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Top-gate ZnO thin-film transistors with a polymer dielectric designed for ultraviolet optical gating

Kimoon Lee[a], Jeong-M. Choi[a], D.K. Hwang[a], Min Suk Oh[a], J.K. Kim[b], Y. Jung[b], K. Oh[a], Seongil Im[a,*]

[a] *Institute of Physics and Applied Physics, Yonsei University, Seoul 120-749, Republic of Korea*
[b] *Department of Information and Communications, Gwangju Institute of Science and Technology, 1 Oryong-dong, Buk-gu, Gwangju 500-712, Republic of Korea*

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Abstract

We report on the fabrication of ultraviolet (UV)-sensing top-gate ZnO thin-film transistors (TFTs) with a poly-4-vinylphenol (PVP) polymer gate dielectric on glass substrate. Our top-gate ZnO-TFT showed a field-effect mobility of 0.05 cm^2/V s, maximum saturation current of 0.11 μA at a gate bias of 10 V and an on/off ratio of ~10^3 in the dark. Under UV illumination with a wavelength of 364 nm the ZnO-TFT exhibited ~4.7 μA for a drain current (at the same gate bias of 10 V), which is ~50 times higher than without UV. Such photo-transistor action appeared more pronounced under a depletion regime of 0 V gate bias and the photo-to-dark current ratio was more than about 10^4. By adopting this high UV-sensitivity, our inverter device with the top-gate ZnO-TFT and a load resistance well demonstrated its optical gating behavior.

Keywords: ZnO; Thin-film transistor; UV-detector; Optical gating

1. Introduction

ZnO-based thin-film transistors (TFTs) have attracted much attention over the last several years because of the following several potentials toward future electronic and optoelectronic applications: replacing conventional amorphous-Si TFT [1,2], realizing transparent electronics [3,4], and functioning as an efficient photo-detector [5]. Especially, ZnO-based photo-transistor has recently been one of the candidates as a ultraviolet (UV)-detecting device for its high responsivity compared with diode structure [5,6]. Usual types of ZnO-TFTs have been bottom-gated so far and their gate dielectrics were inorganic materials [1–6]. Those UV-detecting bottom gate ZnO-TFTs on SiO$_2$/Si substrate have quite a high mobility over 0.7 cm^2/V s and fast UV response due to the flat ZnO channel/SiO$_2$ dielectric interface [5]. However, they also needs quite complicated device processes such as ion-beam-induced (IBI) technique for gate isolation and high temperature (over 1000 °C) oxidation. In order to solve the complications and also to introduce glass-based inorganic–organic electronics for UV-detecting, we previously reported a fabrication of top-gate ZnO-TFTs with a low-temperature-deposited ZnO channel layer and a thick organic poly-4-vinylphenol (PVP) dielectric [7]. Those top-gate ZnO-TFTs showed a low mobility of $\sim 3 \times 10^{-3}$ cm^2/V s due to a low deposition temperature for ZnO channel besides the low capacitance of the thick organic dielectric. In the present study, we increased the channel mobility of the top-gate ZnO-TFT up to 0.05 cm^2/V s by increasing the channel deposition temperature and also realized a UV-detecting optical inverter which dynamically operates at a low supplied voltage of 5 V.

2. Experimental

The glass (Corning 1737) substrate was cleaned with acetone, ethanol, and de-ionized water, in that order. Then a 200 nm-thick ZnO film was deposited on the glass at 300 °C by radio frequency magnetron sputtering in a vacuum chamber (with basal pressure of 1×10^{-6} and working pressure of 10 mTorr

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[*] Corresponding author. Tel.: +82 2 2123 2842; fax: +82 2 392 1592.
E-mail address: semicon@yonsei.ac.kr (S. Im).

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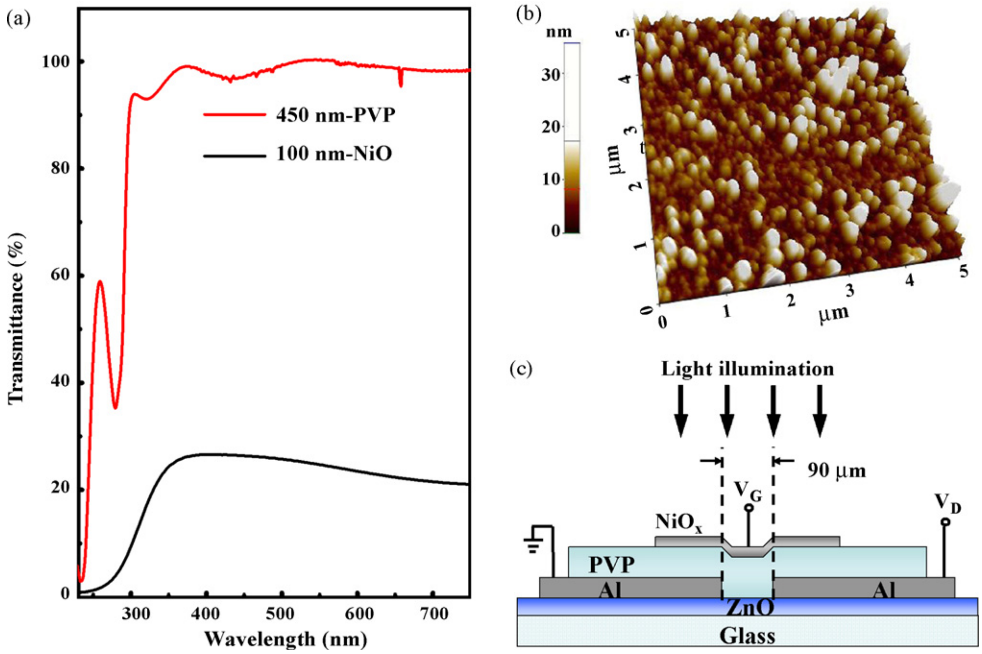

Fig. 1. (a) Transmittance spectra taken from 450 nm-PVP and 100 nm-NiO_x on glass substrate. (b) Atomic force microscopy image of the 300 °C-deposited ZnO film surface showing an rms roughness of ~4.8 nm. (c) Schematic cross-sectional view of ZnO-TFTs (channel length, $L = 90\ \mu m$, width, $W = 1000\ \mu m$). Lights illuminate the ZnO channel (dotted region) through the NiO_x gate window.

composed of the mixture of $Ar:O_2 = 5:2$). Fig. 1(b) shows the atomic force microscopy (AFM) surface image of our 300 °C deposited ZnO layer, that displays a rms roughness of ~4.9 nm. Al source/drain (S/D) electrodes were deposited on the ZnO through a shadow mask by thermal evaporation at room temperature (RT) and then spin casting was performed to cover the device with a 450 nm-thick PVP polymer dielectric layer, followed by a curing process at 175 °C for 1 h in vacuum. Our PVP dielectric showed a low capacitance of 7.4 nF/cm^2 as estimated by capacitance–frequency (*C*–*f*) measurement [8]. Semitransparent conducting 100 nm-thick NiO_x top-gate electrodes with a sheet resistance of $60\ \Omega/\square$ were finally deposited by thermal evaporation [9]. Fig. 1(a) shows the transmittance data of 100 nm-thick NiO_x layer and 450 nm-thick PVP layer, to be 30% and almost 100%, respectively in the optical range of 350–750 nm. Fig. 1(c) shows a schematic cross-sectional view of our top-gate device, which has a nominal channel length (*L*) of 90 μm and a width/length (*W*/*L*) ratio of ~11.

All electrical and photo-response characterizations were carried out with a semiconductor parameter analyzer (Model HP 4155C, Agilent Technologies) at RT. Photo-response measurements were performed under light illumination, as shown in Fig. 1(c), with a light source (Oriel Optical System) which employed a 500-W Hg(Xe) arc lamp and a monochromator covering the range of 254–670 nm. The optical power of the monochromatic light was measured by a UV-enhanced Si detector and in the present study the optical power density was fixed to ~0.2 mW/cm^2. Since the NiO_x gate electrode shows a transmittance of only 30%, we expect that an effective UV-power density for photo-response measurements would be even less than 60 $\mu W/cm^2$.

3. Results and discussions

Fig. 2(a) and (b) displays the output (drain current–drain voltage, I_D–V_D) and transfer (drain current–gate voltage, I_D–V_G) characteristic of our ZnO-TFT. In Fig. 2(a) the TFT device showed a typical transistor characteristic but with relatively low saturation I_D level of 0.11 μA at 10 V of V_G. From $\sqrt{I_D}$–V_G and $\log_{10} I_D - V_G$ curves in Fig. 2(b) the field-effect mobility in the saturation region was obtained to be 0.05 $cm^2/V\,s$ with the on/off current ratio of $\sim 10^3$ and threshold voltage was 3 V. Compared with our previous device fabricated with thermal SiO_2 deposited on p^+-Si substrate [5], the present ZnO-TFT with PVP dielectric is quite inferior in the aspect of mobility because the present ZnO channel/dielectric interface is quite rough (~4.9 nm in rms standard).

Fig. 3(a) and (b) depicts the static photo-response characteristics of the ZnO-TFT. Under the UV illumination with 364 nm the device showed photo-induced output curves where their current level appeared ~50 times higher than that of initial output current values. It is because the UV energy is nicely matched to the band gap energy of ZnO (~3.4 eV). In contrast, green band photons with 550 nm wavelength (~2.3 eV) little contribute to the current increase because the low energy photons mostly transmit through the band gap of ZnO though they excite some amount of carriers trapped in midgap states [10,11] According to the photo-induced transfer curves (at 10 and 5 V drain bias) of Fig. 3(b), the ratio between photo- and dark-I_D (photo-to-dark current ratio) is as large as 10^4 times at 0 V gate bias (depletion regime) while the ratio is only about 50 at 10 V (accumulation regime). Similar results of UV detection were previously reported but with bottom-gate ZnO-TFTs prepared on SiO_2/p^+-Si substrate [5].

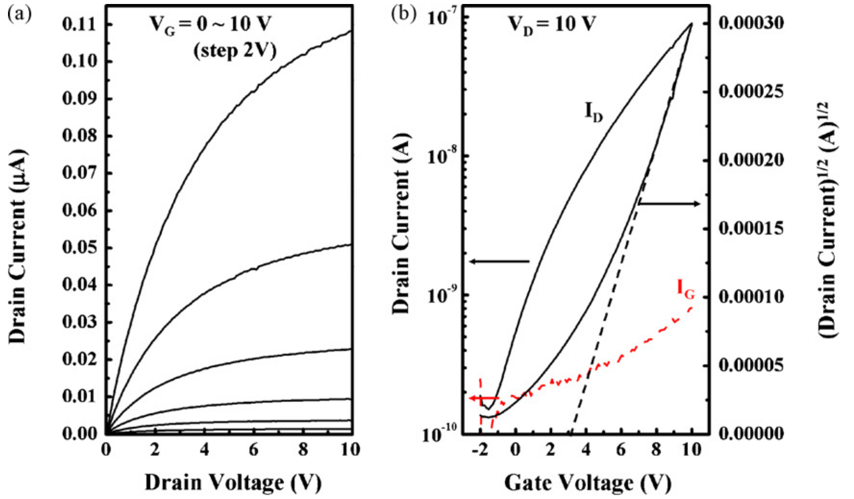

Fig. 2. (a) I_D–V_D output and (b) I_D–V_G transfer curves. The red-dashed line means gate leakage current (I_G) with respect to V_G, (that was less than 1 nA). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The responsivity, R of present UV-detector is derived by using the following equation (1) [12]:

$$R\ [\text{A/W}] = \frac{\Delta I_{\text{photo}}}{P_{\text{opt.}}} \tag{1}$$

where ΔI_{photo} is the value of photo-induced current and P_{opt}. is the optical power of UV photons. A maximum value of responsivity, R was obtained to be 1.1 and 10.5 A/W for $V_D = 5$ and 10 V, respectively, at a depletion regime gate bias ($V_{GS} = 0$ V). The R value is relatively high compared to those of previously reported UV detectors [13].

Fig. 4(a) illustrates an optical inverter set up prepared to demonstrate the UV-induced optical gating performance of our top-gate ZnO-TFT. The inverter consists of the ZnO-TFT and a load-resister with 100 MΩ, so that during the inverting action the dynamic UV response of our TFT might be measured. A supplied voltage, V_{DD} and a gate-source voltage, V_{GS} (=0 V) are applied by a semiconductor parameter analyzer, and an optical (UV) input is delivered through an optical fiber (with 1/20 Hz-chopper system) from Hg(Xe) arc lamp and a monochromator to the device. The basic concept of the optical inverter is based on the electrical inverter composed of a transistor and a load-resistor, except that input gate voltage pulse is now replaced by UV pulse for optical gating [14]. In particular, the 100 nm-thick NiO_x top-gate electrode deposited on PVP dielectric is known to possess a high work function (~more than 5 eV) [7] as well as some transparency over 30% in the UV–vis range of 350–750 nm (Fig. 1(a)). The work function difference between NiO_x [7] and n-ZnO [15] bends the energy bands of both PVP dielectric and n-channel ZnO, leading to a state of channel deple-

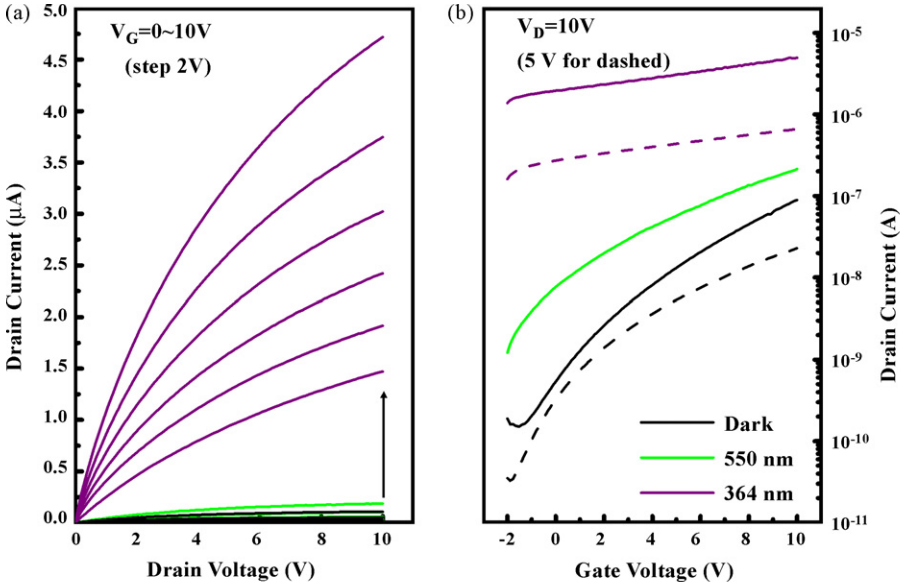

Fig. 3. Static spectral photo-responses of our ZnO-TFT with organic PVP dielectric: (a) I_D–V_D output and (b) I_D–V_G transfer curves under dark, green (550 nm), and UV (364 nm) lights. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

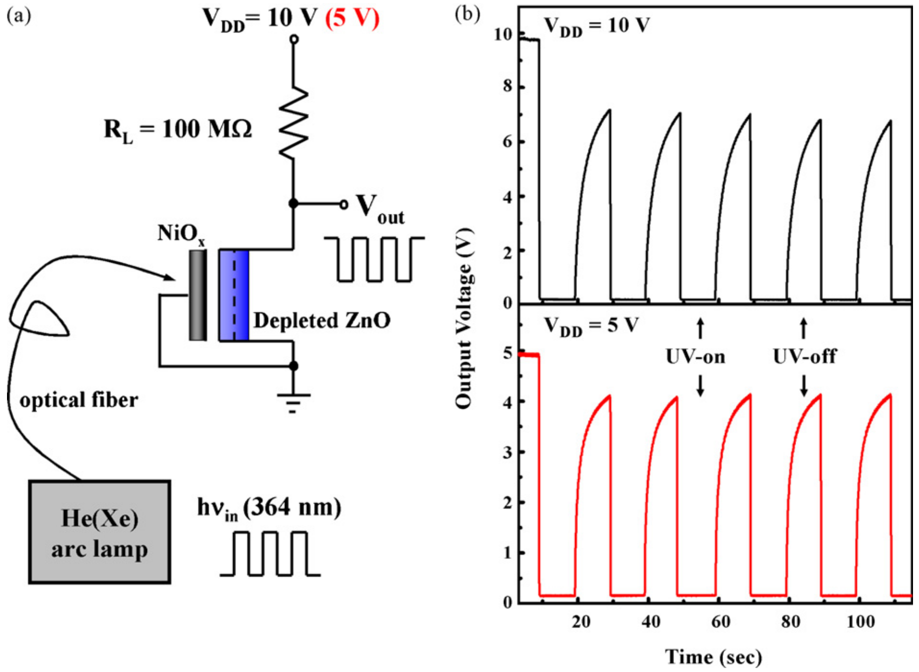

Fig. 4. (a) Circuitry scheme of optical inverter set up with ZnO-TFT and 100 MΩ load resistor (R_L). The modulated input and inverted output signals were illustrated. Illuminated UV light induces photocurrent in the depleted ZnO channel without any gate biasing when transmitted through the semitransparent NiO_x electrode window. Dynamic UV-response of the optical inverter as obtained under the 364 nm UV illumination modulated at 1/20 Hz at (b) $V_{DD} = 10$ V, and (c) $V_{DD} = 5$ V.

tion without any gate biasing, so that the 364 nm UV photons generate photo-current as received into the depleted ZnO (after transmitted through the NiO_x and PVP).

The dynamic photo-response behavior of our optical inverter is shown in Fig. 4(b) and (c) for $V_{DD} = 10$ and 5 V, respectively. When the UV signal is on (UV-on), the output voltage signal is off (V_{out} ~0 V) and when UV signal is off (UV-off), the output voltage signal is on (V_{out} ~10 V). However, in the present case, V_{out} for UV-off appeared to be only about 7.2 V, not attaining to 10 V even during 10 s-long period while V_{out} for UV-on rapidly showed 0 V within 300 ms. Although the UV signal was abruptly turned off to stop the photo-carrier generation in the ZnO channel, the carrier-transport could not be abruptly cut because the depleted ZnO may still possess some density of UV-induced carriers trapped in midgap states. Those photo-induced carriers in midgap states would drift to drain under a V_{DS} (or source-to-drain electric field) being escaped from traps but the escape process usually takes long time [16]. Rising time (for 80% of maximum output signal) was thus estimated to be ~3 s for the case of $V_{DD} = 10$ V. As compared to the case of Fig. 4(b) ($V_{DD} = 10$ V), our optical inverter in Fig. 4(c) displayed somewhat improved performance under a lower V_{DD} (=5 V) but its action was still slow. (V_{out} attained to 4.3 V in 10 s with a rising time of ~1.5 s.)

It is worthy of considering that the previous UV-sensing as obtained in bottom-gated ZnO-TFT prepared on 200 nm-thick thermal SiO_2/p^+-Si substrate [5] occurred in only 10–20 ms under the same V_{DD} (of 5 V) while the present case took ~1.5 s which is two orders of magnitude longer. Since the ZnO channel deposition was performed at the same temperature of 300 °C but the channel formed on a bottom gate dielectric SiO_2 with much smoother surface (0.4 nm in rms roughness) and higher capacitance, the bottom-gated ZnO-TFT showed much higher field mobility (~0.7 $cm^2/V\,s$) than that of our top-gated TFT (~0.05 $cm^2/V\,s$) with a low capacitance organic dielectric that meets a rugged ZnO surface to form an channel/dielectric interface (see Fig. 1(b)). Besides the degraded mobility, the rugged interface might have higher number of interfacial traps than a smooth one because the rugged one has more effective interfacial area. The traps in the rugged interface, also if located in the midgap energy states, make the inverter dynamics slower. However, our device is still worthy of note in that it is a top-gate patterned device with novel inorganic–organic channel/dielectric layered structure on glass substrate and as a matter of fact any UV-detecting device fabricated on glass has rarely been reported so far. Moreover, it is also interesting to expect a self-passivation or ambient-protecting effect by the polymer dielectric layer deposited on ZnO channel as one of the technical advantages of top-gated TFT device.

4. Conclusion

We have fabricated UV-detecting top-gate ZnO-TFT with organic PVP dielectric on a glass substrate. Our top-gate ZnO-TFT showed a field-effect mobility of 0.05 $cm^2/V\,s$, saturated drain current of 0.11 μA (at a gate bias of 10 V) and an on/off current ratio of ~10^3 in the dark. Under UV illumination with a wavelength of 364 nm the ZnO-TFT exhibited very high photo-to-dark ratio of more than about 10^4 at a depletion regime gate bias (0 V). By adopting this high UV-sensitivity, our inverter device with the top-gate ZnO-TFT and a load resistance well demonstrated its optical gating behavior although its dynamics were controlled by the channel/dielectric interface due to the interface roughness and the numbers of interface trap located in midgap states.

Acknowledgements

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Biographies

Kimoon Lee was born in Korea on 22 April 1980. He received his BS degree from the Department of Physics at Yonsei University in 2004. He is currently working towards his PhD degree with a subject of oxide-based electronics and optoelectronics at the same institute.

Jeong-M. Choi was born on 1 February 1981. He received the BS degree from the Department of Materials Science and Engineering at Yonsei University in 2003. He is currently working toward a PhD degree in the research on organic thin-film transistors at the same institute.

D.K. Hwang was born in Korea on 5 May 1980. He received the BS degree in the Department of Materials Science and Engineering at Yonsei University in 2003. He is currently finishing his PhD study, organic device and its stability electronics.

Min Suk Oh was born in Seoul, Korea on 22 May 1973. He received the BS and MS degrees from the Department of Metallurgical Engineering at Yonsei University, Seoul, Korea in 1997 and 1999, respectively. He worked as a research engineer in Iljin Copper Foil, Korea from 2000 to 2002 and in Samsung Electro-Mechanics, Korea from 2002 to 2005. Currently, he is a PhD candidate in the Institute of Physics and Applied Physics at Yonsei University, working on a subject of organic/inorganic hybrid complementary TFT logic circuits.

J.K. Kim was born on 16 October 1975. He received the BS degree in aviation electronics in 2003 from Hankuk Aviation University, and the MS degree in engineering of information and communication from Gwangju Institute of Science and Technology (GIST), in 2004. He is working toward a PhD degree in the area of micro-optic beam shaping using organic–inorganic hybrid structure in the Department of Information and Communications, GIST.

Y. Jung was born, on January 21 according to the lunar calendar, in 1978. He received the BS degree in physics in 2003 from Chung-Ang University, and the MS degree in engineering of information and communications from Gwangju Institute of Science and Technology (GIST), in 2004. He is currently working toward a PhD degree in the area of optical fiber sensors and imaging system in the Department of Information and Communications, GIST.

K. Oh was born in 1963, Seoul, South Korea, and received his PhD in fiber optics and MS in engineering from the Laboratory for Lightwave Technology in Brown University in 1994 and 1991, respectively. He also received MS in physics from Seoul National University in 1988 after finishing BS in physics from the same school in 1986. After PhD, Prof. Oh has had extensive experiences in optical fiber manufacturing and photonic device development in various internationally renown research centers such as Bell labs at Murray Hill, Rutgers University, and Boston University in USA, Optoelectronics Research Centre (ORC) at the University of Southampton in UK, The University of Tokyo in Japan, National Chia Tung University in Taiwan, and Institute of Physical High Technology in Jena, Germany. He is an Alexander von Humboldt Research Fellow (2004) in Germany, a JSPS invitation fellow (2004) in Japan, Chevening Scholar (2003) in UK. His major research area includes specialty optical fiber and fiber devices for optical communications and optical signal processing. He has authored and co-authored more than 200 journal articles and international conference papers.

Seongil Im was born in Korea on 9 November 1962. He received his BS and MS (MSE) degrees from the Department of Metallurgical Engineering at Yonsei University in 1984 and 1986, respectively. Then he moved to University of California at Berkeley for his PhD and achieved the degree in the Department of MSE in 1994. After 2 years of post-doc experience in CALTECH (California Institute of Science and Technology), he joined Yonsei as an assistant professor of MSE Department in 1997. In order to support the applied physics field, he moved to the Department of Physics from MSE in 1999 and was promoted to a full professor of the same department in 2004. His current research interests are thin-film devices and electronics adopting glass or plastic substrates. In recent 5 years, Dr. Im has published more than 50 journal papers on organic and inorganic oxide transistor devices.