Highly Transparent, High-Performance IGZO-TFTs Using the Selective Formation of IGZO Source and Drain Electrodes

Hung-Chi Wu and Chao-Hsin Chien

***Abstract*— In this letter, high-performance, highly transparent amorphous InGaZnO (IGZO) thin-film transistors (TFTs) with IGZO source/drain electrodes were fabricated. Rapid thermal annealing treatment effectively converted IGZO from a semiconductor into a conductor. Using a patterned SiO_2 capping layer, highly transparent IGZO-TFTs with selectively formed IGZO electrodes were fabricated on a glass substrate. The mobility of the fabricated IGZO-TFT was 8.3 cm^2/V s, ON/OFF ratio was 3.1 × 10^6, and subthreshold swing was 0.44 V/decade. Thus, the proposed scheme provides a simple and practical method of fabricating high-performance, highly transparent IGZO TFTs.**

***Index Terms*— RTA, self-aligned, IGZO, TFT.**

I. Introduction

IN-GA-ZN-O (IGZO) is an extremely promising candidate for use in amorphous oxide semiconductors because IGZO thin film transistors (TFTs) typically exhibit excellent electrical performance, including high channel mobility, a favorable on/off ratio, a steep subthreshold swing (S.S.), and an acceptable threshold voltage [1]. IGZO is widely used in flexible electronics, TFTs, electronic paper, and sensors, and is positioned to become mainstream in the next generation of TFT technology [2], [3]. However, controlling the composition of oxygen in IGZO is challenging; the ratio of oxygen atom in IGZO and the oxygen bonding state can be drastically influenced by the deposition condition, heat treatment, and other factors [4], [5]. Chasin *et al.* discovered that changing oxygen content in IGZO by varying oxygen flow during deposition considerably influenced the properties of the contact between electrodes and IGZO. They successfully formed a Schottky contact with metal by using appropriate amounts of IGZO oxygen [6].

Recently, numerous groups have focused on the fabrication of fully transparent, homojunctioned IGZO-TFTs. Ahn *et al*. demonstrated that plasma treatment can form IGZO into an effective electrode; in addition, H_2 plasma treatment increases the carrier concentration in IGZO and effectively defines electrode regions [7]. Chen *et al*. reported that phosphorus implantation enabled IGZO to act as an electrode, demonstrating the possibility of fabricating the IGZO-TFTs by forming self-aligned electrodes [8]. The authors of this study previously demonstrated highly transparent full IGZO-TFTs, in which IGZO was turned into an effective electrode by using rapid thermal annealing (RTA) [9]. However, the previously proposed fabrication process was more complicated compared with the processes used in other studies [7]–[9]; IGZO was required to be deposited twice—once for the electrode, and once for the semiconductor channel region.

In the current study, a novel and simple scheme for fabricating highly transparent, high-performance IGZO-TFTs with selectively formed IGZO electrodes is proposed. Using SiO_2 capping on the IGZO channel altered the oxygen bonding states of the uncovered IGZO regions. RTA treatment converted the semiconductor regions into conductor regions, facilitating the formation of highly transparent IGZO TFTs with selectively formed IGZO electrodes.

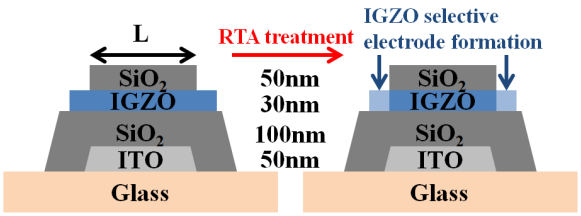

Fig. 1. Schematic structures of IGZO-TFTs in this work.

II. Device Fabrication

Fig. 1 shows the schematic IGZO-TFT structure. A glass substrate was used as the starting material. After cleaning the substrate, a 50-nm ITO layer, connected to the pad for probe contacting, was defined and deposited using lithography, and an E-gun provided the gate electrode. A −100nm SiO_2 layer was then formed at 300 °C by using plasma-enhanced chemical vapor deposition (PECVD). A 200-μm wide, 50-μm long channel region was patterned using lithography. Sputtering was then used to deposit 30 nm of IGZO. The process was previously reported [9]. Next, a 50-nm SiO_2 layer was deposited at 150 °C by using PECVD, and patterned by lithography using the same mask for defining the ITO gate electrode. The channel length was defined based on the length of the SiO_2 cap. After fabrication, the devices were treated using RTA at 400 °C for 1 minute. The electrical characteristics were measured using HP4156 semiconductor parameter

Manuscript received March 23, 2013; revised April 1, 2014; accepted April 8, 2014. Date of publication May 1, 2014; date of current version May 20, 2014. This work was supported by the NSC under Project 101-2628-E-009-011-MY3. The review of this letter was arranged by Editor W. S. Wong.

H.-C. Wu is with the Department of Electronics Engineering and Institute of Electronics, National Chiao-Tung University, Hsinchu 300, Taiwan.

C.-H. Chien is with the Department of Electronics Engineering, Institute of Electronics, National Chiao-Tung University, Hsinchu 300, Taiwan, and also with the National Nano Device Laboratories, Hsinchu 300, Taiwan (e-mail: chchien@faculty.nctu.edu.tw).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2014.2317943

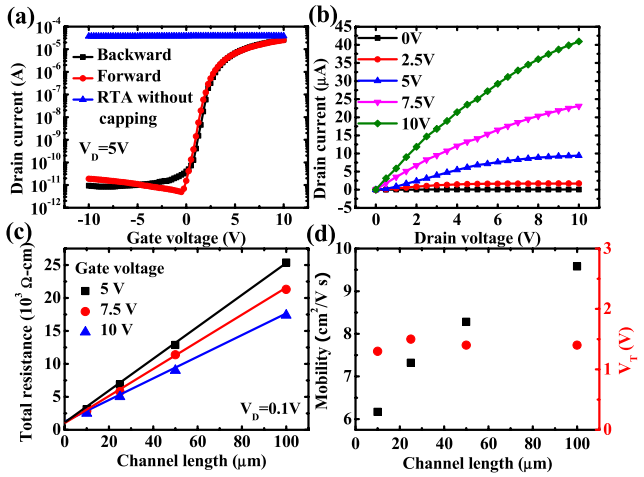

Fig. 2. (a) Transfer and (b) output characteristics of the IGZO-TFTs with W/L = 200/50 μm. The blue line in (a) is for the IGZO-TFT subject to the RTA treatment without SiO_2 capping. (c) Width-normalized on-state resistance as a function of the channel length at different gate voltages. (d) Mobility and threshold voltage in the linear region as a function of the channel length.

analyzer. The thin film properties were measured using X-ray photoelectron spectroscopy (XPS) and Hall measurement, and the optical transmission measurement of the IGZO film was measured using ultraviolet/visible/near infrared spectroscopy (Hitachi U-4100).

III. Results and Discussions

Fig. 2(a) shows the transfer characteristics of the fabricated IGZO-TFT. The differences between two sweeping directions observed in the off-state indicated numerous trap states in the IGZO channel after RTA [10]. The transfer characteristic of an IGZO-TFT that lacked a SiO_2 capping layer yielded only a horizontal line; in other words, no on/off feature was observed. This confirmed the effect of RTA treatment on the properties of IGZO. To determine how RTA treatment affected the interface, an IGZO-TFT involving a Ti electrode, which did not undergo RTA treatment, was also fabricated (not shown). The S.S. was approximately 0.44 V/decade, which was nearly identical to that of the IGZO-TFT with IGZO electrodes. This result indicated that RTA only influenced the IGZO properties near the surface, and did not substantially affect the interface between the IGZO and SiO_2 dielectric layer. Fig. 2(b) shows the corresponding output characteristics; the output behavior was rather normal. Fig. 2(c) shows the channel-width-normalized on-state resistance as a function of the channel length at various gate voltages. The contact resistance extracted using the transfer line method [11] was 713 (Ω-cm), which was larger compared with that in previous studies [7] and [8]. Defining the SiO2 cap by using the same lithography mask as the ITO gate electrode elucidates the upper limit of the contact resistance. In practice, the length of the SiO2 cap (i.e., channel length) must be defined using a separate mask that exhibits smaller dimensions compared with the gate length, generating reduced contact resistance at the cost of increased gate/drain and gate/source overlap capacitance. Fig. 2(d) exhibits the mobility and threshold voltage in the linear region as a function of the channel length. The threshold voltage did not differ markedly among TFTs demonstrating various channel lengths, implying that RTA treatment did not substantially influence the properties of the

TABLE I
Several Parameters of Our and Two Previously Reported IGZO-TFTs

Method	V_{th} (V)	Mobility (cm^2/ V sec)	S.S. (V/decade)	On/Off ratio	Contact resistance (Ω-cm)
In this work	1.4	8.3	0.44	3.1×10^6	713
Plasma [7]	0.96	7.27	0.49	1.2×10^7	75
Ion implantation[8]	5.6	5	0.5	6.0×10^7	260

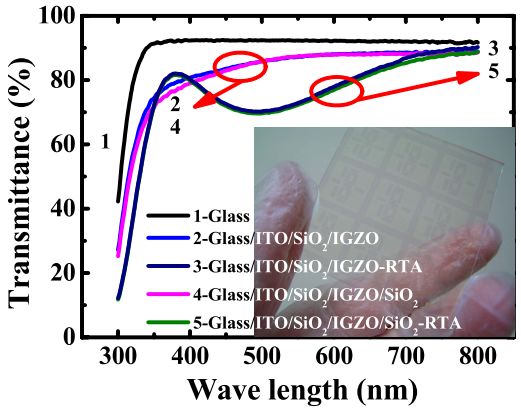

Fig. 3. Transmission spectra of our sample at different stage during IGZO-TFTs fabrication. Inset is the photograph of the fabricated IGZO-TFTs.

IGZO channel. In addition, mobility increased as the channel length increased, indicating that contact resistance limits the effective mobility of the device at short channel lengths; thus, channel length is a critical factor in determining the level of device performance. Table I shows a comparison between the IGZO-TFTs and IGZO electrodes formed using various processes. The electrical performances of the IGZO-TFTs fabricated in this study were comparable to those of electrodes fabricated using plasma and/or ion implantation. Although high contact resistance degraded the electrical performances, the fabricated device exhibited satisfactory device mobility compared with that of devices fabricated in previous studies [7] and [8]. This satisfactory device mobility was attributed to the properties of the IGZO channel rather than the contact resistance. The hydrogen released from the PECVD-deposited SiO_2 may diffuse into the IGZO channel and improve device mobility, because of hydrogen can act as a donor in IGZO. A high carrier concentration in the IGZO channel results in increased device mobility [12]. Thus, RTA treatment enables IGZO to act as an electrode, and reducing the contact resistance warrants further investigated. These results elucidate the possibility of fabricating highly transparent, high-performance IGZO-TFTs by using RTA treatment.

Fig. 3 shows the optical transmittance spectra of the sample at various stages of device fabrication without considering reflectance. The samples were high transparency (70%) at the wavelengths above 350 nm. However, in the visible region, this drop in transparency was obvious when compared with the reference sample. The degradation may have been caused by the presence of the ITO layer or the effect of thin-film thickness. This result demonstrated that the

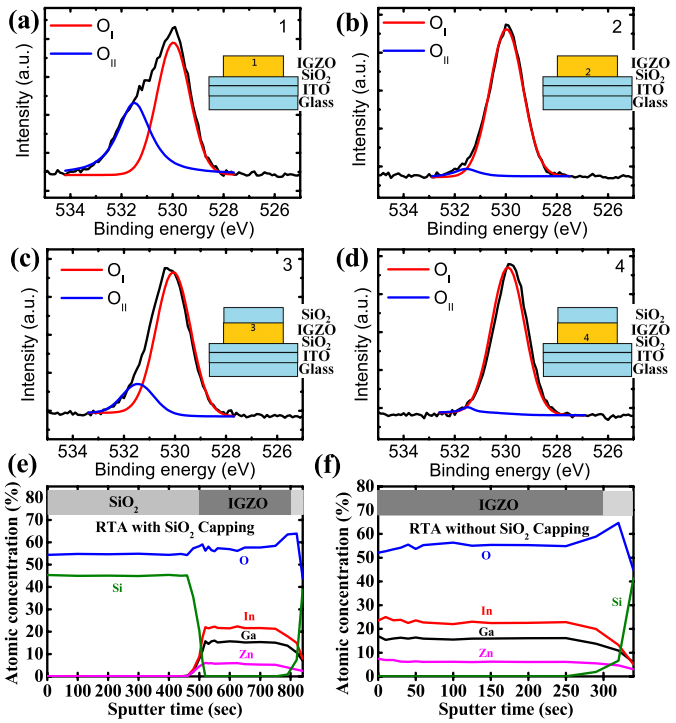

Fig. 4. (a)(b) O 1s XPS narrow scan spectra of the IGZO thin films without SiO_2 capping layer during the RTA treatment. (c)(d) The same condition with SiO_2 capping layer. The number means the analyzed regions (1 and 3 for the surface; 2 and 4 for the bottom). (e)(f) The XPS depth profiles of the IGZO layers with and without SiO_2 capping layer after the RTA treatment.

IGZO layer retained a high level of transmittance after RTA treatment. Therefore, high-performance, highly transparent IGZO-TFTs with selectively formed IGZO electrodes were fabricated using the proposed scheme.

Fig. 4 shows the O_{1s} XPS narrow scan spectra of IGZO thin film with and without a SiO_2 capping layer. All samples were calibrated based on the carbon signal. The IGZO layers with and without SiO_2 capping layer yielded considerable differences in O_{1s} signals near the surface region The O_{1s} peak can be fitted by two nearly Gaussian distributions. O_I(529.96 $\pm$ 0.1eV) is related to the O_2^- ion in the lattice surrounded by the Zn, Ga and In atoms in the IGZO compound system. O_{II} (531.55 $\pm$ 0.1eV) is associated with O_2^- ions located in oxygen-deficient regions within the matrix of IGZO [14] and [15]. The ratio of O_{II} state in the surface region was increased in the absence of a SiO_2 capping layer after RTA treatment, but no obvious difference in O_{II} state ratio was observed in the bottom region in either case. These results further indicated that RTA treatment changes only the properties near the surface region of the IGZO, and maintains the properties of the bottom region. Thus, the IGZO TFT that lacked SiO_2 capping did not exhibit an on/off feature after RTA treatment. Figs. 4(e) and (f) show the XPS depth profiles of the IGZO layer with and without a SiO_2 capping layer after RTA treatment. A greater reduction in oxygen near the surface region occurred in the IGZO layer that lacked capping, compared with the capped IGZO layer. RTA treatment facilitated oxygen out-diffusion from the IGZO layer, generating oxygen vacancies [9], and resulting in an increased carrier concentration (approximately $10^{20}/cm^3$) and Hall mobility of carriers in the IGZO. Therefore, the SiO_2 capping layer can be used to stop oxygen out-diffusion during RTA treatment. The effect of RTA treatment is primarily limited to the surface region, and does not affect the entire IGZO region. Furthermore, oxygen vacancies and oxygen bonding states play a critical role in determining the resultant IGZO properties.

IV. Conclusion

In summary, high-performance and highly transparent IGZO-TFTs with selectively formed IGZO electrodes were developed in this study. The optical transmittance spectra demonstrated that RTA treatment did not considerably degrade the transmittance of IGZO thin film. An XPS analysis demonstrated that the RTA process transformed the oxygen bonding states of the IGZO, causing IGZO to behave as a conductor. In addition, the results indicated that RTA treatment influenced only the surface region of the IGZO layer. The oxygen bonding state in IGZO is essential in determining the electrical performance of IGZO-TFTs. The proposed scheme enables fabricating highly transparent IGZO-TFTs with homojunctioned IGZO electrodes.

References

[1] K. Nomura *et al.*, "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors," *Nature*, vol. 432, pp. 488–492, Nov. 2004.

[2] T. Kamiya, K. Nomura, and H. Hosono, "Present status of amorphous In-Ga-Zn-O thin-film transistors," *Sci. Technol. Adv. Mater.*, vol. 11, no. 4, p. 044305, 2010.

[3] K. Nomura *et al.*, "Thin-film transistor fabricated in single-crystalline transparent oxide semiconductor," *Science*, vol. 300, pp. 1269–1272, May 2003.

[4] J. S. Park *et al.*, "Review of recent developments in amorphous oxide semiconductor thin-film transistor devices," *Thin Solid Films*, vol. 520, no. 6, pp. 1679–1693, 2012.

[5] D. Zhang *et al.*, "In_2O_3 nanowires as chemical sensors," *Appl. Phys. Lett.*, vol. 82, no. 10, pp. 1613–1615, 2003.

[6] A. Chasin *et al.*, "High-performance a-In-Ga-Zn-O Schottky diode with oxygen-treated metal contacts," *Appl. Phys. Lett.*, vol. 101, no. 11, pp. 113505-1–113505-5, 2012.

[7] B. D. Ahn *et al.*, "Comparison of the effects of Ar and H_2 plasmas on the performance of homojunctioned amorphous indium gallium zinc oxide thin film transistors," *Appl. Phys. Lett.*, vol. 93, no. 20, p. 203506, 2008.

[8] R. Chen *et al.*, "Self-aligned indium-gallium-zinc oxide thin-film transistor with phosphorus-doped source/drain regions," *IEEE Electron Device Lett.*, vol. 33, no. 8, pp. 1150–1152, Aug. 2012.

[9] H. C. Wu and C. H. Chien, "High performance InGaZnO thin film transistor with InGaZnO source and drain electrodes," *Appl. Phys. Lett.*, vol. 102, no. 6, pp. 062103-1–062103-4, 2013.

[10] K. Hoshino and J. Wager, *Stability of IGZO-Based Thin-Film Transistor: Stability and Temperature-Dependence Assessment of IGZO TFTs*. Saarbrücken, Germany: LAP LAMBERT Academic Publishing, 2010.

[11] J. Kanicki and S. Martin, *Thin-Film Transistors*, C. R. Kagan and P. A. Dekker, Eds. Cleveland, OH, USA: CRC Press, 2003.

[12] J. S. Lee *et al.*, "The influence of the gate dielectrics on threshold voltage instability in amorphous indium-gallium-zinc-oxide thin film transistors," *Appl. Phys. Lett.*, vol. 95, no. 12, pp. 123–502, Sep. 2009.

[13] H.-J. Chang *et al.*, "RF sputtered low-resistivity and high-transmittance indium gallium zinc oxide films for near-UV applications," *Electrochem. Solid State Lett.*, vol. 14, no. 3, pp. H132–H134, 2011.

[14] Y. Wang *et al.*, "Highly transparent solution processed In-Ga-Zn oxide thin films and thin film transistors," *Sol-Gel Sci. Technol.*, vol. 55, no. 3, pp. 322–327, 2010.

[15] B. Kim *et al.*, "Origin of threshold voltage shift by interfacial trap density in amorphous InGaZnO thin film transistor under temperature induced stress," *Appl. Phys. Lett.*, vol. 99, no. 6, p. 062108, 2011.