Abstract—In this work, the influence of anion composition on the photoresponse characteristics of zinc oxynitride thin film transistors is investigated and compared directly to conventional In-Ga-Zn-O TFTs. Increasing the ratio of N to (N+O) led to higher field effect mobility and improved subthreshold swing. The subgap density of states extracted by monochromatic photonic capacitance-voltage measurement indicated that the nitrogen-related defect states, such as nitrogen vacancies, increased with increasing nitrogen gas flow. Furthermore, the photoconductivity mechanism of ZnON TFTs is discussed in detail.

Index Terms—Zinc oxynitride (ZnON), anion composition, persistent photoconductivity (PPC), subgap density of states (DOS).

I. INTRODUCTION

Increasing demands for low-cost switching or driving transistors by the flat panel display industry have led to the development of amorphous metal oxide based semiconductors (AOSs), such as In-Ga-Zn-O (IGZO) [1]. Compared to amorphous silicon, thin film transistors (TFT) based on AOSs exhibit relatively high field effect mobility (> 10 cm²/Vs), and are suitable for large size and high resolution active matrix light emitting diode panel [1]. However, most AOSs inevitably contain oxygen-related defects, such as oxygen vacancies (Vos) that may induce persistent photoconductivity (PPC) problems under illumination [2, 3].

Recently, a relatively new type of semiconductor, zinc oxynitride (ZnON), succeeded in obtaining high mobility (> 50 cm²/Vs) [2, 4]-[7]. In addition, ZnON is fabricated through a simple and cost-effective process using reactive sputtering with a Zn metal target. The optimization of the associated TFT properties to obtain sufficiently low leakage current levels while maintaining high field effect mobility usually consists of controlling either the anion composition ratio [8], [9] or the doping process [10, 11] in the ZnON layer. It has also been reported that ZnON TFTs exhibit excellent stability with suppressed PPC effects under illumination [3]. It is suggested that the incorporation of nitrogen into ZnO shifts the valence band maximum (VBM) level upwards, effectively passivating the Vos [4], [7]. Nevertheless, the influence of anion composition on the PPC effects and the change in subgap density of states (DOS) in ZnON have scarcely been investigated.

In this work, the PPC phenomenon of ZnON TFTs with various anion compositions was investigated with subgap DOS analysis. The subgap DOS of each device was extracted by the monochromatic photonic capacitance-voltage (MPCV) technique. The anion composition of ZnON was modulated by the flow rate of reactant gas during the sputter deposition. Extracted subgap DOS distribution indicated that the nitrogen-related defect states (VN+) strongly affect the PPC of ZnON. Furthermore, the PPC mechanism of ZnON TFTs is compared in detail to that of conventional amorphous IGZO TFTs.

II. EXPERIMENTS

Firstly, bottom gate IGZO and ZnON TFTs were fabricated using a glass substrate. A 200-nm-thick Mo was utilized for the bottom gate, and deposited by direct-current (DC) sputtering at room temperature. The gate dielectrics of 350-nm-thick SiN and 50-nm-thick SiO2 were then deposited using plasma-enhanced chemical vapor deposition (PECVD) at 350 °C. The ZnON active layer with a thickness of 50 nm was deposited through reactive radio-frequency (RF) magnetron sputtering using a Zn metal target and N2 and O2 gas reactants. To control the anion composition, the gas flow ratio of Ar:O2:N2 (scrm) was modulated as 10:2:100, 10:3:100, and 10:4:100, corresponding to N/(N+O) ratios of 85%, 80%, and 60%, respectively, based on Rutherford backscattering spectrometry analysis. Deposition of the IGZO (50 nm-thick) utilized DC sputtering with an In2Ga2ZnO7 target. The gas mixture ratio of Ar:O2 (scrm) was fixed at 35:20. After active layer deposition, a 100-nm-thick SiO2 etch-stop layer was deposited at 200 °C.
through PECVD. Finally, DC sputtering was used to deposit a 100 nm-thick Mo (IGZO) and AlNd (ZnON) source/drain layer. The channel layer width/length was 50 \( \mu \text{m} \) / 50 \( \mu \text{m} \). The post annealing process was performed in air for one hour at 250 \(^\circ\)C.

All electrical properties were measured using an Agilent 4156C precision semiconductor parameter analyzer. The photoresponse property of the drain current (\( I_{DS} \)) was observed using a laser source with a wavelength of 532 nm. Capacitance-voltage (C-V) data was measured using an HP 4284A precision LCR meter. The subgap DOS of each IGZO and ZnON TFT was extracted using the MPCV technique [12]. The conditions for the C-V characteristics were as follows: \( \lambda_{ph} = 440 \text{ nm} \) (IGZO), 1064 nm (ZnON), \( P_{op} = 4 \text{ mW} \) (IGZO), 2 mW (ZnON), and AC signal frequency = 50 kHz (IGZO), 10 kHz (ZnON).

### III. Results and Discussion

Fig. 1(a) shows the electrical characteristics of IGZO and ZnON TFTs. Here, transfer curves of the ZnON TFTs are illustrated with different N/(N+O) ratios: ZnON (85 %), ZnON (80 %), and ZnON (60 %). The extracted transfer parameters of threshold voltage (\( V_{th} \)), subthreshold swing (S.S.), and field effect mobility (\( \mu_{FE} \)) for each TFT are depicted in Fig. 1(b). In the ZnON TFTs, as the N/(N+O) ratio increases, the \( \mu_{FE} \) is increased, while the S.S. and \( V_{th} \) become lower.

The extracted subgap DOS of IGZO and ZnON TFTs with different N/(N+O) ratios is illustrated in Fig. 2(a)–2(d). The DOS profile is found to be well fitted with the exponential shape and Gaussian peak. In the IGZO case, the \( g_D(E) \), which corresponds to \( V_0 \) states, is dispersed in the band gap energy. The \( g_D(E) \) near the conduction band minimum (CBM) indicates ionized \( V_0 \) states [13–15]. Similarly, ZnON also exhibits \( g_A(E) \) and \( g_D(E) \) regardless of the N/(N+O) ratio, which corresponds to \( V_{NS} \) and ionized \( V_{NS} \), respectively [16]. Moreover, the \( g_D(E) \) of ZnON increased with respect to the N/(N+O) ratio, suggesting that the \( V_{NS} \) is increased. Fig. 2(e) shows the band structure of IGZO and ZnON (60 %), indicating the location of possible defects in IGZO and ZnON.

Fig. 3(a) shows the experimental method for evaluating the PPC test, in which the duration of each light (illumination) and dark (recovery) state was fixed at 300 s. The energy of irradiated light onto IGZO and ZnON TFTs for testing PPC was same (\( E_{ph} = 2.33 \text{ eV} \)). Fig. 3(b) shows the photocurrent of IGZO and ZnON TFTs, where three devices of ZnON TFTs with each N/(N+O) ratio were used for accurate PPC test results. Firstly, IGZO TFTs, as expected, displayed a gradually increasing photocurrent and a high PPC that originated from ionization of \( V_0 \) states. The PPC of ZnON TFTs increased when the N/(N+O) ratio increases, i.e., of ZnON (85 %) TFTs demonstrated higher PPC, while in ZnON (60 %) TFTs exhibited negligible PPC. Fig 3(c) shows the normalized current level of the IGZO and ZnON devices after the second PPC test as a function of time. Fig. 3(d) shows the optical sensitivity (log(I_{DS,1}/I_{DS,0})) and residual current ratio (log(I_{DS,1d}/I_{DS,0})) of the IGZO and ZnON TFTs, where I_{DS,0}, I_{DS,1}, and I_{DS,1d} indicate the initial off-state current before PPC test (10 pA), the photocurrent after 1st illumination (300 s), and the residual current after recovery time (600 s), respectively. All ZnON TFTs exhibited higher optical sensitivity compared to IGZO TFTs. Additionally, while the residual current ratio of ZnON (85 %) was slightly higher than those of IGZO TFTs, IGZO TFTs showed the slowest recovery when the light source was removed, as seen in Fig. 3(b) and (c).

To investigate the origin of PPC in ZnON, the subgap DOS was extracted before and after the PPC test, where...
each N/(N+O) ratio were used for accurate extraction results. Figs. 4(a)–4(h) show the g(E) distribution of IGZO and ZnON TFTs before and after the PPC test. After the PPC test, the $V_o$ ionization results for the IGZO reveal that the $g_D$ near to VBM slightly decreased and $g_D$ near to CBM slightly increased. Similarly, the $g_D$ near the VBM level decreased for all ZnON TFTs. Conversely, large values of $g_D$ near the CBM were observed in ZnON TFTs after the PPC test. Therefore, the PPC of ZnON TFTs may originate from the ionized VN.

The schematic illustration of the carrier generation mechanism and the photoresponse behavior during PPC test of IGZO and ZnON is shown in Fig. 5. As demonstrated by Fig. 5(a), the PPC of IGZO mainly originates from the ionization of VO when a light source with 2.33 eV is used. It has been reported that the VO trap the holes in ZnO-based semiconductors, thus prevent electron-hole recombination after illumination. The defect ionization is a dominant component in this case, which causes PPC in IGZO. Accordingly, such defect-dependent carrier generation appears as the slow recovery regime during the PPC test. However, as shown in Fig. 5(b), the light energy of 2.33 eV is quite large compared to band gap energy of ZnO. Therefore, two types of carrier generation models are anticipated as follows: (i) band-to-band generation, and (ii) ionization of VN. Generally, the band-to-band generation in AOS does not significantly affect the PPC phenomenon, as these generated carriers recombined immediately when the light source was turned off. Accordingly, band-to-band carrier generation represents the fast recovery regime in PPC test. Moreover, it suggests that an ionized VN is the main component in the slow recovery region for ZnO PPC. Similar to VO, VN may prevent the recombination of electrons and holes. This results in an increased slow recovery region as the nitrogen content ratio in the ZnON layer is increasing.

IV. Conclusion

In this work, the effects of anion composition ratio on the subgap DOS and PPC effects of ZnON TFTs were investigated. The extracted subgap DOS revealed that the nitrogen-related defect states, such as VN, increased with increasing nitrogen flow rate during the sputtering process. Moreover, these increased VN caused more severe PPC effects, which can be considered similar to the VO dependent PPC phenomenon in IGZO. Therefore, controlling VN using subgap DOS analysis represents a very important step for obtaining high performance and PPC-free ZnON TFTs.

REFERENCES


