Improving Performances of Oxide Phototransistors Using a Mechano-Chemically Treated Porous Structure as The Visible Light Absorption Layer

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ABSTRACT

In this research, we suggest indium gallium zinc oxide (IGZO) thin film transistors (TFTs) for detection of visible light using a porous oxide layer (POL) resulting from mechano-chemical treatment. When compared with conventional IGZO TFT, the IGZO TFT with the POL exhibits photoresponsivity of 341.32 A/W, photosensitivity of 1.10 x 10^6, and detectivity of 4.54 x 10^{10} Jones under 532 nm light illumination.

1. INTRODUCTION

As the field of internet of things (IoT) 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 electrical and optical characteristics of photonic devices. In recent times, oxide based thin film transistors (oxide TFTs) have exhibited optimal electrical and optical characteristics such as high uniformity over large areas, low off current and high transparency in the visible light region [1-3]. Therefore, these characteristics imply that oxide TFTs are suitable for superior photonic devices [4]. However, oxide TFTs are not able to absorb visible light due to wide bandgap (> 3 eV) of the channel layer, hence their applicability has been limited to ultraviolet and blue light absorption applications [5]. As such, many researches have been conducted to enable oxide TFTs to absorb visible light using absorption layers such as organic polymers, carbon composites, metal nanoparticles and quantum dots [6-8]. Although the use of these materials allowed oxide TFT to absorb visible light, these materials can be costly and complex to fabricate in thin film structures. In this research, we propose a new method for detection of visible light by In-Ga-Zn-O (IGZO) TFTs. For detecting visible light, instead of single layered IGZO TFT, we propose double layered porous oxide layer (POL)/IGZO TFTs. The POL layer was spin coated on the back-channel region of the active layer while the front channel region is composed of IGZO only. The IGZO front channel is responsible for the adequate electron transport and the POL back channel is responsible for detecting the visible light. Thus, this structure can improve the performance of photo sensor while minimizing the degradations of on/off current ratio and the field effect mobility (μ_{FE}) compared with conventional IGZO TFT.

2. EXPERIMENTAL

2.1 Fabrication of IGZO TFT

Fig. 1 (a) depicts the fabrication process of the IGZO TFT. We fabricated the IGZO TFT using a heavily doped p-type Si wafer with 120 nm thick thermally oxidized SiO_2 acting as a gate insulator. We deposited IGZO channel layer on the Si substrate via a shadow mask using a radio frequency (RF) magnetron sputtering at room temperature using a mixed In_2O_3-Ga_2O_3-ZnO sputtering target (the molar ratio in In:Ga:Zn was 1:1:1). The power, working pressure and time of the sputtering were set at 150 W, 5.0 x 10^{-3}, and 5 min respectively. The IGZO film was then treated mechanochemically by placing the adhesive part of cellophane tape on the IGZO for 1 sec leaving organic residues. Aluminum source and drain electrodes were deposited on the treated IGZO channel layer via a shadow mask using magnetron sputtering. The width (W) and length (L) of the channel were 1000 µm and 150 µm respectively.

2.2 Preparation of porous oxide layer

After electrode deposition, POL was deposited on the treated film using spin coating, as shown in **Fig. 1 (b)**. For the spin coating process, 0.1 M Y_2O solution was prepared by dissolving ($Y(NO_3)_3 \cdot 6H_2O$) in 2-methoxyethanol. The prepared solutions were spin coated onto the treated IGZO film at 1000, 2000, and 3,000 rpm for 30 sec following a pre-annealing treatment at 100°C for 10 min to get rid of the organic solvents. The films were post annealed at 350°C for 1 hr to increase metal-oxide bond formation of IGZO and POL.

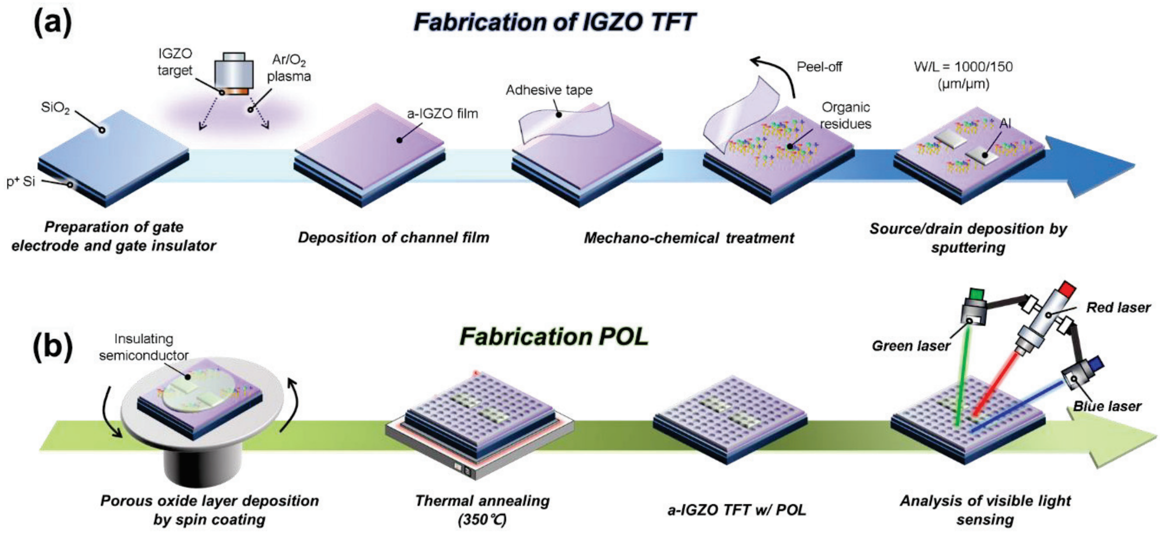

Fig. 1 Schematic diagram of fabrication process for IGZO TFT w/ POL using mechano-chemical treatment.

The electrical characteristics of the fabricated transistors were measured using a semiconductor parameter analyzer (HP 4156C: Agilent Technologies) in probe station at room temperature. The sources of light illumination used were monochromic lasers of red (635 nm), green (532 nm) and blue (405 nm) light.

3. RESULTS AND DISCUSSION

Firstly, to analyze mechano-chemical treated IGZO surface characteristics, the respective without and with mechano-chemical treated sample morphologies were measured by atomic force microscope (AFM). Their 3D images are shown in **Fig. 2**. Each image has 2 μm x 2 μm of measuring area. Three images illustrate different surface morphology appearances as the processing of the mechano-chemical treatment. In the w/o treated IGZO case, the morphology is smooth. On the contrary, the image of w/ treated IGZO reveals extremely populated fine peaks as a result of remained some residues. It is also noted that the RMS roughness of the **Fig. 2 (a)** and **(b)** were calculated to be 0.383 nm and 0.998 nm, where the w/ treated sample created the rough surface. Therefore, this rough surface can cause the surface of IGZO to be hydrophobic [9].

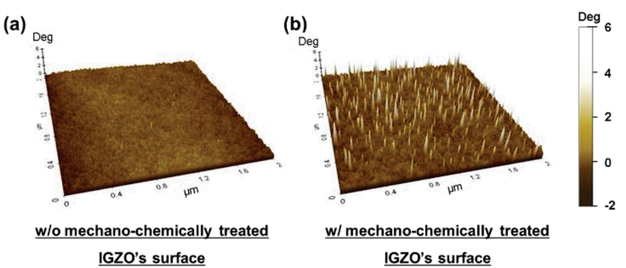

Fig. 2 The AFM analysis of IGZO films; (a) w/o treated surface of IGZO, (b) w/ treated surface of IGZO.

In **Fig. 3 (a)**, the chemical bond existing on the surface resulted from adhesive tape is shown through the Fourier transform infrared (FT-IR) spectrum. Each peak in the **Fig. 3 (a)** is related to the organic materials in the adhesive component [10]. Through FT-IR analysis, it was confirmed that the adhesive surface of tapes consisted of a poly-acrylate group, which forms the hydrophobic dots. **Fig. 3 (b)** shows an illustration of the species in which organic residues transferred to IGZO film due to the treatment [10]. The weak Van der Waals bonds of the organic materials are broken, and organic residues are formed when the polymers are detached from each other. This phenomenon is called "mechano-chemical reaction" [11, 12].

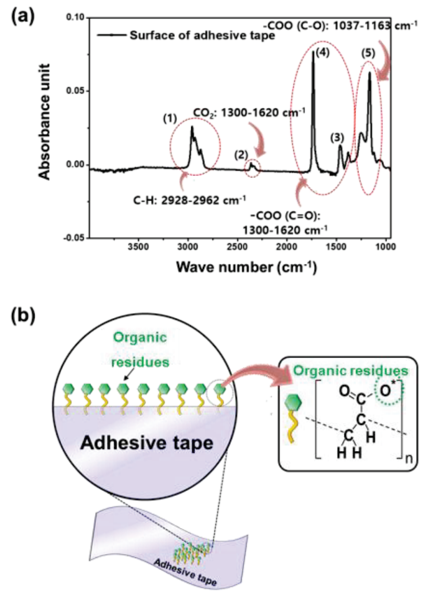

Fig. 3 (a) FT-IR spectroscopy on the surface of adhesive tape and (b) The schematic illustration of poly-acrylate on adhesive tape.

Secondly, after mechano-chemical treatment, as the POL is deposited using spin coating and formed at the back channel. This formation of POL causes porous structure due to hydrophobic dots. To confirm the effect, we fabricated POL under various spin coating conditions (i.e. from 1000 to 3000 rpm). As shown **Fig. 4**, as the spin coating speed increases, the pore size and the number of pores also increases. In this case, many researches demonstrated significant improvements in term of sensing response and sensitivity for the fabricated sensors that can be correlated with the emergence of highly porous-structures on the surface of the films [13, 14]. Therefore, for the estimation of the sensing parameters of the phototransistor we have opted for the 3000 rpm fabricating condition.

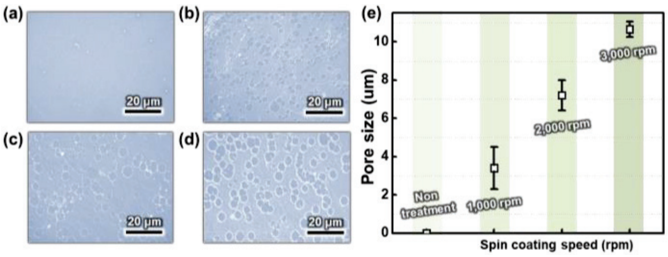

Fig. 4 (a) Optical microscopy (OM) image of the IGZO films. OM images of POL on the IGZO films prepared at spin-coating speeds of (b) 1000 rpm, (c) 2000 rpm, (d) 3000 rpm. (e) Error bars of pore size denote standard deviations over 5 samples.

Next, this further confirms the hypotheses which propose that the porous film can easily detect visible light, we want to apply the POL to the phototransistor and assess its characteristics. **Fig. 5 (a), (c), and (e)** shows the transfer characteristics of IGZO phototransistors without POL under different illumination intensities of red (635 nm), green (532 nm) and blue light (405 nm). A high off current as well as a negative shift in threshold voltage was observed under blue light illumination, while there was little to no change in transfer characteristics of devices under red and green lights. The increase in off current under blue light is due to the ionization of the uncoordinated oxygen species present in the device [15]. Thus, it was established that the IGZO w/o POL is responsive to blue light and non-responsive to red and green light. As depicted in **Fig. 5 (b), (d), and (f)**, a higher off current was observed under red, green and blue light illumination for devices with mechanochemically treated IGZO devices with POL. The off current was higher in all 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 ratio in devices under red light than those under blue light. The saturation mobility, and subthreshold swing for all devices under dark current were similar indicating that the presence of pore sites and Y_2O_3 passivation layer did not affect the electrical characteristics of the IGZO TFTs.

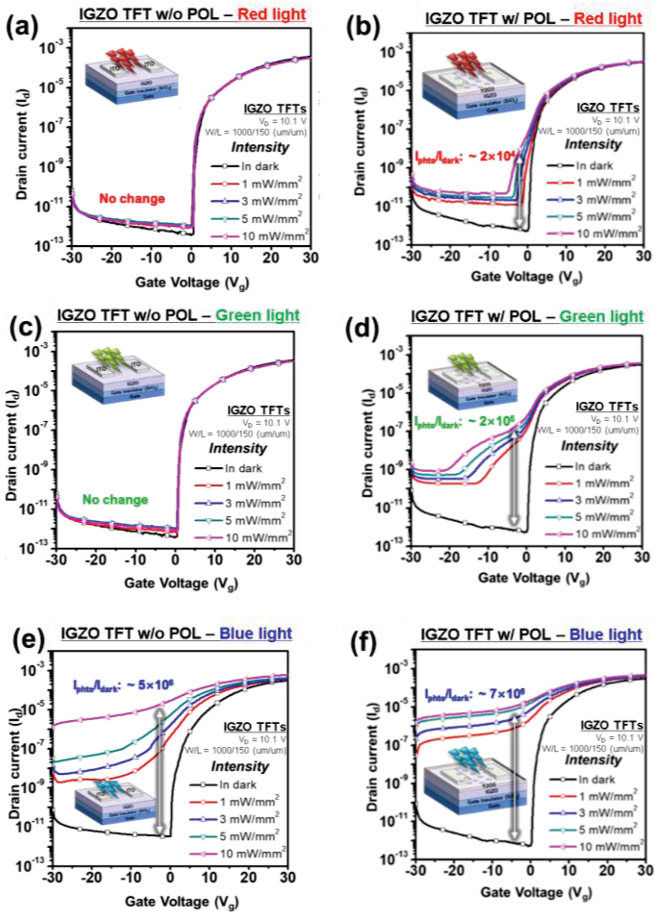

Fig. 5 Transfer characteristics of IGZO phototransistors without POL under (a) red, (c) green, and (e) blue light illumination at different intensities. Transfer characteristics of IGZO phototransistors with POL under (b) red, (d) green, and (f) blue light illumination at different intensities.

Lastly, we explained the mechanism of improved detection ability in the IGZO TFTs with POL. At first, the POL can generate electron-hole pair under visible light through physical defects and oxygen due to generate subgap states into the bandgap which is between the valence band and conduction band [16]. And then, excited carriers transferred to IGZO channel layer resulting in increased off-current and negative V_{th} shift. Hence, the POL can be used to detect visible region of IGZO TFT, and the POL can give rise to lower complexity of fabrication process and higher surface area compared to other research related to photonic devices.

4. CONCLUSION

In this paper, we have suggested porous absorption layer to improving the performance of the IGZO TFT. From these researches, the IGZO TFT w/ POL showed improved photo-responsivity compared with conventional IGZO TFTs w/o POL. These approaches will allow IGZO TFTs to be adapted for photonic devices.

5. ACKNOWLEDGEMENTS

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