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# Improving the performances of oxide phototransistors using a mechanochemically treated porous visible-light absorption layer

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**ABSTRACT**
In this research, the use of indium gallium zinc oxide (IGZO) thin-film transistors (TFTs) with a porous oxide layer (POL) resulting from the mechanochemical treatment of spin-coated oxide films is suggested for the detection of visible light. Mechanochemical treatment is a new technique that uses cellophane tape to induce the selective formation of hydrophobic dots on the surface of the a-IGZO. These dots interfere with the deposition of the film during spin coating, resulting in pore formation. The IGZO TFT with a POL exhibits 341.32 A/W photoresponsivity, $1.10 \times 10^6$ photosensitivity, and $4.54 \times 10^{10}$ Jones detectivity under 532 nm light illumination.

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**KEYWORDS**
Indium gallium zinc oxide; visible light; cellophane tape; mechanochemical; hydrophobic dot

## 1. Introduction

As the field of Internet of Things (IoTs) grows, various sensors have become increasingly important due to their applications in consumer electronics. As such, there has been a growing interest in improving the optoelectrical characteristics of photonic devices. Oxide-based thin-film transistors (TFTs) have exhibited optimal electrical and optical characteristics of late, such as high uniformity over large areas, low off current, and high transparency in the visible-light region [1–3]. These characteristics imply that oxide TFTs are suitable candidates for optoelectrical devices [4]. Oxide TFTs, however, cannot absorb visible light due to the wide bandgap ($>3$ eV) of the channel layer; hence, their applicability has been limited to ultraviolet- and blue-light absorption [5]. As such, several researches have been conducted to enable oxide TFTs to absorb visible light using absorption layers like organic polymers, carbon composites, metal nanoparticles, and quantum dots [6–8]. Although the use of these materials allows oxide TFTs to absorb visible light, such materials can be expensive and difficult to fabricate in thin-film structures. In this research, a new method that enables the detection of visible light by indium gallium zinc oxide (IGZO) thin-film transistors (TFTs) is proposed. For detecting visible light, instead of single-layered IGZO TFTs, double-layered IGZO TFTs with a porous oxide layer (POL) on top of the IGZO layer for the channel is proposed. The POL was spin-coated on the backchannel region of the active layer while the front-channel region was composed only of IGZO. The IGZO front channel is responsible for the adequate electron transport, and the POL backchannel is responsible for detecting visible light. Thus, this structure can improve the performance of photosensors while minimizing the degradation of the on/off current ratio and the field effect mobility ($\mu_{FE}$) compared with the conventional IGZO TFT.

## 2. Experiment

### 2.1. Fabrication of IGZO TFT

Figure 1a depicts the fabrication process of the IGZO TFT. The IGZO TFT was fabricated using a heavily doped p-type Si wafer with 120-nm-thick thermally oxidized $SiO_2$ acting as a gate insulator. The IGZO channel layer was deposited on $SiO_2$ with a shadow mask on top via radio frequency (RF) magnetron sputtering at room temperature, using an $In_2O_3$-$Ga_2O_3$-ZnO (1:1:1 molar ratio) sputtering target. The sputtering power, working pressure, and time were set at 150 W, $5.0 \times 10^{-3}$ Torr, and 5 minutes, respectively. The IGZO film was then mechanochemically treated by placing the adhesive part of the cellophane tape on the IGZO for 1 second, leaving organic residues. Lastly, aluminium source and drain electrodes were deposited on the treated IGZO channel layer via a shadow mask, using magnetron sputtering.

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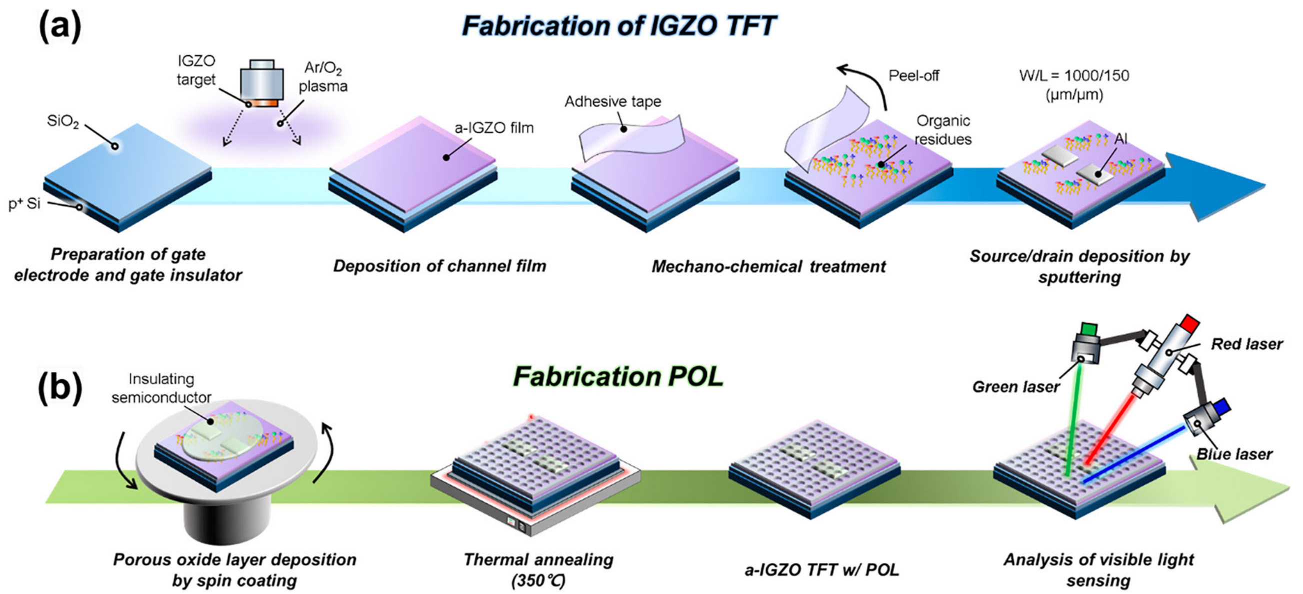


**Figure 1.** Schematic diagram of the fabrication process of IGZO TFTs with a POL using mechanochemical treatment.

The width (W) and length (L) of the channel were 1000 and 150 $\mu$m, respectively.

## 2.2. Preparation of a porous oxide layer

After electrode deposition, the POL ($Y_2O_3$ layer) was deposited on the treated film using spin coating, as shown in Figure 1b. For the spin-coating process, a 0.1 M $Y_2O$ solution was prepared by dissolving $Y(NO_3)_3{\cdot}6H_2O$ in 2-methoxyethanol. The prepared solution was spin-coated onto the treated IGZO film at 1000, 2000, and 3000 rpm for 30 seconds, following pre-annealing treatment at 100°C for 10 minutes to get rid of the organic solvents. The films were then post-annealed at 350°C for 1 hour to increase the metal–oxide bond formation in the IGZO and POL. The electrical characteristics of the fabricated transistors were measured using a semiconductor parameter analyzer (HP 4156C, Agilent Technologies) in a probe station, at room temperature. The sources of light illumination that were used were monochromic lasers of red (635 nm), green (532 nm), and blue (405 nm) light.

# 3. Results and discussion

First, to analyse the mechanochemically treated IGZO's surface characteristics, the morphologies of the devices with and without mechanochemical treatment were scanned via atomic force microscopy (AFM). Their three-dimensional (3D) images are shown in Figure 2. Each image had a $2 \times 2$ $\mu$m scanned area. The two images have different surface morphology appearances after the mechanochemical treatment. In the non-treated IGZO case, the morphology was smooth. On the contrary, the image of the treated IGZO revealed extremely populated fine peaks as a result of some residues. Figure 2a and b also show that the RMS roughness was calculated to be 0.383 and 0.998 nm, where the mechanochemically treated sample had a rougher surface, causing the surface of the IGZO to be hydrophobic [9]. In Figure 3a, the chemical bond existing on the surface resulting from the adhesive tape is shown through the Fourier transform infrared (FTIR) spectrum. Each peak in the said figure is related to the organic materials in the adhesive component [10]. Through FTIR analysis, it can be observed that the adhesive surface of the tape consisted of a polyacrylate group, which formed the hydrophobic dots. Figure 3b shows an illustration of the species in which the organic residues transferred to the IGZO film due to the treatment [10]. The weak Van der Waals bonds of the organic materials were broken, and organic residues were formed when the polymers were detached from each other. This phenomenon is called 'mechanochemical reaction' [11,12]. Then, as shown in Figure 3c, the contact angle for the IGZO can be interpreted as a hydrophilic state. As shown in Figure 3d, however, the contact angle of the adhesive tape was 91.4°, showing a hydrophobic state. Second, after the mechanochemical treatment, the POL ($Y_2O_3$ layer) was deposited using spin coating, and formed the backchannel. In this case, the POL layer was porous due to the evaporation of the hydrophobic dots, along with the spin-coated layer on top of the dots. To confirm the effect of the hydrophobic dots, a POL was fabricated under various spin-coating conditions (1000–3000 rpm). As shown in Figure 4, as the spin-coating speed increased, the pore size and the number of pores also increased. In this case, the emergence of

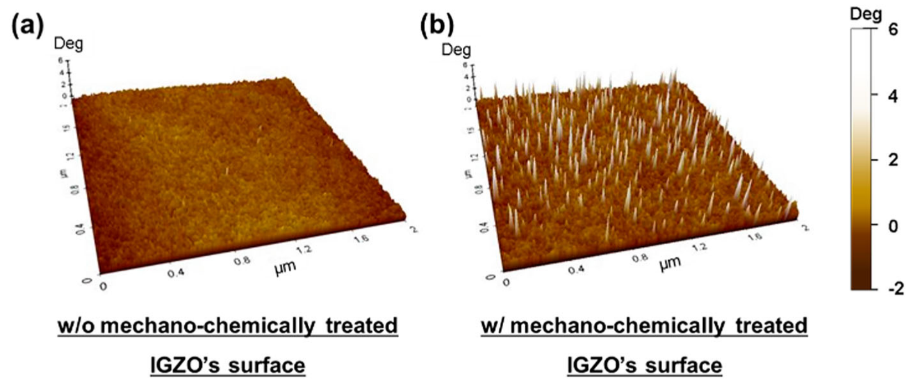


**Figure 2.** AFM analysis results of IGZO films: (a) non-treated IGZO surface; and (b) treated IGZO surface.

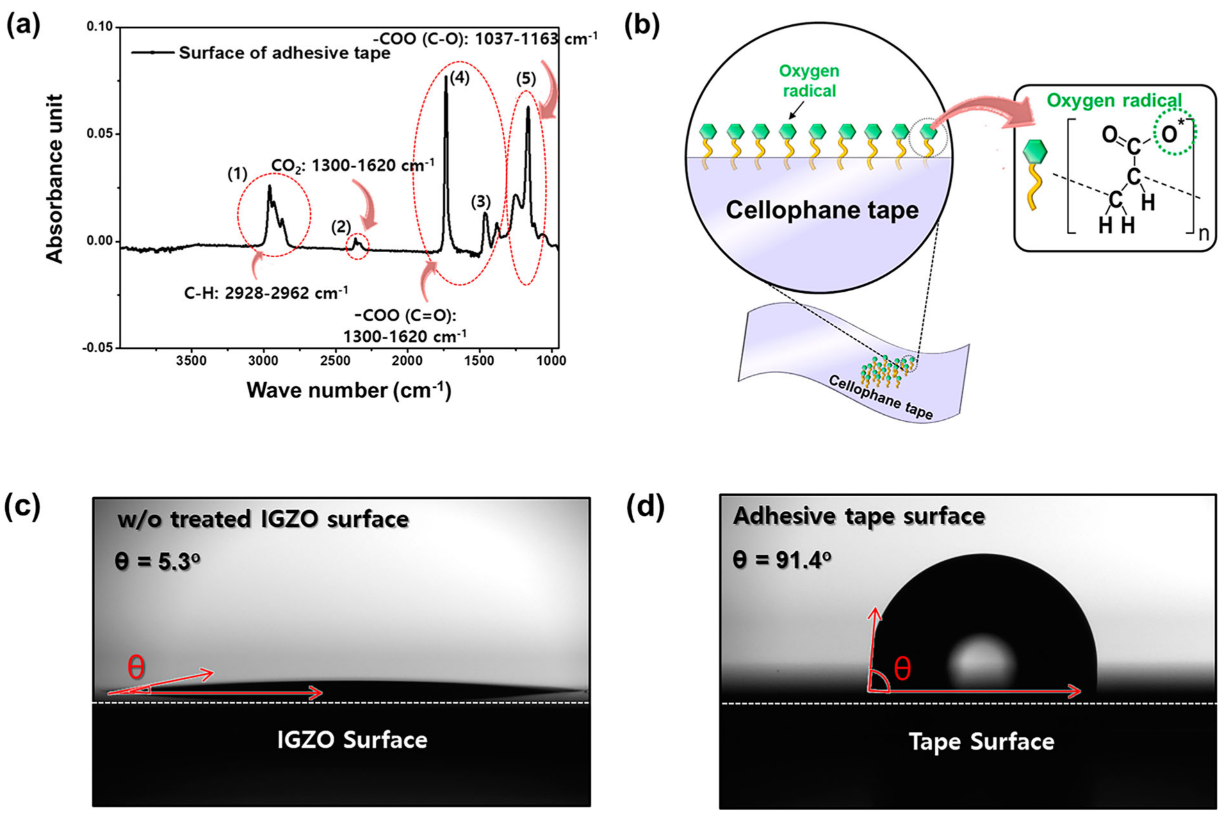


**Figure 3.** (a) FTIR spectroscopy on an adhesive tape surface. (b) Schematic illustration of polyacrylate on adhesive tape. Contact angle results of the surfaces of the (c) non-treated IGZO and (d) adhesive tape.

highly porous structures on the surfaces of the films can be correlated by improving the sensing response and sensitivity of the fabricated sensors [13,14]. Therefore, for the estimation of the sensing parameters of the phototransistor, the 3000 rpm fabricating condition was opted for. Next, to further confirm the hypothesis that the porous film helps in visible-light detection, the POL was applied to the phototransistor, and its characteristics were assessed. Figure 5a, c, and e show the transfer characteristics of the IGZO phototransistors without a POL under red-light (635 nm), green-light (532 nm), and blue-light (405 nm) illumination with different intensities. A high off current as well as a negative shift in threshold voltage was observed only under blue-light illumination, while there was little change in the transfer characteristics of the devices under red and green lights. The increase in off current under blue light was due to the ionization of the uncoordinated oxygen species present in the device [15]. Thus, it was established that the IGZO without a POL is responsive only to blue light for visible light. As shown in Figure 5b, d, and f, a higher off-current was observed under red-, green-, and blue-light illumination for devices with mechanochemically treated IGZO TFTs with a POL. The off current was higher in all the

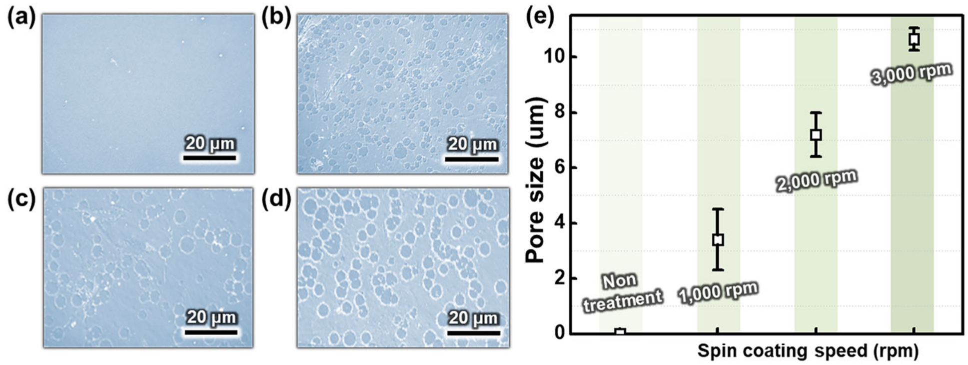


**Figure 4.** (a) Optical microscopy (OM) images of the IGZO films. OM images of POL on the IGZO films prepared at the (b) 1000 rpm, (c) 2000 rpm, and (d) 3000 rpm spin-coating speeds. (e) Error bars of the pore size denoting the standard deviations over five samples.

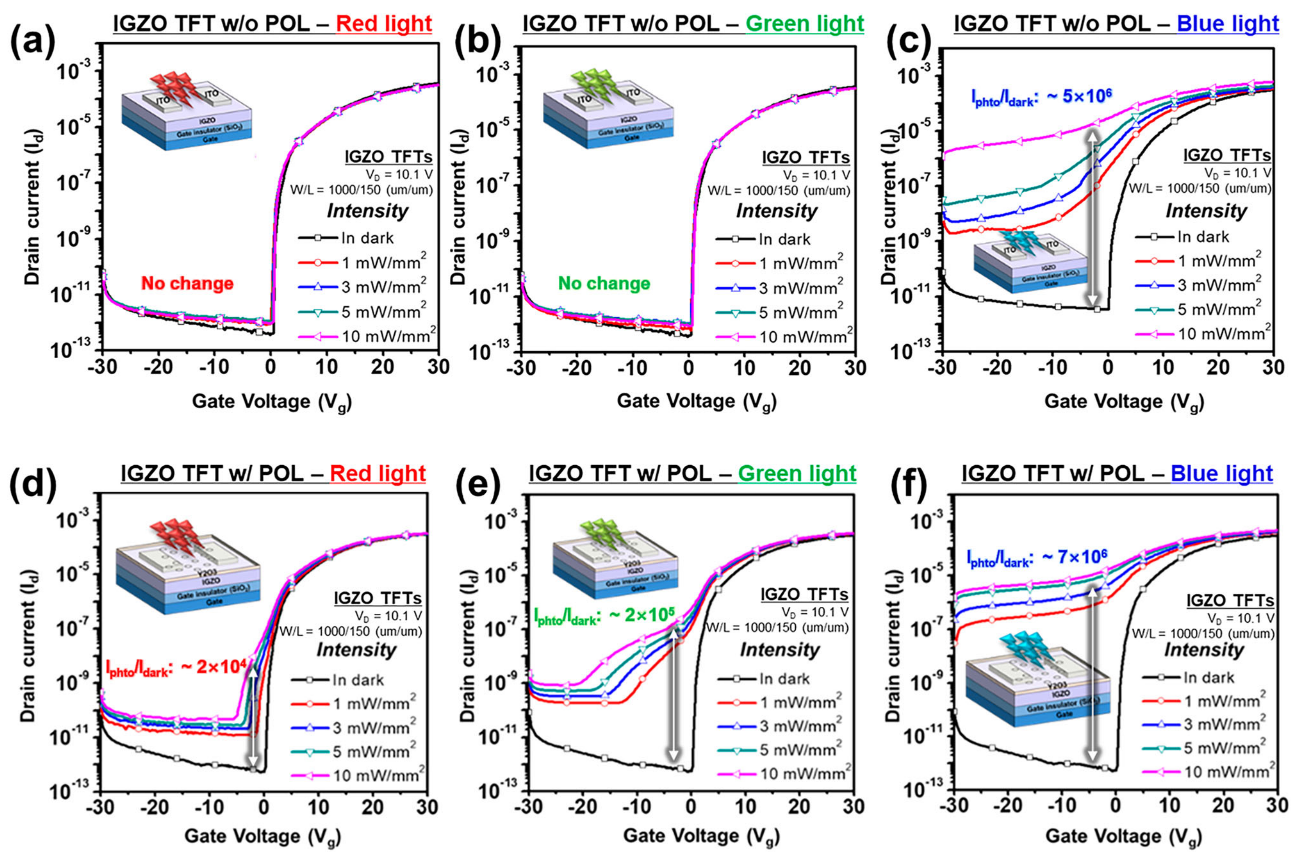


**Figure 5.** Transfer characteristics of IGZO phototransistors without a POL under (a) red-, (c) green-, and (e) blue-light illumination at different intensities. Transfer characteristics of IGZO phototransistors with a POL under (b) red-, (d) green-, and (f) blue-light illumination at different intensities.

cases with a negative shift in threshold voltage. These changes were more evident under blue light, and least evident under red light, implying a higher on/off current in devices under red light than in those under blue light. The saturation mobility and subthreshold swing for all the devices under a dark current were similar, indicating that the presence of pore sites and a $Y_2O_3$ passivation layer did not affect the electrical characteristics of the IGZO TFTs. The following is the mechanism of the improved detection ability in the IGZO TFTs with a POL. At first, the POL can generate an electron–hole pair under visible light through the physical defects and oxygen due to the generation of subgap states within the bandgap, which is between the valence and conduction bands [16]. Then the generated electrons are transferred to the IGZO channel layer, resulting in increased off current and a negative $V_{th}$ shift. Hence, POL can be used to detect visible light for IGZO TFTs, and has a less complex fabrication

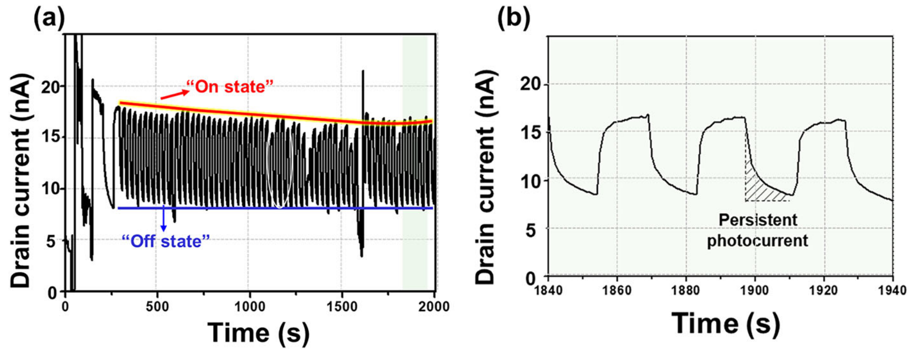


**Figure 6.** (a) Endurance test with green-light (532 nm) illumination at 0.02 Hz over 2000 seconds. (b) Magnified results of the endurance test from 1840 to 1940 seconds.

process and a higher surface area compared to other photonic devices. Lastly, as shown in Figure 6a, measurement was conducted at $V_G = -0.1$ V and $V_D = 10.1$ V for 2000 seconds (switching the same green-laser illumination condition at 0.02 Hz). As a result, the device exhibited high durability and clear switching between the on and off states, as can be seen in Figure 6b.

## 4. Conclusion

In this paper, the use of a porous oxide layer (POL) is suggested to improve the performance of the indium gallium zinc oxide (IGZO) thin-film transistors (TFTs). From these researches, the IGZO TFT with a POL showed improved photoresponsivity compared with the conventional IGZO TFT without a POL. These approach will allow IGZO TFTs to be adopted for photonic devices.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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## References

[1] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, Room-Temperature Fabrication of Transparent Flexible Thin-Film Transistors Using Amorphous Oxide Semiconductors, Nature **432**, 488–492 (2004).

[2] K. Nomura, H. Ohta, K. Ueda, T. Kamiya, M. Hirano, and H. Hosono, Thin-Film Transistor Fabricated in Single-Crystalline Transparent Oxide Semiconductor, Science **300** (5623), 1269–1272 (2003).

[3] S. Hong, J.W. Park, H.J. Kim, Y.-g. Kim, and H.J. Kim, A Review of Multi-Stacked Active-Layer Structures

for Solution-Processed Oxide Semiconductor Thin-Film Transistors, J. Inf. Disp. **17**, 93–101 (2016).

[4] J.-S. Park, J.K. Jeong, H.-J. Chung, Y.-G. Mo, and H.D. Kim, Electronic Transport Properties of Amorphous Indium-Gallium-Zinc Oxide Semiconductor Upon Exposure to Water, Appl. Phys. Lett. **92**, 072104 (2008).

[5] W.-K. Kim, J.-E. Jeong, J.H. Park, Y.C. Cho, S. Lee, S.-Y. Jeong, C.-R. Cho, and J.-S. Bae, The Effect of Hydrogen on the Electric Properties of Amorphous InGaZnO with Varying Zn Content, J. Korean Phys. Soc. **63**, 209–213 (2013).

[6] X. Yu, T.J. Marks, and A. Facchetti, Metal Oxides for Optoelectronic Applications, Nat. Mater. **15**, 383–396 (2016).

[7] J.S. Park, J.K. Jeong, Y.G. Mo, H.D. Kim, and S.I. Kim, Improvements in the Device Characteristics of Amorphous Indium Gallium Zinc Oxide Thin-Film Transistors by Ar Plasma Treatment, Appl. Phys. Lett. **90**, 262106 (2007).

[8] D. Kufer, and G. Konstantatos, Photo-FETs: Phototransistors Enabled by 2D and 0D Nanomaterials, ACS Photonics **3**, 2197–2210 (2016).

[9] J.W. Na, H.J. Kim, S. Hong, and H.J. Kim, Plasma Polymerization Enabled Polymer/Metal–Oxide Hybrid Semiconductors for Wearable Electronics, ACS Appl. Mater. Inter. **10**, 37207–37215 (2018).

[10] G. Jiao, G. Yu, W. Wang, X. Zhao, J. Zhang, and S.H. Ewart, Properties of Polysaccharides in Several Seaweeds from Atlantic Canada and their Potential Anti-influenza Viral Activities, J. Ocean Univ. China **11**, 205–212 (2012).

[11] M.K. Beyer, and H.C. Schaumann, Mechanochemistry: The Mechanical Activation of Covalent Bonds, Chem. Rev. **8**, 2922–2948 (2005).

[12] B. Baytekin, H.T. Baytekin, and B.A. Grzybowski, What Really Drives Chemical Reactions on Contact Charged Surfaces?, J. Am. Chem. Soc. **134**, 7223–7226 (2012).

[13] M.I. Azmer, Z. Ahmad, K. Sulaiman, F. Touati, T.M. Bawazeer, and M.S. Alsoufi, VOPcPhO: P3HT Composite Micro-Structures with Nano-Porous Surface Morphology, Appl. Surf. Sci. **399**, 426–431 (2017).

[14] Z. Chen, and C. Lu, Humidity Sensors: A Review of Materials and Mechanisms, Sensor Lett. **3**, 274–295 (2005).

[15] Y.J. Tak, D.J. Kim, W.G. Kim, J.H. Lee, S.J. Kim, J.H. Kim, and H.J. Kim, Boosting Visible Light Absorption of Metal-Oxide-Based Phototransistors via Heterogeneous In–Ga–Zn–O and $CH_3NH_3PbI_3$ Films, ACS Appl. Mater. Inter. **10**, 12854–12861 (2018).

[16] J. Chung, Y.J. Tak, W.G. Kim, B.H. Kang, and H.J. Kim, Artificially Fabricated Subgap States for Visible-Light Absorption in Indium–Gallium–Zinc Oxide Phototransistor with Solution-Processed Oxide Absorption Layer, ACS Appl. Mater. Inter. **11**, 38964–38972 (2019).