Available online at www.sciencedirect.com
SciVerse ScienceDirect
Ceramics International 39 (2013) 2561–2566
CERAMICS INTERNATIONAL
www.elsevier.com/locate/ceramint

Transparent Al–In–Zn–O Oxide semiconducting films with various in composition for thin-film transistor applications

Jun Yong Bak[a], Shinhyuk Yang[b,c], Sung Min Yoon[a,*]

[a]Department of Advanced Materials Engineering for Information & Electronics, Kyung Hee University, Yongin, Gyeonggi-do 446-701, Repbulic of Korea
[b]Department of Information Display, Kyung Hee University, Seoul 130-701, Repbulic of Korea
[c]Electronics and Telecommunications Research Institute (ETRI), Daejeon 305-700, Repbulic of Korea

Received 10 July 2012; received in revised form 28 August 2012; accepted 5 September 2012
Available online 13 September 2012

Abstract

Al–In–Zn–O thin-film transistors were fabricated. To examine the effect of In composition, we adopted a co-sputtering method using Al–Zn–O and In_2O_3 targets. The sputtering power of In_2O_3 was varied to 200, 150, and 50 W. The mobility and turn-on voltage of each device were 27.8 $cm^2V^{-1}s^{-1}$ and −4.2 V, 4.5 $cm^2V^{-1}s^{-1}$ and −3.5 V, 0.7 $cm^2V^{-1}s^{-1}$ and −3 V, respectively. We also investigated instabilities under negative gate bias stress (NBS) and negative bias illumination stress (NBIS). While the NBS was not influenced by the In contents, the NBIS characteristics were optimized for the device with In_2O_3 sputtering at 150 W.

Keywords: Thin film transistors; Oxide semiconductor; Al–In–Zn–O

1. Introduction

Oxide thin-film transistors (TFTs) have been vigorously researched and developed for various promising applications that demand good uniformity in device behaviors, high carrier mobility, and low temperature process compatibility [1,2]. Many factors affect the oxide TFT performance, including the fabrication methods, device structures, and material composition of the semiconducting active channels. Among them, the constituent elements and composition of a channel material have a great impact on its electrical characteristics. So far, various materials of oxide semiconductors, such as ZnO [3], In–Zn–O (IZO) [4], In–Ga–Zn–O (IGZO) [5,6], Al–Zn–Sn–O (AZTO) [7], and Al–In–Zn–Sn–O [8], have been intensively studied. In the case of IGZO, it is generally accepted that In, Ga, and Zn have distinct roles, to form the electron pathways, suppress carrier generation, and stabilize atomic networks, respectively. The Sn element in the AZTO active layer could be a mobility enhancer [7]. Meanwhile, the Hf [9] and Si [10] were confirmed to act as carrier suppressors. In designing the channel composition for the oxide TFT, two major concerns must be considered, in order to find a compromise between moderate carrier mobility and excellent device reliabilities under bias and illumination stress conditions. Although we know that In plays a large role in increasing the carrier mobility, an excessive addition of In might deteriorate the stability of device characteristics [11]. Especially for oxide TFT, it is very important to guarantee photo-induced stability, due to its high transparency to the visible light: the oxide channel inevitably experiences light illuminations from the backlight unit of liquid crystal display or from natural light. Consequently, studies of new material compositions are needed in order to realize highly functional and highly stabilized oxide TFTs for promising applications in the near future.

In this work, we propose a new composition of Al–In–Zn–O (AIZO) as an active channel material for the oxide TFT, in which Al and In are expected to act as suitable carrier suppressor and enhancer, respectively. We evaluated the device characteristics of the fabricated TFTs using AIZO channels while the In concentrations in the AIZO were varied. The electrical stabilities and light responses of the fabricated AIZO TFTs were also investigated.

*Corresponding author. Tel.: +82 31 201 3617; fax: +82 31 204 8114.
E-mail address: sungmin@khu.ac.kr (S.M. Yoon).

0272-8842/$ - see front matter
http://dx.doi.org/10.1016/j.ceramint.2012.09.016

2. Material and methods

We fabricated AIZO TFTs with bottom-gate-bottom-contact structure on a glass substrate. The 150 nm thick In–Sn–O (ITO) electrodes were prepared as source/drain and gate electrodes by the sputtering method. They were annealed in vacuum at 200 °C in order to reduce their resistance. A 176 nm thick Al_2O_3 gate insulator layer was grown by means of atomic layer deposition (ALD) at 150 °C using trimethylaluminum (TMA) as an Al and H_2O as an oxygen precursor. The AIZO layers were deposited by the co-sputtering method using an AZO (2 wt% Al) and an In_2O_3 target, in which the sputtering power of the In_2O_3 target was varied to 200, 150, and 50 W in order to verify the effects of the In contents on the AIZO channels. The sputtering power of the AZO target was fixed at 200 W. The thicknesses of the AIZO with different compositions were controlled to be 20 nm. The deposition rates under different power conditions and the corresponding film thicknesses were measured using a surface profiler. The detailed deposition conditions of AIZO layer are given in Table 1. As shown in Fig. 1(a) and (b), The compositional ratio of AIZO channel layers was analyzed by Auger Electron Spectroscopy (AES), in which the relative In contents were estimated to be approximately 5.5 (200 W): 3.5 (100 W): 1 (50 W) by integrating the In etch profiles of each condition. Although this was only a relative comparison between the conditions, it was obvious that the In composition of the prepared AIZO channels could be controlled by the sputtering power for the In_2O_3 target. Considering that oxide TFTs are highly sensitive to the environmental condition, a passivation layer was adopted to prevent the adsorption and desorption of oxygen and water molecules at the back channel. The 40 nm thick Al_2O_3 layer was grown at 150 °C by the ALD method using the same precursors as for the gate insulator. All the patterning processes for the device fabrications were performed by using conventional photolithography and the wet etching method with a diluted hydrofluoric acid-based etchant. Finally, all devices were annealed at 250 °C in ambient air. A schematic diagram of the fabricated AIZO is shown in Fig. 1(c). The electrical performances of the AIZO TFTs were measured by using a semiconductor parameter analyzer (Agilent, B1500A) in a dark box. The defined gate channel width (W) and length (L) of the evaluated devices were 40 μm and 20 μm, respectively.

3. Results and discussion

Fig. 2(a) shows the drain current (I_{DS})–gate voltage (V_{GS}) transfer characteristics of the fabricated AIZO TFTs with various In composition ratios, which were measured for forward and reverse sweeps in V_{GS} at a drain voltage (V_{DS}) of 15.5 V. All devices exhibited a sufficiently low off-current (I_{off}) level and a negligible hysteresis in I_{DS}. When the sputtering power of In_2O_3 was varied to 200, 150, and 50 W, the saturation mobility (μ_{sat}) and turn-on voltage (V_{on}) of each controlled device were estimated to be approximately 27.8 $cm^2\,V^{-1}\,s^{-1}$ and −4.2 V, 4.5 $cm^2\,V^{-1}\,s^{-1}$ and −3.5 V, and 0.7 $cm^2\,V^{-1}\,s^{-1}$, and −3.0 V, respectively. The V_{on} was defined as the voltage where the I_{DS} approached 1 pA from the off state in the transfer curves. The (μ_{sat}) was calculated with the following equation:

$$I_{DS} = \frac{w}{2L}\mu_{sat}C_{ox}(V_{GS} - V_{TH})^2$$

(C_{ox} and V_{TH} correspond to the capacitance of Al_2O_3 gate insulator and the threshold voltage, respectively.)

The subthreshold swing (S.S.) and the ratio of on current (I_{on}) and off-current (I_{off}) were 0.51 V/decade and 2.01×10^9 (In_2O_3 200 W), 0.69 V/decade and 1.67×10^8 (In_2O_3 150 W), 0.63 V/decade and 3.80×10^7 (In_2O_3 50 W), respectively. As summarized in Fig. 2(b), the electrical characteristics of the AIZO TFTs were confirmed to be dependent on the sputtering power of In_2O_3. With the increase in In contents of the AIZO active channels, the saturation mobility and I_{on}/I_{off} ratio were enhanced and V_{on} was shifted in the negative direction. For the TFT with a sputtering power of 200 W, the transfer curve is distorted; this appears to be very closely related to the relatively higher amounts of In content. These trends are in good agreement with the previous results for IZO TFTs that the higher In contents incorporated in the oxide active channel can enhance the carrier mobility and shift the V_{on} in the negative direction [11]. From these obtained characteristics, the proposed AIZO TFTs showed promising operation, and that their operational behaviors could be controlled by modifying the In contents.

The second goal of this work is to verify the device reliabilities of the AIZO TFTs, which were severely evaluated under negative gate bias stress conditions with and without an illumination source. First, for the negative bias stress (NBS) tests, a V_{GS} of = −20 V

Table 1
The detailed deposition conditions of AIZO channel layer. The calculated In_2O_3 thickness ratio of each deposition condition was about 2.6 (In_2O_3 200 W):2.25 (In_2O_3 150 W):1 (In_2O_3 50 W).

Co-deposition power	Deposition-rate (Å/s)	Thickness ratio (Å) (estimated)	Deposition time (s)/total thickness (Å) (estimated)
AZO (200 W): In_2O_3 (200 W)	0.52:0.47	105.04:94.94	202/199.98
AZO (200 W): In_2O_3 (150 W)	0.52:0.36	118.56:82.08	228/200.64
AZO (200 W): In_2O_3 (50 W)	0.52:0.12	162.76:36.56	313/200.32

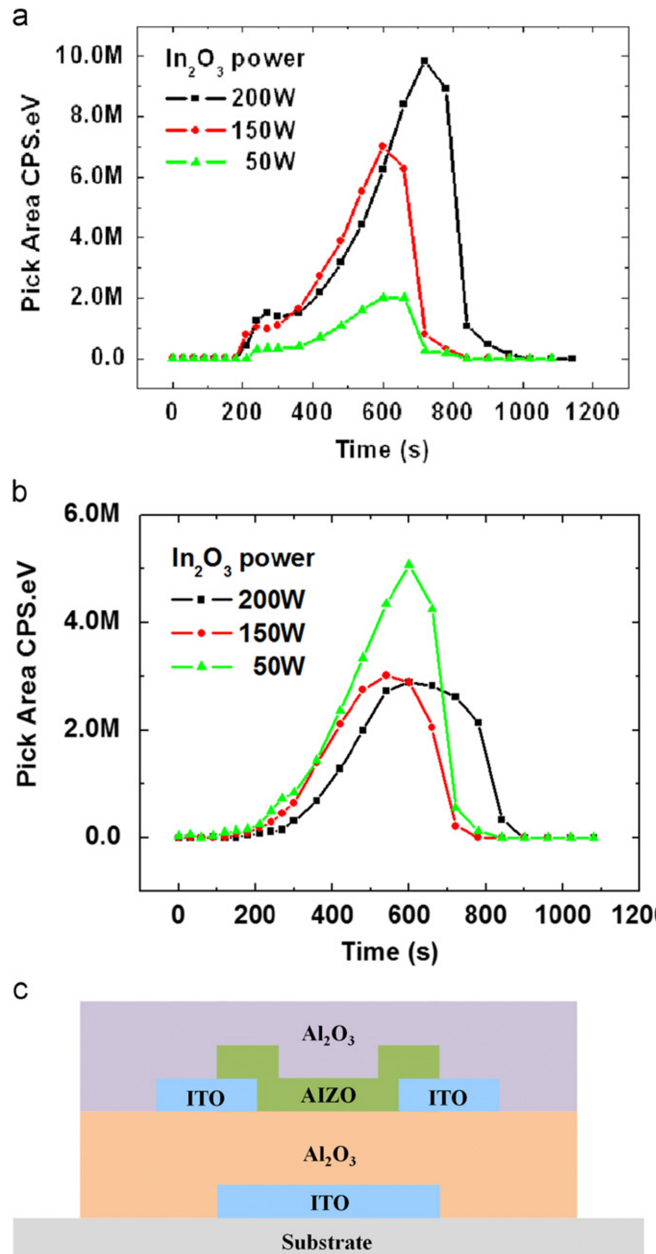

Fig. 1. Auger electron spectroscopy (AES) etch profiles of each composition for the AIZO active layers deposited with different In target powers. (a) In, (b) Zn, (c) schematic cross-sectional diagram of the fabricated AIZO TFT.

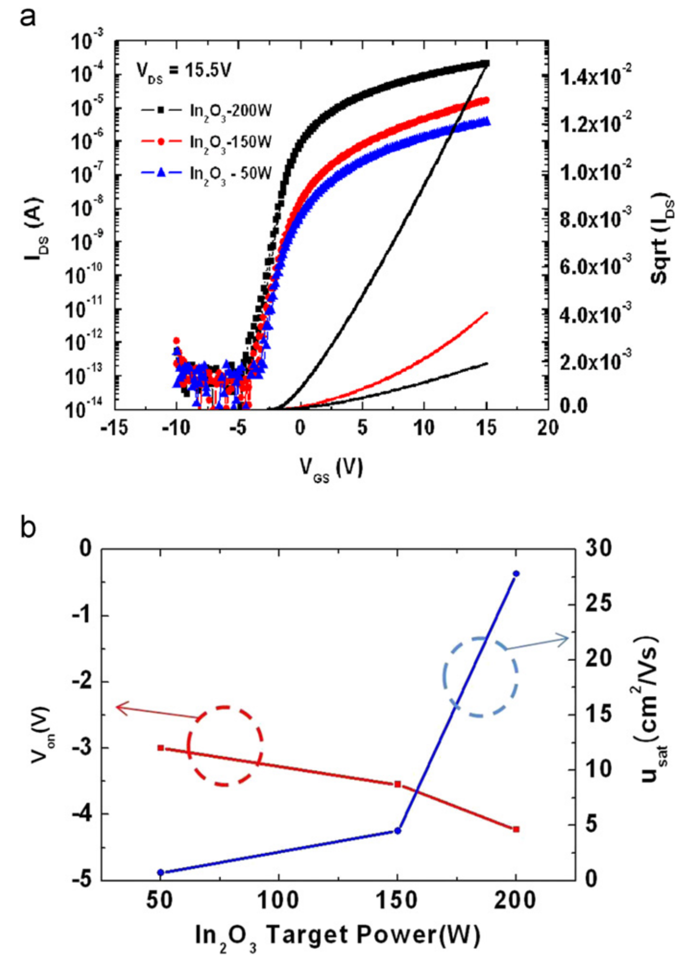

Fig. 2. (a) I_{DS}–V_{GS} transfer characteristics of fabricated AIZO TFTs on logarithmic and square root scales when the sputtering power of In_2O_3 was varied to 200, 150, and 50 W. (b) Variations in the V_{on} and μ_{sat} were calculated as a function of In_2O_3 sputtering power. All the characteristics were measured after the post-annealing at 250 °C.

was applied to the gate terminal of the AIZO TFTs for 10^4 s at room temperature. Fig. 3(a–c) shows the variations in the transfer curves during the NBS tests for the AIZO TFTs prepared with different In_2O_3 sputtering powers of 200, 150, and 50 W, respectively. All devices exhibited negligible ΔV_{on}. Under the NBS conditions, well-fabricated oxide TFTs do not experience critical degradation, because the carrier generation of holes in the n-type oxide semiconductors is assumed to be very difficult due to their wide band-gap and Fermi-level pinning caused by the high density of oxygen vacancy states [12].

The NBS stability could also be confirmed by the evidence that the I_{off} of TFTs remained at a very low level even after the NBS tests. The fabricated AIZO TFTs were fully satisfactory for these criteria of the NBS tests. Furthermore, it is also noticeable that the AIZO TFTs with a higher In content, with an μ_{sat} as high as 27.8 cm^2 V^{-1} s^{-1}, showed sufficiently robust characteristics under the NBS conditions. These results indicate that the Al works as an effective carrier suppressor and stabilizer in the AIZO channel for stable device operations. One further contributing factor to these stable behaviors can be explained by the preparation of the passivation layer, considering that the back-channel effect is one of the main reasons for the instability phenomena [5,6]. A dense Al_2O_3 passivation layer, like that introduced in this work, can be a strong prescription to enhance the NBS stability, even though the active channel with higher In content could have inherent instability during the stress tests.

Then, for the negative bias illumination stress (NBIS) tests, a V_{GS} of -20 V was applied for 10^4 s at room temperature under green light irradiation. We used a

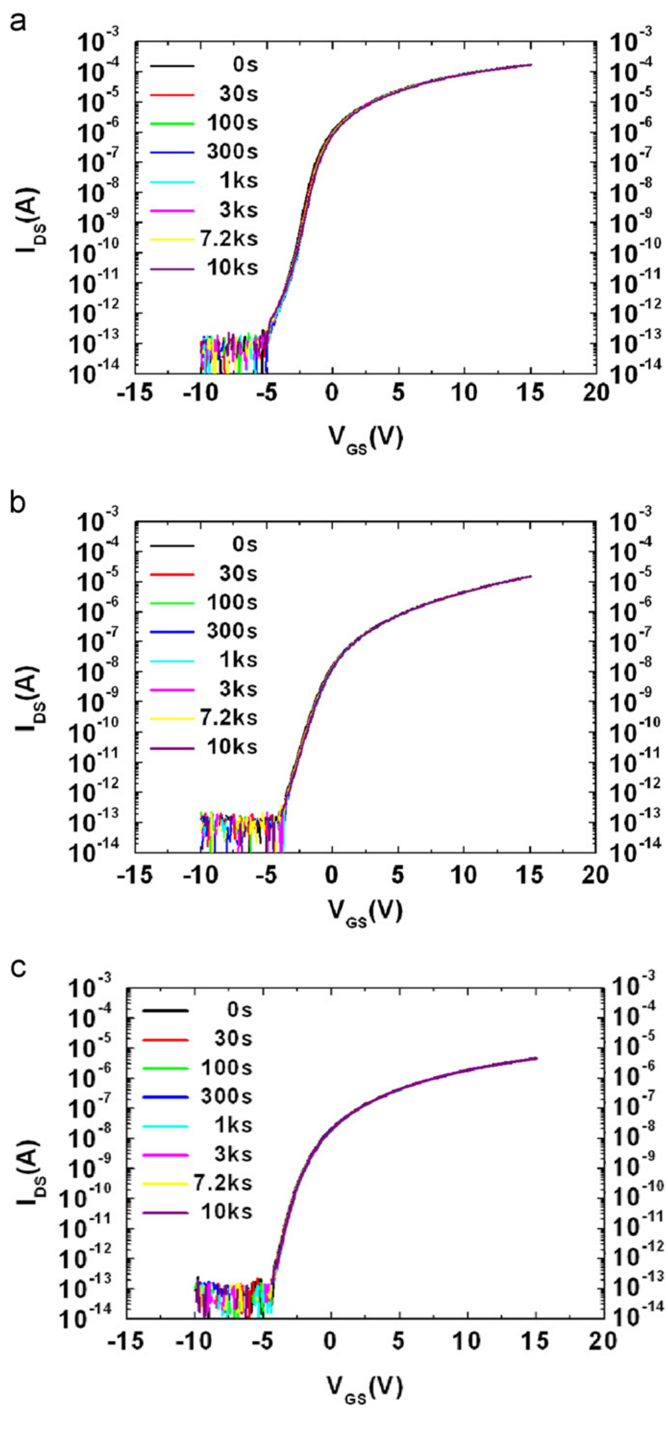

Fig. 3. Variations in transfer characteristics of AIZO TFTs under negative gate bias stress condition ($V_{GS}=-20$ V) for 10^4 s when the In_2O_3 sputtering power was chosen as (a) 200, (b) 150, and (c) 50 W during the deposition of AIZO.

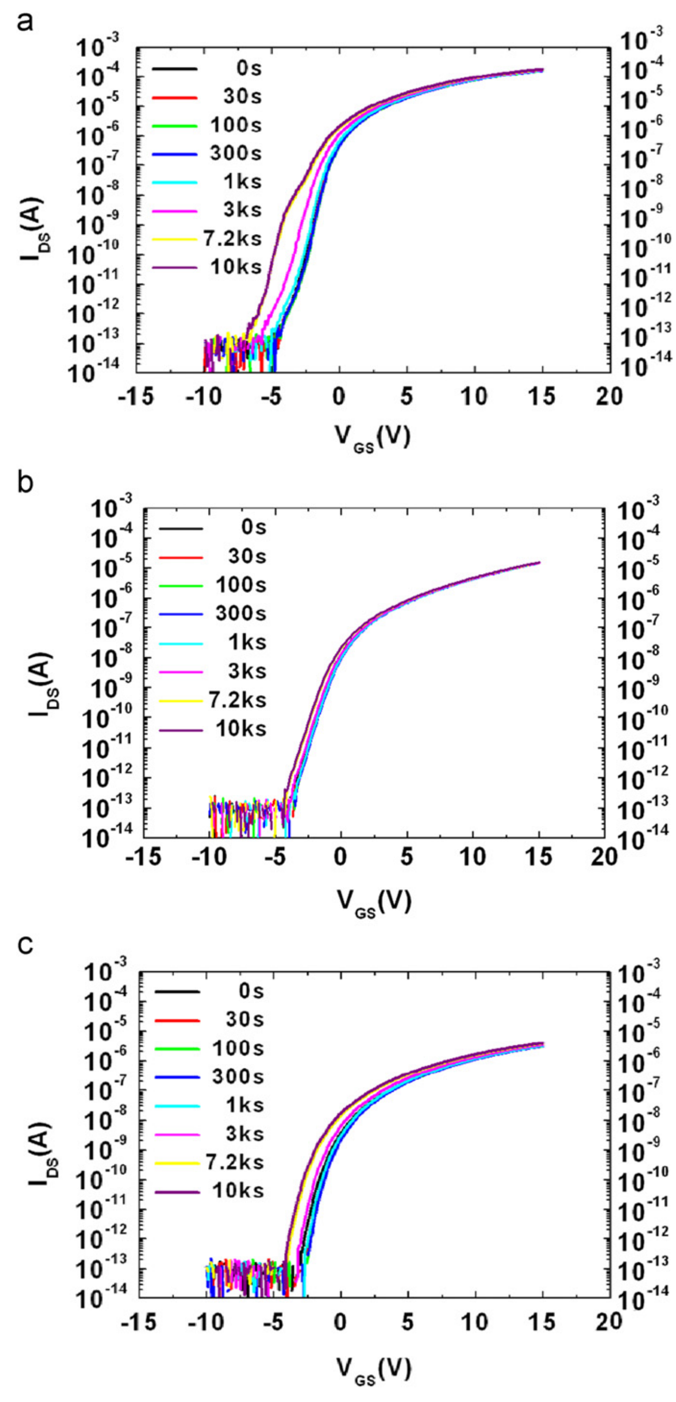

Fig. 4. Variations in transfer characteristics of AIZO TFTs under the negative gate bias ($V_{GS}=-20$ V) illumination stress condition for 10^4 s when the In_2O_3 sputtering power was chosen as (a) 200, (b) 150, (c) 50 W during the deposition of AIZO. The wavelength and the intensity of irradiation light source were 530 nm and 0.1 mW/cm^2 respectively.

halogen lamp and a band-pass filter to expose the green light with wavelength of 530 nm ($\pm$10 nm). The intensity was fixed at 0.1 mW/cm^2. Fig. 4(a–c) shows the transfer curve variations during the NBIS tests for the AIZO TFTs prepared with different In_2O_3 sputtering powers of 200, 150, and 50 W, respectively. The ΔV_{on} of these devices was measured to be -2.3 (200 W), -0.4 (150 W), and -1.1 V (50 W), respectively. The most stable NBIS characteristics were obtained for the TFT with the In_2O_3 sputtering power of 150 W. The origin of light instability for the amorphous oxide TFTs have been explained by the following phenomena and their complex effects [13–16]: (1) hole trapping at the interface between the active layer and gate insulator and within the bulk insulator which has a considerable number of hole trap-sites, (2) transition of ionized oxygen vacancies from the deep level states to shallow donors, and (3) oxygen desorption at the back-channel and carrier generation accelerated by illumination. Because the devices were well passivated with a dense Al_2O_3 layer, as discussed above, scenario (3) can be ruled out. The results suggest that the NBIS instabilities were caused by carrier generation [scenario (2)] from the high In contents and deep level defects change from compositions of AIZO channel layer. As shown in Fig. 4(a), excessively introduced In amounts might induce a large quantity of oxygen vacancies within the deep levels; these vacancies could be activated as additional carriers owing to the light illumination. Hence, the carrier generation effect was more dominant for this case and a marked NBIS instability was observed. Although we obtained the highest carrier mobility for this device, this NBIS instability critically limits the feasible applications. On the other hand, the origin of the relatively small instability observed for the TFT with the In_2O_3 sputtering power of 50 W might be more complicated. Apart from the higher In contents, the relative compositional variation in the AIZO channel is one further possibility for the carrier generation, because the Zn composition showed a relatively high content as shown in Fig. 1(b). If this effect was dominantly activated in the TFT with In_2O_3 sputtering at only 50 W, additional trap/detrap processes of carriers generated by light illumination might be incorporated in the obtained characteristics. In order to elucidate this issue, we will perform more detailed studies as future work. Consequently, our results show that the optimum combination between the appropriate carrier concentration contributing to the moderate value of carrier mobility (4.5 $cm^2 V^{-1} s^{-1}$) and the strong immunity to NBIS condition could be established for the AIZO TFTs when the sputtering power of In_2O_3 was controlled to be 150 W. We can conclude that the AIZO active channel with suitably controlled In amount can be a very promising and new composition for the oxide TFTs with both requirements of high performance and excellent stability.

4. Conclusions

In conclusion, we have fabricated the AIZO TFTs with various In concentrations by controlling the sputtering power. The transfer characteristics were strongly dependent on the In concentration in the channel layer. The saturation mobility (μ_{sat}) and turn-on voltage (V_{on}) of each device exhibited 27.8 $cm^2 V^{-1} s^{-1}$ and -4.2 V (In_2O_3 200 W), 4.5 $cm^2 V^{-1} s^{-1}$ and -3.5 V (In_2O_3 150 W), 0.7 $cm^2 V^{-1} s^{-1}$ and -3.0 V (In_2O_3 50 W), respectively. Thanks to the introduction of a dense Al_2O_3 passivation layer, we could obtain electrically stable devices under the NBS regardless of the variations in channel composition. To the contrary, for the NBIS tests, the composition dependences were remarkable, and the AIZO TFT with medium amount of In (In_2O_3 150 W) showed the best performance. This could be explained by the complex effects. We can conclude that an AIZO channel layer with suitable In composition successfully leads to high performance and excellent stability for a TFT application.

Acknowledgments

This research was supported by the Basic Science Research Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0008716).

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST) (No. 2012011730).

References

[1] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, H. Hosono, Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors, Nature 432 (2004) 488–492.
[2] J.F. Wager, Transparent electronics, Science 300 (2003) 1245–1246.
[3] S.H. Ko Park, C.S. Hwang, M.K. Ryu, S.H. Yang, C.W. Byun, J.H. Shin, J.I. Lee, K.M. Lee, M.S. Oh, S.I. Im, Transparent and photo-stable ZnO thin-film transistors to drive an active matrix organic-light-emitting-diode display panel, Advanced Materials 21 (2008) 678–682.
[4] P. Barquinha, G. Gonçalves, L. Pereira, R. Martins, E. Fortunato, Effect of annealing temperature on the properties of IZO films and IZO based transparent TFTs, Thin Solid Films 515 (2007) 8450–8454.
[5] J.K. Jeong, H.W. Yang, J.H. Jeong, Y.G. Mo, H.D. Kim, Origin of threshold voltage instability in indium-gallium-zinc oxide thin film transistors, Applied Physics Letters 93 (2008) 123508.
[6] J.S. Park, J.K. Jeong, H.J. Chung, Y.G. Mo, H.D. Kim, Electronic transport properties of amorphous indium–gallium–zinc oxide semiconductor upon exposure to water, Applied Physics Letters 92 (2008) 072104.
[7] D.H. Cho, S.H. Yang, C.W. Byun, J.H. Shin, M.K. Ryu, S.H. Ko Park, C.S. Hwang, S.M. Chung, W.S. Cheong, S.M. Yoon, H.Y. Chu, Transparent Al–Zn–Sn–O thin film transistors prepared at low temperature, Applied Physics Letters 93 (2008) 142111.
[8] S.H. Yang, D.H. Cho, M.K. Ryu, S.H. Ko Park, C.S. Hwang, J. Jang, J.K. Jeong, High-performance Al–Sn–Zn–In–O thin-film transistors – impact of passivation layer on device stability, IEEE Electron Device Letters 31 (2010) 144–146.
[9] C.J. Kim, S.W. Kim, J.H. Lee, J.S. Park, S.I. Kim, J.C. Park, E.H. Lee, J.C. Lee, Y.S. Park, J.H. Kim, S.T. Shin, U.I. Chung, Amorphous hafnium-indium-zinc oxide semiconductor thin film transistors, Applied Physics Letters 95 (2009) 252103.
[10] E.G. Chung, Y.S. Chun, S.Y. Lee, Amorphous silicon–indium–zinc oxide semiconductor thin film transistors processed below 150 °C, Applied Physics Letters 97 (2010) 102102.
[11] N. Itagaki, T. Iwasaki, H. Kumomi, T. Den, K. Nomura, T. Kamiya, H. Hosono, Zn–In–O based thin-film transistors-compositional dependence, Physica Status Solidi 205 (2008) 1915.
[12] T. Kamiya, K. Nomura, H. Hosono, Present status of amorphous In–Ga–Zn–O thin-film transistors, Science and Technology of Advanced Materials 11 (2010) 044305.
[13] K.H. Ji, J.I. Kim, Y.G. Mo, J.H. Jeong, S.H. Yang, C.S. Hwang, S.H. Ko Park, M.K. Ryu, S.Y. Lee, J.K. Jeong, Comparative study on light-induced bias stress instability of IGZO transistors with SiNx and SiO_2 gate dielectrics, IEEE Electron Device Letters 31 (2010) 1404–1406.

[14] B. Ryu, H.K. Noh, E.A. Choi, K.J. Chang, O-vacancy as the origin of negative bias illumination stress instability in amorphous In–Ga–Zn–O thin film transistors, Applied Physics Letters 97 (2010) 022108.

[15] S.H. Yang, D.H. Cho, M.K. Ryu, S.H. Ko Park, C.S. Hwang, J. Jang, Improvement in the photon-induced bias stability of Al–Sn–Zn–In–O thin film transistors by adopting AlO_x passivation layer, Applied Physics Letters 96 (2010) 213511.

[16] S.W. Kim, S.I. Kim, C.J. Kim, J.C. Park, I.H. S, S.H. Jeon, S.E. Ahn, J.S. Park, J.K. Jeong, The influence of visible light on the gate bias instability of In–Ga–Zn–O thin film transistors, Solid State Electronics 62 (2011) 77–81.