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Improvement of Mobility in Oxide-Based Thin Film Transistors: A Brief Review

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Amorphous oxide-based thin-film transistors (TFTs) have drawn a lot of attention recently for the next-generation high-resolution display industry. The required field-effect mobility of oxide-based TFTs has been increasing rapidly to meet the demands of the high-resolution, large panel size and 3D displays in the market. In this regard, the current status and major trends in the high mobility oxide-based TFTs are briefly reviewed. The various approaches, including the use of semiconductor, dielectric, electrode materials and the corresponding device structures for realizing high mobility oxide-based TFT devices are discussed.

Keywords: Metal oxide semiconductors, High mobility TFT, Flat panel displays

1. INTRODUCTION

Flat panel displays (FPDs) are thin electronic devices and a frequent feature widely used in our daily lives; e.g. laptops, smartphones, tablets, and 3D/high-definition (HD) curved televisions (TVs). According to the market statistics, transparent and flexible display revenue will reach $87.2 billion by 2025 [1,2]. Most of the leading FPDs manufacturers across the globe, i.e. Samsung, LG, and Sharp are investing huge money for next-generation flat panel technology. The current FPD industry is being driven towards the development of future generation HD technology, such as ultra-definition (UD, or 4 K×2 K) and/or super hi-vision (8 K×4 K), large area (>70"), high frame rate (>240 Hz), and 3D displays [3] due to the less radiation, produce less screen flash and consume less power. In 2013, a 55” active matrix (AM)-OLED TV (LG Electronics), with options for curved/flat panels, was available in commercial markets [4]. Recently, LG had commercialized 55”, 65”, and 77” 4 K OLED TVs [5]. In order to realize such high end products like ultra-HD (UHD) TVs that do not require specialized glasses, using either AM-LCDs or AM-OLED panels, and high-performance thin-film transistor (TFT) devices acting as driving elements are necessary, preferably with field-effect mobility (μ_{FE}) values over 30 cm^2/V-s, (as shown in Fig. 1; depending on display resolution and frame rate) [6], because OLED pixels need high current in order to emit light through current injection. Since the publication of the seminal paper by Nomura, et al. [7] in 2004, the amorphous oxide-based semiconductor materials has emerged as a strong candidate to be the backplane technology for next-generation UHD AM-LCD/AM-OLED panels. They offer high mobility, good transparency to visible light, and excellent uniformity for a large area, compared with conventional a-Si and poly-Si TFTs [3,8,9]. Therefore, the

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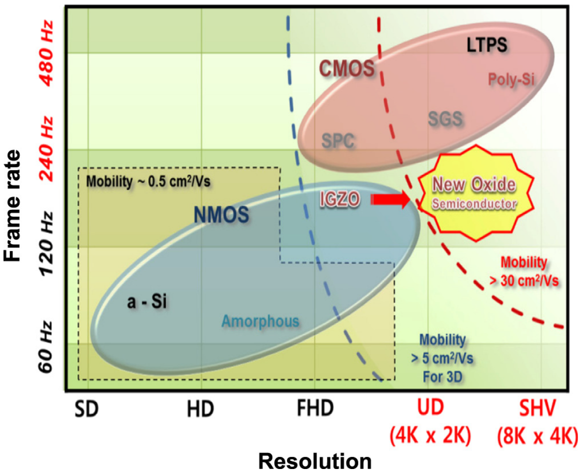

Fig. 1. Required field-effect mobility for hi-resolution ultra-definition (4 k × 2 k) and super hi-vision (8 k × 4 k) of next generation FPDs. Data from [6], Jang Yeon Kwon and Jae Kyeong Jeong, Recent progress in high performance and reliable n-type transition metal oxide-based thin film transistors, Semicond. Sci. Technol. 30, 024002 (2015). Permission granted. Copyright © IOP Publishing 2015.

discussion on the challenges as well as overall understanding for improving mobility of oxide-based TFTs is timely for next-generation FPD applications. In this review paper, various approaches for the improvement of mobility in oxide-based TFTs are discussed including designs of semiconductor (as the active channel), dielectric, electrode materials as well as alteration of traditional device structures.

2. MATERIALS FOR HIGH MOBILITY OXIDE-BASED TFTs

2.1 Semiconductor materials (Binary, Ternary, and Multi-component)

In this section many active materials for high mobility TFT applications have been discussed with respect to composition of binary, ternary and multi-component semiconductor materials. The key binary oxide semiconductors (SnO_2, In_2O_3, Ga_2O_3 and ZnO) have a wide band gap (>3.0 eV) and high electrical conductivity (10^{-2} to 10^2 $\Omega^{-1}cm^{-1}$), which may be attributed due to native defects, such as oxygen vacancies, cation interstitials, substitutional/interstititial hydrogen to act as shallow donors [10]. Binary oxides have high electron mobility (>10 cm^2/V-s) when they are amorphous, which originates from the intercalation of the ns orbital of the cations [11]. For these reasons, these oxides have been considered widely as the base materials for oxide-based TFTs. ZnO is the most widely used binary oxide material. Boesen, et al. [12] published in 1968, the first report on TFTs using single crystal ZnO. After a long period, ZnO based TFT research was reelected by other researchers after 2003 [13,14]. However, the high deposition and annealing temperature approaches were still significant problems for low temperature TFT applications. Carcia, et al. fabricated low temperature ZnO TFTs by controlling oxygen partial-pressure of ZnO film growth [14]. Fortunato, et al. [15] reported room temperature fabricated ZnO TFTs with high μ_{FE} of ~50 cm^2/V-s by carefully optimizing oxygen partial pressure during ZnO growth. The control of oxygen partial pressure suggested a path to the fabrication of highly performance and reliable TFTs.

Several research groups have explored SnO_2 and In_2O_3 as channel layers for TFT fabrications. Presley, et al. [16] demonstrated a bottom-gate SnO_2 TFT using AlTiOx as the gate insulator, and ITO as the gate, source-drain contacts. The SnO_2 channel was deposited by radio frequency (RF) sputtering and then subjected to 600°C in rapid thermal annealing (RTA) treatment. The device performance exhibited a μ_{FE} of 2.0 cm^2/V-s and an on/off current ratio of 10^5. However, binary oxide of SnO_2 are not suitable compound for making TFTs, owing to its difficulty to achieve at low deposition temperatures, unlike other binary oxide semiconductors. High value of μ_{FE} could be achieved for the In_2O_3 TFTs, which may be attributed to the overlaps of the In 5s orbital [17]. As reported in the literatures [18,19] the μ_{FE} of In_2O_3 TFTs is >30 cm^2/V-s. However, the high carrier density (N_d) and poor control of defects of In_2O_3 are the disadvantage as used in AM-OLED applications. On the other hand, Ga_2O_3 films have high resistivity of >10^8 Ω-cm, presumably due to large density of trap sites and low carrier density, in addition to the large band gap energy (>4 eV), which results very poor TFT performance, with μ_{FE} of 0.05 cm^2/V-s and turn on voltage (V_{on}) of >10 V [20]. However, binary oxide semiconductors themselves are polycrystalline in nature with poor uniformity [21,22], so they are often unsuitable material for the active channel in TFTs. Ternary, quaternary and or multi-component oxide materials, in general, allow for considerably higher μ_{FE} with better device performance than binary compound devices. Most of the ternary/quaternary oxide materials are amorphous in nature, which can be beneficial for fabricating high performance TFTs. The a-ZnSnO, a-InZnO, a-HfInZnO, a-GaInZnO, a-InSnZnO, and a-GaZnSnO are the most prominent ternary/multi component materials for TFT applications [9,23-32]. All of these materials exhibit n-type conductivity due to the existence of intrinsic donors.

In 2005, Oregon State University and Hewlett-Packard reported a high temperature fabrication process of a-ZnSnO TFTs, which exhibited a high μ_{FE} of ~50 cm^2/V-s [23]. Generally, the carrier concentration and mobility of oxide material increase as the In to Zn ratio increases. The InZnO exhibits a high carrier concentration (>10^{17} cm^{-3}), which can lead to large-off current and small on/off current ratio [11]. In 2007, Fortunato, et al. [24] reported bottom-gate InZnO TFTs, using a ceramic oxide target with composition of In_2O_3:ZnO (9:1), achieving a μ_{FE} of 107.2 cm^2/V-s and large off-current. In 2004, Nomura, et al. proposed another kind of quaternary compound InGaZnO (IGZO) semiconductor [7], which is now most widely used in commercial products [25,33]. LG display has implemented a 240Hz 55” UD TV panel using a-IGZO TFTs with copper signal lines [33]. One promising composition toward high mobility in quaternary compound materials is the InSnZnO (ITZO) semiconductor. The μ_{FE} of ITZO TFT can reach >30 cm^2/V-s [28,29,34]. Fukumoto, et al. [28] proposed that the Ga atoms can be replaced by cost-effective Sn atoms in ITZO materials for TFT application, which has highest μ_{FE} of 30.9 cm^2/V-s with steeper sub-threshold swing at < 210 mV/dec. Also, a high μ_{FE} of 52.4 cm^2/V-s and low SS of 0.2 V/dec had been observed without a deterioration of the off current, using ITZO for TFT application as reported by Song, et al. [29]. With more than three times the μ_{FE} of a-IGZO TFT, ITZO has been found to be the better choice to drive the OLED display panel developments. Recently, AUO demonstrated the 56” a-ITZO OLED TV [35], which panels achieve a good image quality characteristics, such as wide viewing angle, high contrast ration, and fast response time.

2.2 Gate insulator materials

Silicon-based dielectric materials (SiO_2, SiN_x) are widely preferred as gate insulator in most of oxide-based TFTs due to the material abundancy as well as the well-known deposition process i.e. PECVD with a large area of uniform coverage.

With excellent advantages such as low gate leakage and high stability, the TFTs with SiO_2 insulators however have low dielectric constant (κ ~3.9), which requires high operating voltages [36]. Reducing power consumption is one of the key issues in development of portable battery-powered appliances (e.g., smartphones, smart watches, etc), due to the limited capacity of the battery life. An effective approach to reduce the power consumption is the use of high-κ dielectric materials and double/multilayer stacked dielectric structures [37,38], which decrease the driving voltage of TFTs. These benefits have been pursued through a variety of transition metal oxide based high-κ gate dielectrics for TFT applications, such as Al_2O_3, HfO_2, ZrO_2, or Ta_2O_5. With a large band gap (E_g ~8.8 eV) and a high dielectric constant (κ = 9), Al_2O_3 is a good candidate in oxide-based TFTs, which reduce the interface trap density and an increase in the TFT mobility [39-41]. We have fabricated a-ITZO based TFTs using an Al_2O_3/SiN_x dielectric layer, which exhibited an improved μ_{FE} of 26.8 cm^2/V-s, while the same device obtained 17.1 cm^2/V-s with a traditional SiN_x dielectric layer [41]. HfO_2 is another high-κ material used in TFT as a dielectric layer because it exhibits a high-κ (~25), E_g ~8.8 eV, and a good conduction/valence-band offset value with Si. Lee, et al. [38] explored high performance a-IGZO TFTs that use 200-nm thick HfO_2 deposited by RF sputtering system. These devices exhibit very high μ_{FE} of 130 cm^2/V-s. Stoichiometric ZrO_2 is one of the most promising high-κ materials because of its high-κ (~25), high breakdown field intensity (~15 MV/cm), relatively low leakage current, and large band gap (~5.6 eV). Lee, et al. [42] reported a-IGZO TFT with a high μ_{FE} of 28 cm^2/V-s at 10 V applied gate voltage using ZrO_2 gate dielectric.

Hsu, et al. [43] reported a-IGZO based TFTs fabricated at room temperature with high μ_{FE} of 76 cm^2/V-s using trilayer stacked gate dielectric ($SiO_2/TiO_2/SiO_2$) structure on flexible substrate. The TiO_2 has a very high-κ value of >40, which can benefit the driving current and reduce the gate voltage. Liu, et al. [44] reported a-ZITO (amorphous-Zinc Indium Tin Oxide) channel based TFT with a high μ_{FE} of 110 cm^2/V-s at gate voltage of 1 V using self-assembled nanodielectric. Chiu, et al. [45] used Ta_2O_5 gate insulators and demonstrated a high μ_{FE} of 61.5 cm^2/V-s in a-IGZO TFTs fabricated by RF sputtering. Ta_2O_5 is well-known to have good chemical stability, low optical loss, and high refractive index, which are important in optoelectronic device applications. However, high-κ dielectric has some drawbacks such as large leakage current, high defect states, comparatively low band gap, low stability and polycrystalline structure (most of the high-κ dielectric), which is adverse to TFTs operations.

2.3 Source-drain electrode materials

The influence of source-drain (S-D) electrodes (including materials, contact quality and parasitic resistance) in contact with the semiconductor channel interface has also been a major impact on TFT performance. Proper selection of S-D contact materials is crucial for high performance oxide-based TFTs because parameters such as, μ_{FE}, and V_{th} are dependent on the "contact resistance" between channel and S-D [46]. When S-D contact resistance are higher, a higher applied bias is required across the S-D to inject carriers into the channel, resulting in current crowding effects causing lower current [47]. In general various metal like Al, Ag, Au, Ni, Ti, Mo, and transparent ITO, IZO electrodes are used in oxide-based TFT devices. Although the ITO and IZO electrodes allow fully transparent TFTs, but large electron affinity of the oxide electrodes cause nonlinear behaviors [48] in the linear regime of output characteristics due to the formation of Schottky like barrier between the electrodes and the a-IGZO films.

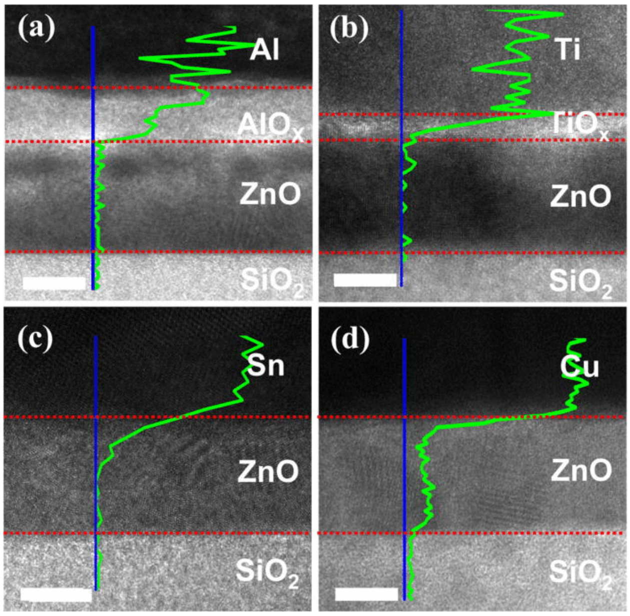

Fig. 2. Cross-sectional HRTEM images and metal element depth profiles of the interlayer between the S-D electrodes and ZnO channel layer. Data from [54], L. Xu, et al., The different roles of contact materials between oxidation interlayer and doping effect for high performance ZnO thin film transistors, Appl. Phys. Lett. 106, 051607 (2015). Permission granted. License number 3682920872374. Copyright © 2015 AIP Publishing LLC.

In oxide-based TFTs, various contact resistance reducing techniques are used like, doped contacts/Ag nanoparticles [48,49], plasma treatments [50], and barrier/oxidation-free layers [51]. In general, heavily doped regions below S/D electrodes are adopted to obtain good Ohmic contact properties. Na, et al. [48] reported a highly conductive (N_d ~1.6×10^{18} cm^3) a-IGZO buffer layer assisted to form a good Ohmic region between a-IGZO channel and Al S-D electrodes, which exhibit an improvement of μ_{FE} to 16.6 cm^2/V-s from 11.39 cm^2/V-s. Similarly, Xu, et al. [49] reported the incorporation of Ag nanoparticles at the homojunction interface between the conducting IZO S/D electrodes and the a-IZO channel, consequently a reduction of the specific contact resistance down to ~10^{-2} Ω.cm^2. Park, et al. [50] reported that a-GIZO TFTs with a contact layer modified by Ar plasma treatment, which was reduced contact resistance from 1550 to 330 Ω-cm.

It is well known that the inter-diffusion of metal atoms into the semiconductor are one of the major drawbacks in the preparation of oxide-based TFTs [51-53]. The inter-diffusion is prevented by the inserting the barrier layer/oxidation-free layer between the S-D and channel layers. Recently, Xu, et al. [54] showed the role of Sn (as an oxidation-free layer) in ZnO and compared the properties with Al, Ti, and Cu. The Al and Ti reacted with oxygen atoms from ZnO to form interfacial layer of ~5 nm thick AlOx and ~3 nm thick TiO_x (shown in Fig. 2) between the ZnO and S-D layers. The results indicate that Al electrode with a lower Gibbs free energies induce a thicker interlayer to form. The perfect barrier to prevent the formation of oxidation layers at the metal S-D and oxide interface may be performed by graphene and carbon nanofilms, which offer the high electrical performance and stable TFT devices [55,56].

2.4 Doping materials

Doping in semiconductors is often achieved by introducing

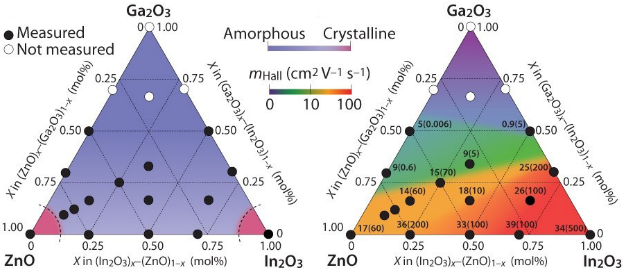

Fig. 3. The structures and Hall mobility of ternary a-IGZO films as a function of chemical composition. Data from [60], T. Kamiya, et al., Material characteristics and applications of transparent amorphous oxide semiconductors, NPG Asia Mater. 2, 15 (2010). Permission granted. License number 3682911117228. Copyright © 2010 Nature Publishing Group.

foreign atom (dopants/impurities) into the semiconductor host material. Doping is a unique approach, proposed to increase the μ_{FE} and stability of oxide-based TFTs. Generally, the conductivity mechanism of oxide-based materials is associated with oxygen vacancies, which appear to be the origin of the carrier generation center in the performance of oxide-based TFTs. Incorporating various dopants, such as In, C, Al, N, Mg, or Ti, into the oxide-based semiconductors can increase the μ_{FE} through control of the carrier density, which proves its utility in different applications. Serin, et al. [57] showed that conductivity of ZnO may be enhanced due to the incorporation of In dopant. Even the doping approach enhances the electrical properties and devices stability in oxide-based TFTs. The incorporation of In cations to ZnO-based channels is one of best ways to enhance the μ_{FE} of the resulting oxide TFTs [58,59]. The In cations provide more conducting pathways for electrons, and hence increase the channel mobility. Hosono, et al. [60] explained the structures and Hall mobility of IGZO films deposited at room temperature as a function of chemical composition (in Fig. 3). The pure ZnO and In_2O_3 are crystalline phase even when deposited at room temperature. As seen in Fig. 3 a-IZO has higher mobilities than a-IGZO films. The increasing In content in the a-IGZO channel of fabricated TFTs yields higher μ_{FE} [59], which can be explained by the formation of shallow level oxygen vacancies facilitated by increasing the coordination number of In cations around the oxygen atom. However, the degradation of off-current and $I_{on/off}$ ratio are observed in the a-IGZO TFT device. This trade-off behavior limits the use of the In fraction to achieve high μ_{FE}.

Parthiban, et al. [61] fabricated low temperature C-doped IZO (CIZO) TFTs, which exhibited improved μ_{FE} of 16.5 cm^2/V-s whereas the values for control IZO TFT was 6.55 cm^2/V-s. A few research groups are also fabricated In-free oxide-based TFTs, which has high electrical performance. Cai, et al. [62] fabricated Al doped ZnO (AZO) TFTs with high μ_{FE} of 143 cm^2/V-s and low V_{th} of 0.9 V. Nitrogen (N) is another excellent dopant in Zn based oxide materials due to its ionic radius and electronegativity, which is close to oxygen, and serve as oxygen-related defects binder. Some reports have highlighted the N-doping approach to enhance the mobility [63,64] and stability [7,65-67] of oxide based TFTs. Similarly, N-doped ZnO of zine oxynitride (ZnON) semiconductor are another promising semiconductor material in high mobility transistor applications. Ye, et al. [68] reported on ZnON TFTs with high μ_{FE} of 110 cm^2/V-s, demonstrating application in pixel switching devices in ultra-high definition and large area displays.

3. DEVICE STRUCTURES FOR HIGH MOBILITY OXIDE-BASED TFTs

3.1 Impact of device configuration

The μ_{FE} value and stability are primarily related to the configuration of the oxide-based TFTs. There are four major classes of configurations are used in fabricating the oxide-based TFTs, (i) back channel etch (BCE) structure, (ii) etch stopper (ES) structure, (iii) top gate (TG) structure, and (iv) double gate (DG) structure. Each device configuration has its own advantages and disadvantages. BCE and ES type oxide-based TFTs exhibit good uniformity and stability as well as reasonable μ_{FE}. During the S-D patterning process of TFT fabrications, physical and/or chemical damage are possible and may degrade the device properties. To solve these problems, the ES layer (e.g., SiO_x, SiN_x) are deposited by a PECVD system under the S-D metal electrodes, but requires an additional patterning process. Both structures have been employed for the mass production of oxide-based TFTs. However, the existence of the ES layer on the oxide semiconductor layer limits the design of short-channel devices due to the misalignment between the S-D to ES or ES to gate. The floating double gate (DG) contact was proposed to modulate the V_{th} and to increase the μ_{FE} [69]. Lee, et al. [70] reported DG a-IGZO TFTs to have considerable attention due to their advantages such as V_{on}, controllability and on-current enhancement. Bottom-gate type structures with a SiO_x ES layer have been widely employed for IGZO TFTs [71]. However, one of the serious drawbacks of this structure is a large parasitic capacitance [72] of gate-to-drain and gate to-source due to overlap between gate and S-E electrodes, which also induce poor chemical stability [8].

Large parasitic capacitance reduces operation speed of the TFT device based circuits and induces signal delay in the TFT backplane. Moreover, large capacitance gate to drain of selection TFTs in OLED display strongly influences uniformity of the luminescence of the pixels because the capacitance gate to drain is the main cause of the kickback effect [73] through voltage which influences an operation voltage of driving TFTs. Therefore, a self-aligned structure is an essential for oxide TFTs to achieve system-on-panel and high-resolution LCD/OLED displays. Self-aligned patterning is another device gaining interest to realize high-resolution high-quality displays. Park, et al. [74] reported a high μ_{FE} of 157 cm^2/V-s in self-aligned coplanar TFTs with a channel layer of a-IZO electrode instead of a-IGZO.

3.2 Single and Double-channel approaches

Another approach to enhance the μ_{FE} and stability of oxide-based TFTs utilizes the double-channel structures. The double channel structure consisted of back and front layers. The mobility is primarily influenced by the current path boosted at the bottom of the front layer that is adjacent to the gate insulator in bottom-gate structure. Highly conductive (eg. ITO, IZO) and oxygen deficient front layers are mostly preferable to construct the TFT devices. Kim, et al. [75] reported optimized HIZO/IZO TFTs, which exhibited improvement in both the μ_{FE} and NBIS stability compared to single channel devices. Hsu, et al. [76] proposed a bilayer IGZO/IGZO:Ti device, which presented the highest μ_{FE} of 49 cm^2/V-s by modulating the IGZO:Ti thickness. Similarly, the double channel TFTs with a back ZTO/front IZO (5 nm) showed a high μ_{FE} of 32.3 cm^2/V-s and a low V_{th} of ~0.5 V [77]. The thickness of IZO (>8 nm) in double channel TFT devices can cause a large negative V_{on} and V_{th} values. An ITO/IGZO double-channel structure [78] shows excellent TFT properties with a high μ_{FE} of 104 cm^2/V-s and a low V_{th} of ~0.5 V. As a result, the mobility of double layer devices can be improved significantly compared to the single active channel devices. In addition, the devices stability are also improved but control of the carrier concentration and thickness of conducting layers remain a challenge.

3.3 Nano materials and nanostructures

Nano materials and nanostructures have been proposed to improve the effective mobility in oxide-based TFTs. By incorporating carbon nanotube (CNT), graphene, nanodots, nanowire and nanocrystalline (nc) metal/ metal oxides into the oxide-based semiconductors, the current path in the channel may be enhanced. Recently, we have reported [79] a high performance hybrid oxide TFTs fabricated using an interlayer of the nc-ITO:Zr and an active channel of a-ITZO. Due to the presence of nc-ITO:Zr layer, an improvement of μ_{FE} of 86.4 cm^2/V-s and lower V_{th} of 0.43 V are observed. Such hybrid TFT devices may be a promising approach for making next generation display panels of the future. Liu, et al. [80] reported a-IZO/single walled-CNT composite TFTs exhibiting a high mobility of 132 cm^2/V-s. Similarly, Liu, et al. [81] reported a very high μ_{FE} of 140 cm^2/V-s in sol-gel a-IZO/SW-CNT composite based TFTs (shown in Fig. 4). The reason for the high μ_{FE} is the CNTs in the composite channel providing fast carrier movement owing to their electrical properties.

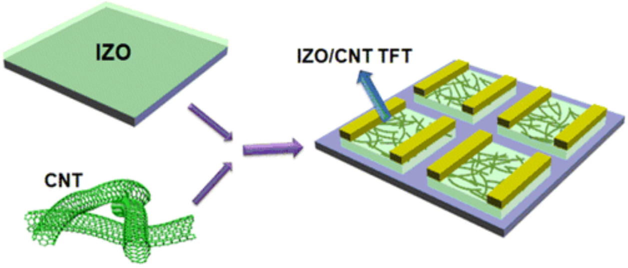

Fig. 4. Schematic of the a-IZO/SW-CNT hybrid TFT arrays. Reprinted with permission from [81], X. Liu, C. Wang, B. Cai, X. Xiao, S. Guo, Z. Fan, J. Li, X. Duan, and L. Liao, Rational Design of Amorphous Indium Zinc Oxide/Carbon Nanotube Hybrid Film for Unique Performance Transistors, Nano Letter 12, 3596 (2012). Copyright © 2012 American Chemical Society.

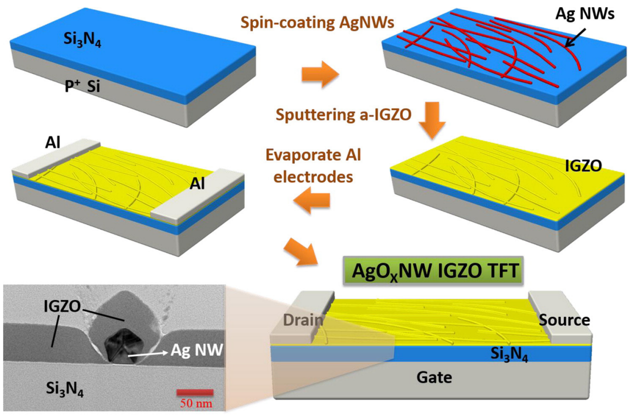

Fig. 5. Schematic of the AgOxNW a-IGZO TFT fabrication steps. Reprinted with permission from [82], H. C. Liu, Y. C. Lai, C. C. Lai, B. S. Wu, H. W. Zan, P. Yu, Y. L. Chueh, and C. C. Tsai, Highly Effective Field-Effect Mobility Amorphous InGaZnO TFT Mediated by Directional Silver Nanowire Arrays, ACS Appl. Mater. Interfaces, 7, 232 (2015). Copyright @ 2015 American Chemical Society.

Liu, et al. [82] demonstrated a very high μ_{FE} of 174 cm^2/V-s in RF sputtered a-IGZO TFTs with silver nanowires into the active region. The schematic of the AgOxNW a-IGZO TFT fabrication steps are depicted in the Fig. 5. Additionally, the composite TFTs also showed exceptional mechanical robustness for flexible applications. Similar to the nanostructure approach, Zan, et al. [83] proposed a top-gate self-aligned a-IGZO TFT with nanometer-scale dotted channel doping. With a low-cost, simple, and lithography-free process, the effective mobility level of TG a-IGZO TFT became 19 times higher than that of the control sample and the maximum effective mobility reached 79 cm^2/V-s due to barrier lowering effect.

4. CONCLUSIONS

Oxide-based TFTs have an optimistic future for the application in commercial high-resolution FPDs. We reviewed the different approaches of improving the field-effect mobility of oxide-based thin film transistors. The various approaches, including the selection of materials for semiconductor, dielectric, electrode materials and device structures for realizing high mobility oxide-based TFT devices are discussed. Oxide-based TFTs have an optimistic future for the application of commercial high-resolution FPDs. In this review paper, a detailed discussion on the different aspects of TFTs will directed to fabricate a high quality TFT devices.

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REFERENCES

[1] P. Barquinha, R. Martins, L. Pereira, and E. Fortunato, *Transparent Oxide Electronics: From Materials to Devices* (John Wiley& Sons, Ltd., 2012). [http://dx.doi.org/10.1002/9781119966999]

[2] DisplayBank (2011) *Transparent Display Technology and Market Forecast*.

[3] T. Kamiya, K. Nomura, and H. Hosono, *Sci. Technol. Adv. Mater.*, **11**, 044305 (2010). [DOI: http://dx.doi.org/10.1088/1468-6996/11/4/044305]

[4] C. W. Han, J. S. Park, H. S. Choi, T. S. Kim, Y. H. Shin, H. J. Shin, M. J. Lim, B. C. Kim, H. S. Kim, B. S. Kim, Y. H. Tak, C. H. Oh, S. Y. Cha, and B. C. Ahn, *J. Soc. Inf. Disp.*, **22**, 552 (2015). [DOI: http://dx.doi.org/10.1002/jsid.287]

[5] http://www.lgnewsroom.com/newsroom/contents/64643

[6] J. Y. Kwon and J. K. Jeong, *Semicond. Sci. Technol.*, **30**, 024002 (2015). [DOI: http://dx.doi.org/10.1088/0268-1242/30/2/024002]

[7] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, *Nature*, **432**, 488 (2004). [DOI: http://dx.doi.org/10.1038/nature03090]

[8] M. K. Kim, J. H. Jeong, H. J. Lee, T. K. Ahn, H. S. Shin, J. S. Park, J. K. Jeong, Y. G. Mo, and H. D. Kim, *Appl. Phys. Lett.*, **90**, 212114 (2007). [DOI: http://dx.doi.org/10.1063/1.2742790]

[9] H. Yabuta, M. Sano, K. Abe, T. Aiba, T. Den, H. Kumomi, K. No-

mura, T. Kamiya, and H. Hosono, *Appl. Phys. Lett.*, **89**, 112123 (2006). [DOI: http://dx.doi.org/10.1063/1.2353811]

[10] M. D. McCluskey and S. J. Jokela, *J. Appl. Phys.*, **106**, 071101 (2009). [DOI: http://dx.doi.org/10.1063/1.3216464]

[11] H. Hosono, *J. Non. Cryst. Solids*, **352**, 851 (2006). [DOI: http://dx.doi.org/10.1016/j.jnoncrysol.2006.01.073]

[12] G. F. Boesen and J. E. Jacobs, *Proc. of the IEEE*, **56**, 2094 (1968). [DOI: http://dx.doi.org/10.1109/PROC.1968.6813]

[13] R. L. Hoffman, M. H. Reilly, and G. Nunes, *Appl. Phys. Lett.*, **82**, 733 (2003). [DOI: http://dx.doi.org/10.1063/1.1542677]

[14] P. F. Carcia, B. J. Norris, and J. F. Wager, *Appl. Phys. Lett.*, **82**, 1117 (2003). [DOI: http://dx.doi.org/10.1063/1.1553997]

[15] E. Fortunato, P. Barquinha, A. Pimentel, A. Gonsalves, A. Marques, L. Pereira, and R. Martins, *Adv. Mater.*, **17**, 590 (2005). [DOI: http://dx.doi.org/10.1002/adma.200400368]

[16] R. E. Presley, C. L. Munsee, C. H. Park, D. Hong, J. F. Wager, and D. A. Keszler, *J. Phys. D. Appl. Phys.*, **37**, 2810 (2004). [DOI: http://dx.doi.org/10.1088/0022-3727/37/20/006]

[17] K. Nomura, T. Kamiya, H. Ohta, T. Uruga, M. Hirano, and H. Hosono, *Phys. Rev. B, Condens. Mater.*, **75**, 035212 (2007). [DOI: http://dx.doi.org/10.1103/PhysRevB.75.035212]

[18] S. S. Dhanajay, C. Y. Cheng, C. W. Yang, Y. C. Ou, M. C. Chuang, C. W. Wu, and J. Chu, *J. Phys. D. Appl. Phys.*, **41**, 092006 (2008). [DOI: http://dx.doi.org/10.1088/0022-3727/41/9/092006]

[19] M. H. Lee, C. C. Shih, J. S. Chen, W. M. Huang, F. Y. Gan, Y. C. Shih, C. X. Qiu, and I. S. Shih, *SID Symp. Dig. Tech. Paper*, **40**, 191 (2009). [DOI: http://dx.doi.org/10.1889/1.3256729]

[20] H. Q. Chiang, D. Hong, C. M. Hung, R. E. Presley, J. F. Wager, C. H. Park, D. A. Keszler, and G. S. Herman, *J. Vac. Sci. Technol. B*, **24**, 2702 (2006). [DOI: http://dx.doi.org/10.1116/1.2366569]

[21] Z. R. Li, *Organic Light-Emitting Materials and Devices*, 2nd Ed. (CRC Press, Boca Raton, FL, 2015).

[22] J. F. Wager, D. A. Keszler, and R. E. Presley, *Transparent Electronics* (Springer Science and Business Media, New York, 2008).

[23] H. Q. Chiang, J. F. Wager, R. L. Hoffman, J. Jeong, and D. A. Keszler, *Appl. Phys. Lett.*, **86**, 013503 (2005). [DOI: http://dx.doi.org/10.1063/1.1843286]

[24] E. Fortunato, P. Barquinha, A. Pimentel, L. Pereira, G. Goncalves, and R. Martins, *Phys. Status Solidi (RRL)*, **1**, R34 (2007). [DOI: http://dx.doi.org/10.1002/pssr.200600049]

[25] T. H. Shih, H. C. Ting, C. L. Chen, L. Tsai, C. Y. Chen, L. F. Lin, H. S. Lin, L. H. Chang, and Y. H. Lin, *AM-FPD'14*, 17-20 (2014).

[26] J. Raja, K. Jang, H. H. Nguyen, T. T. Trinh, W. Choi, and J. Yi, *Curr. Appl. Phys.*, **13**, 246 (2013). [DOI: http://dx.doi.org/10.1016/j.cap.2012.07.016]

[27] J. Raja, K. Jang, N. Balaji, S. Q. Hussain, S. Velumani, S. Chatterjee, T. Kim, and J. Yi, *Materials Science in Semiconductor Processing*, **37**, 129 (2015). [DOI: http://dx.doi.org/10.1016/j.mssp.2015.02.036]

[28] E. Fukumoto, T. Arai, N. Morosawa, K. Tokunaga, Y. Terai, T. Fujimori, and T. Sasaoka, *J. Soc. Inf. Disp.*, **19**, 867 (2011). [DOI: http://dx.doi.org/10.1889/JSID19.12.867]

[29] J. H. Song, K. S. Kim, Y. G. Mo, R. Choi, and J. K. Jeong, *IEEE Electron Device Lett.*, **3**5, 853 (2010). [DOI: http://dx.doi.org/10.1109/LED.2014.2329892]

[30] J. Raja, K. Jang, C.P.T. Nguyen, N. Balaji, S. Chatterjee, and J. Yi, *IEEE Electron Devices Lett.*, **35**, 756 (2014). [DOI: http://dx.doi.org/10.1109/LED.2014.2318754]

[31] C. J. Kim, S. Kim, J. H. Lee, J. S. Park, S. Kim, J. Park, E. Lee, J. Lee, Y. Park, and J. H. Kim, *Appl. Phys. Lett.*, **95**, 252103 (2009). [DOI: http://dx.doi.org/10.1063/1.3275801]

[32] E. M. C. Fortunato, L.M.N. Pereira, P.M.C. Barquinha, A.M.B. Rego, G. Gonçalves, A. Vilà, J. R. Morante, and R.F.P. Martins, *Appl. Phys. Lett.*, **92**, 222103 (2008). [DOI: http://dx.doi.org/10.1063/1.2937473]

[33] N. Gong, C. Park, J. Lee, I. Jeong, H. Han, J. Hwang, J. Park, K. Park, H. Jeong, Y. Ha, and Y. Hwang, *SID Symp. Dig. Tech. Paper*, **43**, 784 (2012). [DOI: http://dx.doi.org/10.1002/j.2168-0159.2012.tb05902.x]

[34] K. Jang, J. Raja, Y. J. Lee, D. Kim, and J. Yi, *IEEE Electron Device Lett.*, **34**, 1151 (2013). [DOI: http://dx.doi.org/10.1109/LED.2013.2272084]

[35] T. H. Shih, H. C. Ting, P. L. Lin, C. L. Chen, L. Tsai, C. Y. Chen, L. F. Lin, C. H. Liu, C. C. Chen, H. S. Lin, L. H. Chang, Y. H. Lin, and H. J. Hong, *SID Symp. Dig. Tech. Paper*, **45**, 766 (2014). [DOI: http://dx.doi.org/10.1002/j.2168-0159.2014.tb00201.x]

[36] S. Chang, Y. W. Song, S. Lee, S. Y. Lee and B. K. Ju, *Appl. Phys. Lett.*, **92**, 192104 (2008). [http://dx.doi.org/10.1063/1.2924769]

[37] S. M. Yoon, S. H. K. Park, S. H. Yang, C. W. Byun, and C. S. Hwang, Electrochemical and Solid-State Letters, 13, H264 (2010). [DOI: http://dx.doi.org/10.1149/1.3428745]

[38] S. Y. Lee, S. Chang, and J. S. Lee, *Thin Solid Films*, **518**, 3030 (2010). [DOI: http://dx.doi.org/10.1016/j.tsf.2009.09.165]

[39] H. H. Hsieh and C. C. Wu, *Appl. Phys. Lett.*, **89**, 041109 (2006). [DOI: http://dx.doi.org/10.1063/1.2235895]

[40] J. B. Kim, C. Fuentes-Hernandez, W. J. Potscavage, X. H. Zhang, and B. Kippelen, *Appl. Phys. Lett.*, **94**, 142107 (2009). [DOI: http://dx.doi.org/10.1063/1.3118575]

[41] K. Jang, J. Raja, J. Kim, C. Park, Y. J. Lee, J. Yang, H. Kim, and J. Yi, *Semicond. Sci. Technol.*, **28**, 085015 (2013). [DOI: http://dx.doi.org/10.1088/0268-1242/28/8/085015]

[42] J. S. Lee, S. Chang, S. M. Koo, and S. Y. Lee, *IEEE Electron Device Lett.*, **31**, 225 (2010). [DOI: http://dx.doi.org/10.1109/LED.2009.2038806]

[43] H. H. Hsu, C. Y. Chang and C. H. Cheng, *IEEE Electron Device Lett.* **34** (6) 768-770 (2013). [DOI: http://dx.doi.org/10.1109/LED.2013.2258455]

[44] J. Liu, D. B. Buchholz, R.P.H. Chang, A. Facchetti, and T. J. Marks, *Adv. Mater.*, **22**, 2333 (2010). [DOI: http://dx.doi.org/10.1002/adma.200903761]

[45] C. J. Chiu, S. P. Chang, and S. J. Chang, *IEEE Electron Device Lett.*, **31**, 1245 (2010). [DOI: http://dx.doi.org/10.1109/LED.2010.2066951]

[46] C. P. T. Nguyen, T. T. Trinh, J. Raja, A. H. Tuan Le, Y.J. Lee, V. A. Dao, and J. Yi, *Materials Science in Semiconductor Processing*, **39**, 649 (2015). [DOI: http://dx.doi.org/10.1016/j.mssp.2015.05.069]

[47] J. K. Jeong, H.J. Chung, Y.G. Mo, and H. D. Kim, *Journal of The Electrochemical Society*, **155**, H873 (2008). [DOI: http://dx.doi.org/10.1149/1.2972031]

[48] J. H. Na, M. Kitamura, and Y. Arakawa, *Appl. Phys. Lett.*, **93**, 063501 (2008). [DOI: http://dx.doi.org/10.1063/1.2969780]

[49] R. Xu, J. He, Y. Song, W. Li, A. Zaslavsky, and D.C. Paine, *Appl. Phys. Lett.*, **105**, 093504 (2014). [DOI: http://dx.doi.org/10.1063/1.4894769]

[50] J. S. Park, J. K. Jeong, Y. G. Mo, and H. D. Kim, *Appl. Phys. Lett.*, **90**, 262106 (2007). [DOI: http://dx.doi.org/10.1063/1.2753107]

[51] L. F. Lan, M. Xu, J. B. Peng, H. Xu, M. Li, D. X.Luo, J. H.Zou, H. Tao. L.Wng, and R. H. Yao, *J. Appl. Phys.*, **110**, 103703 (2011). [DOI: http://dx.doi.org/10.1063/1.3660791]

[52] Y. Ueoka, Y. Ishikawa, J. P. Bermundo, H. Yamazaki, S. Urakawa, Y. Osada, M. Horita, and Y. Uraoka, *Jpn. J. Appl. Phys.*, **53**, 03CC04 (2014). [DOI: http://dx.doi.org/10.7567/JJAP.53.03CC04]

[53] P. Barquinha, A. Vilà, G. Gonçalves, L. Pereira, R. Martins, J. Morante, and E. Fortunato, *IEEE Trans. Electron Devices*, **55**, 954 (2008). [DOI: http://dx.doi.org/10.1109/TED.2008.916717]

[54] L. Xu, C. W. Huang, A. Abliz, Y. Hua, L. Liao, W. W. Wu, X. Xiao, C. Jiang, W. Liu, and J. Li, *Appl. Phys. Lett.*, **106**, 051607 (2015). [DOI: http://dx.doi.org/10.1063/1.4907680]

[55] J. E. Lee, B. K. Sharma, S. K. Lee, H. Jeon, B. H. Hong, H. J. Lee, and J. H. Ahn, *Appl. Phys. Lett.*, **102**, 113112 (2013). [DOI: http://

dx.doi.org/10.1063/1.4798288]

[56] Luo, H. Xu, M. Zhao, M. Li, M. Xu, J. Zou, H. Tao, L. Wang, and J. Peng, *ACS Appl. Mater. Interfaces*, **7**, 3633 (2015). [http://pubs.acs.org/doi/abs/10.1021/am5079682]

[57] T. Serin, A. Yildiz, S. Uzun, E. Çam, and N. Serin, *Phys. Scr.*, **84**, 065703 (2011). [DOI: http://dx.doi.org/10.1088/0031-8949/84/06/065703]

[58] R. Martins, P. Barquinha, I. Ferreira, L. Pereira, G. Goncalves, and E. Fortunato, *J. Appl. Phys.*, 101, 044505 (2007). [http://dx.doi.org/10.1063/1.2495754]

[59] G. H. Kim, B. D. Ahn, H. S. Shin, W. H. Jeong, H. J. Kim, and H. J. Kim, *Appl. Phys. Lett.*, **94**, 233501 (2009). [DOI: http://dx.doi.org/10.1063/1.3151827]

[60] T. Kamiya and H. Hosono, *NPG Asia Materials*, **2**, 15 (2010). [DOI: http://dx.doi.org/10.1038/asiamat.2010.5]

[61] S. Parthiban, K. Park, H.J. Kim, S. Yang and J. Y. Kwon, *Journal of Electronic Materials*, **43**, 4224 (2014). [DOI: http://dx.doi.org/10.1007/s11664-014-3333-9]

[62] J. Cai, D. Han, Y. Geng, W. Wang, L. Wang, S. Zhang, and Y. Wang, *IEEE Trans. Electron Devices*, **60**, 2432 (2013). [DOI: http://dx.doi.org/10.1109/TED.2013.2264319]

[63] C. E. Kim, and I. Yun, *Appl. Phys. Lett.*, **100**, 013501 (2012). [DOI: http://dx.doi.org/10.1063/1.3673556]

[64] P. T. Liu, Y. T. Chou, L. F. Teng, F. H. Li, and H. P. Shieh, *Appl. Phys. Lett.*, **98**, 052102 (2011). [DOI: http://dx.doi.org/10.1063/1.3551537]

[65] J. Raja, K. Jang, N. Balaji, W. Choi, T. T. Trinh, and J. Yi, *Appl. Phys. Lett.*, **102**, 083505 (2013). [DOI: http://dx.doi.org/10.1063/1.4793535]

[66] J. Raja, K. Jang, N. Balaji, and J. Yi, *Semicond. Sci. Technol.*, **28**, 115010 (2013). [DOI: http://dx.doi.org/10.1088/0268-1242/28/11/115010]

[67] B. D. Ahn, H. J. Jeon, and J. S. Park, *ACS Appl. Mater. Interfaces*, **6**, 9228 (2014). [DOI: http://dx.doi.org/10.1021/am5013672]

[68] Y. Ye, R. Lim, and J. M. White, *J. Appl. Phys.*, **106**, 074512 (2009). [DOI: http://dx.doi.org/10.1063/1.3236663]

[69] H. W. Zan, W. T. Chen, C. C. Yeh, H. W. Hsueh, C. C. Tsai, and H. F. Meng, *Appl. Phys. Lett.*, **98**, 153506 (2011). [DOI: http://dx.doi.org/10.1063/1.3578403]

[70] J. M. Lee, I. T. Cho, J. H. Lee, and H. I. Kwon, *Jpn. J. Appl. Phys.*, **48**, 100202 (2009). [DOI: http://dx.doi.org/10.1143/JJAP.48.100202]

[71] T. Hirao, M. Furuta, T. Hiramatsu, T. Matsuda, C. Li, H. Furuta, H. Hokari, M. Yoshida, H. Ishii, and M. Kakegawa, *IEEE Trans. Electron Devices*, **55**, 3136 (2008). [DOI: http://dx.doi.org/10.1109/TED.2008.2003330]

[72] S. H. Ryu, Y. C. Park, M. Mativenga, D. H. Kang, and J. Jang, ECS Solid State Letters, **1**, Q17 (2012). [DOI: http://dx.doi.org/10.1149/2.004202ssl]

[73] M. Mativenga, M. H. Choi, D. H. Kang, and J. Jang, *IEEE Electron Device Lett.*, **32**, 644 (2011). [DOI: http://dx.doi.org/10.1109/LED.2011.2119290]

[74] J. C. Park, H. N. Lee, and S. Im, *ACS Appl. Mater. Interfaces*, **5**, 6990 (2013). [DOI: http://dx.doi.org/10.1021/am401128p]

[75] H. S. Kim, J. S. Park, H. K. Jeong, K. S. Son, T. S. Kim, J. B. Seon, E. Lee, J. G. Chung, D. H. Kim, M. Ryu, and S. Y. Lee, *ACS Appl. Mater. Interfaces*, **4**, 5416 (2012). [DOI: http://dx.doi.org/10.1021/am301342x]

[76] H. H. Hsu, C. Y. Chang, C. H. Cheng, S. H. Chiou, C. H. Huang, and Y. C. Chiu, *IEEE Transactions on Nanotechnology*, **13**, 933 (2014). [DOI: http://dx.doi.org/10.1109/TNANO.2014.2332395]

[77] H. Y. Jung, Y. Kang, A. Y. Hwang, C. K. Lee, S. Han, D. H. Kim, J. U. Bae, W. S. Shin, and J. K. Jeong, *Sci. Rep.*, **4** (3765) 2014. [DOI: http://dx.doi.org/10.1038/srep03765]

[78] S. I. Kim, C. J. Kim, J. C. Park, I. Song, S. W. Kim, H. Yin, E. Lee, J. C. Lee, and Y. Park, *in IEDM Tech. Dig.*, 73 (2008).

[79] J. Raja, K. Jang, S. Q. Hussain, N. Balaji, S. Chatterjee, S. Velumani, and J. Yi, *Appl. Phys. Lett.*, **106**, 033501 (2015). [DOI: http://dx.doi.org/10.1063/1.4906159]

[80] X. Liu, C. Wang, X. Xiao, J. Wang, S. Guo, C. Jiang, W. J. Yu, W. Hu, J. Li, and L. Liao, *Appl. Phys. Lett.*, **103**, 223108 (2013). [DOI: http://dx.doi.org/10.1063/1.4834375]

[81] X. Liu, C. Wang, B. Cai, X. Xiao, S. Guo, Z. Fan, J. Li, X. Duan, and L. Liao, *Nano Letter.*, **12**, 3596 (2012). [DOI: http://dx.doi.org/10.1021/nl3012648]

[82] H. C. Liu, Y. C. Lai, C. C. Lai, B. S. Wu, H. W. Zan, P. Yu, Y. L. Chueh, and C. C. Tsai, *ACS Appl. Mater. Interfaces*, **7**, 232 (2015). [DOI: http://dx.doi.org/10.1021/am5059316]

[83] H. W. Zan, W. W. Tsai, C. H. Chen, and C. C. Tsai, *Adv. Mater.*, **23**, 4237 (2011). [DOI: http://dx.doi.org/10.1002/adma.201102530]