6.92	0.64	1.4 × 10 ⁵	3.5 × 10 ⁴	3.55	0.29
60	5.46	0.84	4.7 × 10 ⁴	1.3 × 10 ⁴	3.73	0.45

Table 3. Performance comparison of the various solution-processed SnO₂ TFTs.

Ref.	Gate insulator	Capacitance per unit area (nF cm ⁻²)	Annealing conditions	Channel length/width (μm)	μ _{sat} (cm ² V ⁻¹ s ⁻¹)	On/off I _{DS} ratio
This work	SiO ₂	34.5	450 °C for 1 h	100/1000	10.1	10 ⁶
[38]	SiO ₂	11.5	450 for 4 h	100/600	0.37	10 ⁶
[39]	SiO ₂	11.5	450 for 4 h	100/600	0.19	10 ³
[12]	SiO ₂	31.4	500 for 1 h	5/110	0.23	10 ⁶
[40]	SiO ₂	34.5	600 for 4 h	100/1000	10.87	10 ⁷
[41]	Al ₂ O ₃	225	450 for 30 min	60/1400	96.4	10 ⁶

$$\theta_c = \lambda \sqrt{\rho_e r_e / \pi} \quad (4)$$

$$\rho_m = \frac{\rho_e A}{N_A Z} \quad (5)$$

where θ_c is the critical angle, λ is the wavelength of x-ray source (1.5418 Å for Cu K α), ρ_e is the electron density, r_e is the classical radius of the electron (2.818×10^{-13} cm), ρ_m is the mass density, A is the atomic weight (150.71 g mol⁻¹ for SnO₂), N_A is Avogadro's number (6.023×10^{23} mol⁻¹), and Z is the atomic number (66 for SnO₂) [34, 35]. While increasing the UV/O₃-exposure time from 0 to 45 minutes, the mass density of SnO₂ films increased from 3.17 to 3.90 g cm⁻³ owing to eliminating organic residue. However, the mass density of SnO₂ films decreased to 3.19 g cm⁻³ when the UV/O₃-exposure time was 60 minutes because the reduced M-O-M network by hydrogen compounds are excessively decomposed, as mentioned in the XPS analysis. Regardless of UV/O₃-exposure time, the thickness of all SnO₂ films was approximately 4.53 nm ± 3.6 Å, calculated with the periodicity of the fringes using XRR simulation. These values are similar to the thickness analyzed by transmission electron microscopy (TEM) in a previous study [11]. We conducted GIXD analysis to investigate the crystallinity of SnO₂ films with different UV/O₃-exposure times, as depicted in figure 3(b). All diffraction peaks well-matched a tetragonal rutile SnO₂ pattern (JCPDS 41-1445) and had almost the same shape irrespective of UV/O₃-exposure time. The crystallite size of the films was obtained using the Scherrer formula; all films had a similar crystal size of approximately 7 ± 0.8 Å. Figure 4 illustrates the AFM images and corresponding height profile of SnO₂ films with different UV/O₃-exposure times. The root-mean-square (RMS) roughness increased from 0.20

to 0.32 nm with increasing UV/O₃-exposure time up to 60 minutes. Nevertheless, this small surface damage did not affect the electrical properties of the SnO₂ TFT since values of RMS roughness differed only slightly in the angstrom-range and the TFTs are fabricated with bottom-contact structure. The values of critical angle, mass density, and RMS roughness of SnO₂ films with different UV/O₃-exposure times were summarized in table 1.

Figures 5(a)–(e) exhibit the output characteristics of SnO₂ TFTs with different UV/O₃-exposure times (I_{DS} – V_{DS} curves at V_{GS} from –30 to +30 V with an increment of 10 V). All devices exhibited conventional n-type semiconductor behavior and a normally-turned-on state regardless of UV/O₃-exposure time. Changes in the transfer characteristics (I_{DS} – V_{GS}) of SnO₂ TFT were observed with respect to UV/O₃-exposure time, as depicted in figure 5(f). All the TFTs were operated in the saturation regime by applying a constant V_{DS} of +30 V. As UV/O₃-exposure time increased, the off-current increased and turn-on voltage (V_{ON}) shifted slightly negatively from –26 to –28 V as free carrier concentration increased, associated with O_v. Furthermore, the subthreshold swing characteristics (SS) improved from 2.44 (0 minutes) to 1.83 V/decade (30 minutes) due to reduced organic-based content, whereas SS deteriorated to 4.31 V/decade (60 minutes) since an excessively increased O_v ratio leads to many oxygen deficiency defects and a high off-current [36, 37]. The field-effect mobility was estimated from the following conventional MOS transistor saturation mobility equation:

$$\mu_{sat} = \frac{2L}{WC_i} \left(\frac{\partial \sqrt{I_{sat}}}{\partial V_{GS}} \right)^2 \quad (6)$$

where C_i is the gate insulator capacitance per unit area and L and W are the channel length and width. While increasing UV/O₃-exposure time from 0 to 30 minutes, the extracted

field-effect mobility increased from 6.27 to 10.1 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ because of the enhanced M-O-M network and mass density of SnO_2 films, leading to the highest on-current (on/off ratio of 1.2×10^6). In contrast, the field-effect mobility decreased to 4.31 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ owing to the reduced M-O-M network and high oxygen deficiency defects. The electrical characteristics of the SnO_2 TFT for different UV/ O_3 -exposure times are summarized in table 2 with both means and standard deviations deduced from 20 devices for each condition. Table 3 shows the performance comparison of the various solution-processed SnO_2 TFTs with the different fabrication processes. The device of this work exhibits higher field-effect mobility than other studies with a fabrication process analogous to ours (same gate insulator and similar post-annealing temperature). In addition, there is similar field-effect mobility with ours in spite of high post-annealing temperature for a long time. If UV/ O_3 -exposure is applied to other SnO_2 TFTs with high-k gate insulator or high post-annealing temperature, the electrical performance would be improved as in this work.

4. Conclusion

High-performance solution-processed SnO_2 TFTs were fabricated by the controlling of UV/ O_3 -exposure on films during the pre-annealing stage. We identified the optimal UV/ O_3 -exposure time for suitable electrical characteristics of SnO_2 films. When the UV/ O_3 -exposure time was 30 minutes, the SnO_2 TFTs exhibited the highest electrical performance compared to TFTs without UV/ O_3 -exposure, with field-effect mobility of 10.1 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ and on/off ratio of 1.2×10^6 resulting from the enhanced M-O-M network, mass density, and oxygen vacancies of films. In contrast, the SnO_2 TFTs treated with UV/ O_3 exposure time for 60 minutes show inferior field-effect mobility of 6.15 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ and on/off ratio of 2.2×10^4 , which is lower than TFTs without UV/ O_3 -exposure, because M-O-M network and mass density decreased and oxygen vacancies were excessively increased. Furthermore, significant changes were not observed in the SnO_2 (Sn^{4+}) phase, thickness, or surface morphology of SnO_2 films irrespective of UV/ O_3 -exposure time. The SnO_2 TFT exposed to UV/ O_3 for 30 minutes during the pre-annealing stage demonstrates superior electrical performance, adequate for use in high-resolution active-matrix LCDs or OLED displays that demand a high field-effect mobility ($>10 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$) and on/off ratio ($>10^6$).

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References

- [1] Kamiya T and Hosono H 2010 Material characteristics and applications of transparent amorphous oxide semiconductors *NPG Asia Mater.* **2** 15–22
- [2] Wager J F 2003 Transparent electronics *Science* **300** 1245–7
- [3] Nomura K, Ohta H, Ueda K, Kamiya T, Hirano M and Hosono H 2003 Thin-film transistor fabricated in single-crystalline transparent *Science* **300** 1269–73
- [4] Hosono H 2006 Ionic amorphous oxide semiconductors : material design, carrier transport, and device application *J. Non. Cryst. Solids* **352** 851–8
- [5] Minami T 2005 Transparent conducting oxide *Semicond. Sci. Technol.* **20** S35–44
- [6] Minami T 2000 New n-type transparent conducting oxides *MRS Bull.* **25** 38–44
- [7] Kwon J Y, Lee D J and Kim K B 2011 Review paper: transparent amorphous oxide semiconductor thin film transistor *Electron. Mater. Lett.* **7** 1–11
- [8] Haxel G B, Hedrick J B and Orris G J 2002 *Rare Earth Elements—Critical Resources for High Technology* (National Minerals Information Center, Reston, Virginia: U.S. Geological Survey)
- [9] Kim S J, Yoon S and Kim H J 2014 Review of solution-processed oxide thin-film transistors *Jpn. J. Appl. Phys.* **53** 02BA02
- [10] Jang J, Kitsomboonloha R, Swisher S L, Park E S, Kang H and Subramanian V 2013 Transparent high-performance thin film transistors from solution-processed $\text{SnO}_2/\text{ZrO}_2$ gel-like precursors *Adv. Mater.* **25** 1042–7
- [11] Jang B, Kim T, Lee S, Lee W, Kang H, Cho C S and Jang J 2018 High performance ultrathin SnO_2 thin-film transistors by Sol–Gel method *IEEE Electron Device Lett.* **39** 1179–82
- [12] Priyadarshini D M, Mannam R, Rao M S R and Dasgupta N 2017 Effect of annealing ambient on SnO_2 thin film transistors *Appl. Surf. Sci.* **418** 414–17
- [13] Sheng J, Choi D, Lee S, Park J and Park J 2016 Performance modulation of transparent ALD indium oxide films on flexible substrates : transition between metal-like conductor and high performance semiconductor states *J. Mater. Chem. C* **4** 7571–6
- [14] Chiang H Q, Wager J F, Hoffman R L, Jeong J and Keszler D A 2005 High mobility transparent thin-film transistors with amorphous zinc tin oxide channel layer *Appl. Phys. Lett.* **86** 013503
- [15] Kwack Y and Choi W 2013 Electrohydrodynamic jet spraying technique for oxide thin-film transistor *IEEE Electron Device Lett.* **34** 78–80
- [16] Kim Y, Heo J, Kim T, Park S, Yoon M, Kim J, Oh M S, Yi G, Noh Y and Park S K 2012 Flexible metal-oxide devices made by room-temperature photochemical activation of sol–gel films *Nature* **489** 128
- [17] Kwon J H, Choi J H, Bae J H and Park J 2019 Hysteresis reduction for organic thin film transistors with multiple stacked functional zirconia polymeric films *Crystals* **9** 634
- [18] Avis C, Hwang H R and Jang J 2014 Effect of channel layer thickness on the performance of indium-zinc-tin oxide thin film transistors manufactured by inkjet printing *ACS Appl. Mater. Interfaces* **6** 10941–5

- [19] Park J I, Jeong H S, Kim D K, Jang J, Kang I M, Lang P, Kim Y H, Kim H and Bae J H 2019 Importance of blade-coating temperature for diketopyrrolopyrrole-based thin-film transistors *Crystals* **9** 346
- [20] Kim D K, Jeong H S, Kim Y R, Kwon H B, Kang S W and Bae J H 2018 Enhanced electrical properties in solution-processed InGaZnO thin-film transistors by viable hydroxyl group transfer process *Jpn. J. Appl. Phys.* **57** 05GC02
- [21] Kim S J, Yoon S and Kim H J 2014 Review of solution-processed oxide thin-film transistors *Jpn. J. Appl. Phys.* **53** 02BA02
- [22] Kim G H, Shin H S, Ahn B D, Kim K H, Park W J and Kim H J 2009 Formation mechanism of solution-processed nanocrystalline InGaZnO thin film as active channel layer in thin-film transistor *J. Electrochem. Soc.* **156** H7-9
- [23] Kwon J M, Jung J, Rim Y S, Kim D L and Kim H J 2014 Improvement in negative bias stress stability of solution-processed amorphous In-Ga-Zn-O thin-film transistors using hydrogen peroxide *ACS Appl. Mater. Interfaces* **6** 3371-7
- [24] Park W, Son I, Park H, Chung K, Xu Y, Lee T and Noh Y 2015 Facile routes to improve performance of solution-processed amorphous metal oxide thin film transistors by water vapor annealing *ACS Appl. Mater. Interfaces* **7** 13289-94
- [25] Ji K H, Kim J I, Jung H Y, Park S Y, Choi R, Kim U K, Hwang C S, Lee D, Hwang H and Jeong J K 2011 Effect of high-pressure oxygen annealing on negative bias illumination stress-induced instability of InGaZnO thin film transistors *Appl. Phys. Lett.* **98** 103509
- [26] Rim Y S, Jeong W H, Kim D L, Lim H S, Kim K M and Kim H J 2012 Simultaneous modification of pyrolysis and densification for low-temperature solution-processed flexible oxide thin-film transistors *J. Mater. Chem.* **22** 12491
- [27] Mativenga M, Choi J W, Hur J H, Kim H J and Jang J 2011 Highly stable amorphous indium-gallium-zinc-oxide thin-film transistor using an etch-stopper and a via-hole structure *J. Inf. Disp.* **12** 47-50
- [28] Lee W Y, Ha S H, Lee H, Bae J H, Jang B, Kwon H J and Jang J 2019 Densification control as a method of improving the ambient stability of Sol-Gel-processed *IEEE Electron Device Lett.* **40** 905-8
- [29] Kim J-H, Ma J, Lee S, Jo S and Kim C S 2019 Effect of ultraviolet-ozone treatment on the properties and antibacterial activity of zinc oxide Sol-Gel film *Materials* **12** 2422
- [30] Vig J R 1985 UV/ozone cleaning of surfaces *J. Vac. Sci. Technol. A* **3** 1027
- [31] Jadhav H, Suryawanshi S, More M A and Sinha S 2017 Pulsed laser deposition of tin oxide thin films for field emission studies *Appl. Surf. Sci.* **419** 764-9
- [32] Liang L Y, Liu Z M, Cao H T and Pan X Q 2010 Microstructural, optical, and electrical properties of SnO thin films prepared on quartz via a two-step method *ACS Appl. Mater. Interfaces* **4** 1060-5
- [33] Hwang Y H, Seo J, Yun J M, Park H, Yang S, Park S K and Bae B 2013 An 'aqueous route' for the fabrication of low-temperature-processable oxide flexible transparent thin-film transistors on plastic substrates *NPG Asia Mater.* **5** e45
- [34] Birkholz M 2006 *Thin Film Analysis by X-Ray Scattering* (Weinheim: Wiley-VCH)
- [35] Veldhuis S A, Brinks P, Stawski T M, Göbel O F and Ten Elshof J E 2014 A facile method for the density determination of ceramic thin films using X-ray reflectivity *J. Sol-Gel Sci. Technol.* **71** 118-28
- [36] Noh H-K, Chang K J, Ryu B and Lee W J 2011 Electronic structure of oxygen-vacancy defects in amorphous In-Ga-Zn-O semiconductors *Phys. Rev. B* **84** 115205
- [37] Kamiya T, Nomura K, Hirano M and Hosono H 2008 Electronic structure of oxygen deficient amorphous oxide semiconductor a-InGaZnO_{4-x}: optical analyses and first-principle calculations *Phys. Status Solidi c* **5** 3098-100
- [38] Zhai J, Zhang X, Hai F S, Yu X, Zhu R and Zhang W 2014 Fabrication and characterization of thin-film transistors with SnO₂ channel by spray pyrolysis *Jpn. J. Appl. Phys.* **53** 10-13
- [39] Zhang X A, Zhai J X, Yu X K, Zhu R J and Zhang W F 2015 Effect of annealing temperature on the performance of SnO₂ thin film transistors prepared by spray pyrolysis *J. Nanosci. Nanotechnol.* **15** 6183-7
- [40] Lee H, Ha S, Bae J H, Kang I M, Kim K, Lee W Y and Jang J 2019 Effect of annealing ambient on SnO₂ thin film transistors fabricated via an ethanol-based Sol-Gel route *Electron* **8** 1-9
- [41] Huang G, Duan L, Dong G, Zhang D and Qiu Y 2014 High-mobility solution-processed tin oxide thin-film transistors with high-κ alumina dielectric working in enhancement mode *ACS Appl. Mater. Interfaces* **6** 20786-94