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Effects of the composition of sputtering target on the stability of InGaZnO thin film transistor

Jun-Young Huh [a], Jae-Hong Jeon [a,*], Hee-Hwan Choe [a], Kang-Woong Lee [a], Jong-Huyn Seo [b], Min-Ki Ryu [c], Sang-Hee Ko Park [c], Chi-Sun Hwang [c], Woo-Seok Cheong [c]

[a] School of Electronics, Telecommunications and Computer Engineering, Korea Aerospace University, 200–1 Goyang, Gyeongki 412–791, Republic of Korea
[b] Department of Materials, Korea Aerospace University, 200–1 Goyang, Gyeongki 412–791, Republic of Korea
[c] Oxide Electronics Research Team, Electronics and Telecommunication Research Institute, 138 Yuseong, Daejeon 305–350, Republic of Korea

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ABSTRACT

In this study, we investigated the electrical characteristics and the stability of amorphous indium gallium zinc oxide (a-IGZO) thin film transistors (TFTs) from the viewpoint of active layer composition. Active layers of TFTs were deposited by r.f. sputtering. Two kinds of sputtering targets, which have different compositional ratios of In:Ga:Zn, were used to make variations in the active layer composition. All the fabricated IGZO TFTs showed more excellent characteristics than conventional amorphous silicon TFTs. However, in accordance with the Ga content, IGZO TFTs showed somewhat different electrical characteristics in values such as the threshold voltage and the field effect mobility. The device stability was also dependent on the Ga content, but had trade-off relation with the electrical characteristics.

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1. Introduction

Hydrogenated amorphous silicon thin film transistors (a-Si:H TFTs) have been widely used as a switching device in large area electronics. Especially, excellent performance of liquid crystal display (LCD) is attributable to a-Si:H TFT, which renders active matrix driving method. One of the latest issues on LCD is a capability of displaying moving pictures in as many frames as possible to suppress image blurring. However, the field effect mobility of conventional a-Si:H TFT is not sufficient for that purpose. Therefore, new materials for the active layer of TFT have been intensively investigated [1,2]. Amorphous indium gallium zinc oxide (a-IGZO) is the most promising due to its high field effect mobility, uniform characteristics and compatibility with low temperature processes [3,4]. Because IGZO is a multi-component material, it can be expected that its performances such as electrical characteristics and device stability depend on the chemical composition. There have been important reports on the effect of the chemical composition on the device characteristics [5,6]. However, the effect on the device stability has not been studied enough.

In this study, we fabricated IGZO TFTs using r.f. magnetron sputtering for the deposition of the IGZO active layer. In order to produce the variations in the composition of the active layer, we used two kinds of sputtering targets which have different compositional ratios of each metallic component. The transfer characteristics of fabricated IGZO TFTs were measured and compared. The electrical bias stress test was also performed on each device. As the Ga content exceeds the Zn content, the turn-on characteristics of TFT degrades, however, the device stability enhances. The reasons for the trade-off relation between the electrical characteristics and the device stability with the Ga content are discussed.

2. Experiments

Fig. 1 shows a cross-section view of our IGZO TFTs fabricated in a top-gate structure on a glass substrate. Two kinds of IGZO active layers with the same thickness of 30 nm were deposited by r.f. magnetron sputtering. One of the sputtering targets had an In:Ga:Zn ratio of 2:1:2 in atomic ratio (at.%), which was labeled as IGZO A. The other had 2:2:1 at.% and labeled as IGZO B. Therefore, the In content was fixed and the Ga content was higher or lower than the Zn content. The gate insulator of a 185 nm-thick Al_2O_3 was deposited by an atomic layer deposition (ALD) method. The metal electrodes were deposited by r.f. magnetron sputtering with indium tin oxide (ITO) target. All the patterning processes were performed by conventional photolithography and wet etch methods.

Electrical measurements and bias stress tests were carried out with a probe station system isolated from external light by a shielding box. An Agilent 4155C semiconductor parameter analyzer was utilized for the electrical measurements and bias stress tests. The bias stress conditions were split by the polarity of gate biases (+20 V and −20 V). The maximum time duration of each stress condition

* Corresponding author. Tel.: +82 2 300 0411; fax: +82 2 3159 9257.
E-mail address: jjh123@kau.ac.kr (J.-H. Jeon).

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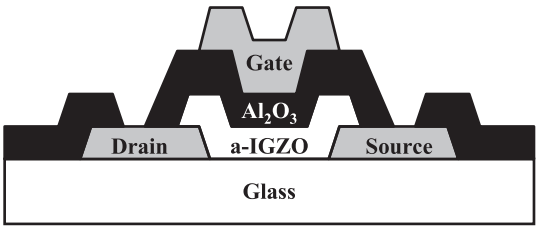

Fig. 1. Cross-section view of IGZO TFT used in this study.

was 10^4 s and the changes of device characteristics during stress were checked by measuring the transfer characteristics in logarithmic time scale.

3. Results and discussions

Fig. 2 shows the transfer characteristics of fabricated IGZO TFTs which differ in the compositional ratio of the active layer. There are somewhat big differences in electrical characteristics between the two devices. The extracted device parameters are summarized in Table 1. IGZO A TFT (In:Ga:Zn = 2:1:2) exhibits higher driving current and higher field effect mobility than IGZO B TFT (In:Ga:Zn = 2:1:2). However, its V_{on} (−4.8 V), which is defined as the bias point at which the subthreshold current starts to increase, is a more negative value than that of IGZO B TFT (−0.8 V). In other words, the carrier density in the active layer of IGZO A TFT is higher at zero gate voltage than that of IGZO B TFT. Because the gate electrode material and the gate insulator material were the same for the two devices, the flat band voltage seems not to be much different between the two devices. The Fermi level of IGZO A TFT is closer to the conduction band edge at zero gate voltage than that of IGZO B TFT. Therefore IGZO A TFT seems to have a slightly upward band-bending at the gate insulator interface. It is believed that the higher carrier concentration of IGZO A is predominantly related with the lower Ga content than that of IGZO B. This result coincides with the previous reports of other workers [6,7]. The Ga^{3+} ion has been reported to be a superior oxygen binder, therefore the release of free carrier from donor centers such as oxygen vacancies can be suppressed as the Ga content increases [7]. This is also the reason for the lower threshold voltage of IGZO A TFT.

However, the higher Ga content resulted in the lower field effect mobility. The In^{3+} ion has been reported to form extended conduction band minima by the percolation of In's 5s orbitals and provide main electron conduction path [8]. On the other hand, randomly distributed Ga or Zn sites play a role of potential barriers to electron conduction. It is considered that the anti-bonding states of Ga, of which binding energy with oxygen is higher than that of Zn, appear above those of Zn. Therefore, the energy barrier of Ga may be higher than that of Zn. Consequently, IGZO B TFT (higher Ga content) shows lower field effect mobility.

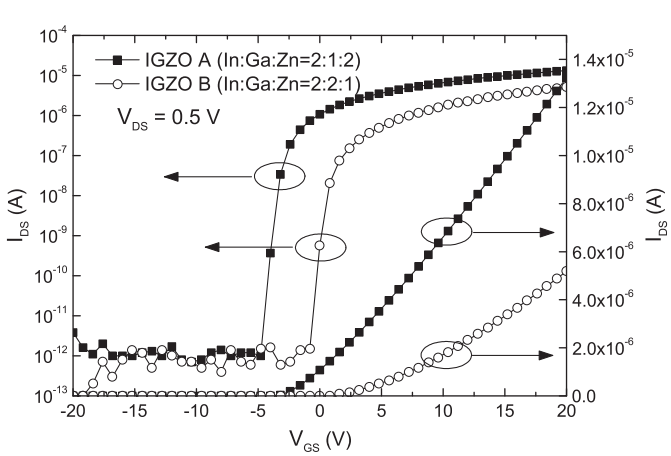

Fig. 2. Two initial transfer characteristics of the amorphous IGZO TFTs.

Table 1
Comparison of the electrical parameters according to different compositional ratios of the sputtering target.

	Mobility (cm^2/Vs)	V_{th} (V)	SS (V/dec)	V_{on} (V)
IGZO A	14	0.05	0.35	−4.8
IGZO B	9.3	4.75	0.39	−0.8

It is another interesting point that the subthreshold slopes (SSs) of the two devices are nearly the same (IGZO A: 0.35 V/dec, IGZO B: 0.39 V/dec). The calculated densities of the interface trap states ($D_{it} = C_i$ SS log(e)/kT − C_i/q)) were 1.00×10^{12} cm^{-2} for IGZO A TFT and 1.14×10^{12} cm^{-2} for IGZO B TFT, respectively. Because the input r.f. power of sputtering was the same and the post processes were all the same, the interface characteristics could be similar for the two devices. Therefore the difference in the field effect mobility (IGZO A: 14 cm^2/Vs, IGZO B: 9.3 cm^2/Vs) can be attributed to the bulk characteristics of IGZO rather than the interface characteristics.

We also investigated the effect of the composition on the device stability. Fig. 3 shows the changes of transfer characteristics before and after electrical bias stress. A positive gate bias of +20 V was continuously applied to TFTs for 10^4 s at a substrate temperature of 340 K. The substrate was heated in order to accelerate degradation. Although degradation is not so significant in both the devices, it can be found that there is difference in the degree of change. IGZO B TFT (higher Ga content, Fig. 3(b)) shows more stable characteristics. It

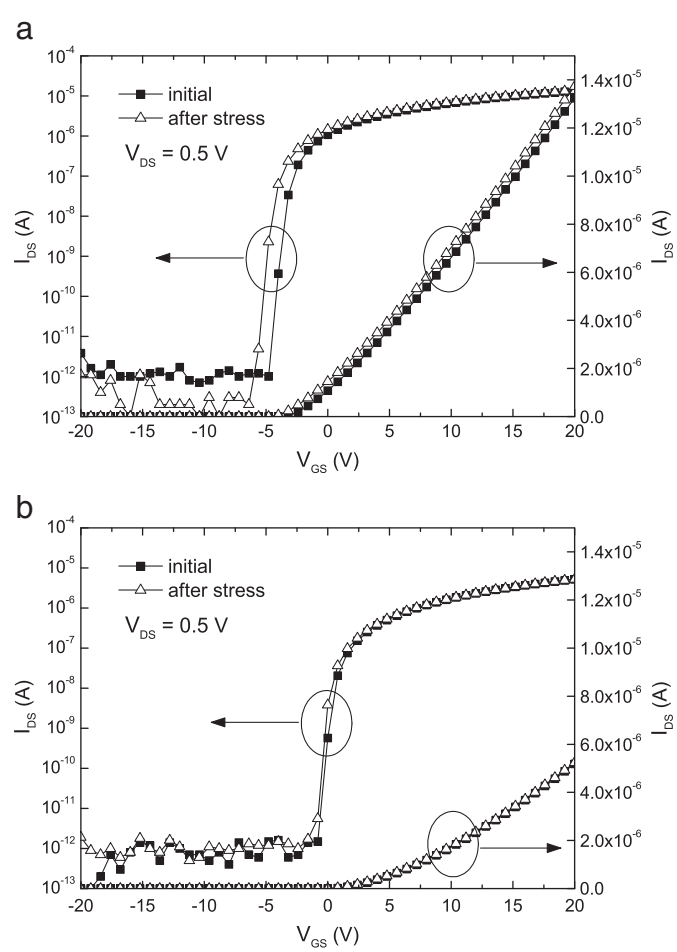

Fig. 3. Transfer characteristics of IGZO TFTs before and after +20 V gate bias stress at 340 K (a) IGZO A TFT, and (b) IGZO B TFT.

should be noted that the transfer curves shift in a negative direction on the V_{GS} axis.

Conventionally the transfer curve shifts in the positive direction under the positive gate bias for n-channel device mainly due to electron trapping if trap sites exist inside the insulator. In the case of our devices, the high quality of the Al_2O_3 gate dielectric layer seems to suppress electron trapping. Another scenario for the anomalous behavior can be attributed to the movement of mobile ion such as sodium (Na^+) in the gate insulator. The direction of movement of the mobile ions under the positive gate bias is to shift the transfer characteristics in the negative direction. However, if the mobile ions exist, the direction of the transfer curve under the negative gate bias is the opposite direction from that under the positive gate bias. The experimental result of the negative gate bias stress does not coincide with the scenario, which will be presented in the later part of this section. Therefore, we consider that the cause of the negative shift is related with the change in the properties of the active layer. Because IGZO lies in the amorphous phase, weak bonds between metal and oxygen generally exist in the active layer. If the metal ions at weak bonding sites capture electrons under the positive gate bias, their binding force with oxygen anions will be lowered temporarily for the moment of electron capture. They can be broken with the help of enhanced phonon vibration promoted by substrate heating up to 340 K and act as shallow donors. Carriers released from broken metal components make the transfer curve to shift in the negative direction. Difference in the Ga content may be related with the amount of weak bonds. Because Ga's binding energy with oxygen is the highest among the three metal components, the concentration of the weak bonds in the overall active layer seems to be suppressed with the increase of the Ga content. Fig. 4 shows the variations in V_{on} during the positive gate bias. The final variation of IGZO A TFT is two times larger than that of IGZO BTFT.

Fig. 5 shows the changes of transfer characteristics before and after negative gate bias stress of −20 V for 10^4 s. The substrate temperature was also 340 K. In this case, IGZO B TFT also shows better stability than IGZO A TFT. Conventionally the transfer curve shifts in the negative direction due to trapping holes, accumulated by the negative gate bias. It is not clear that hole accumulation layer would form in n-type material with wide band gap. The same gate dielectric layers adopted in both the devices cannot provide the different concentrations of the hole trap site. Therefore this result also seems to be related with the compositional ratios of the active layer. Under the negative gate bias, most of electrons will be depleted. Furthermore, some deep donors such as oxygen vacancies, of which the transition levels are different with the surrounding bond configurations so that some of them can be shallow donors and some of them can be deep donors, may be positively ionized with the help of the negative gate bias and the thermal energy supplied from the heated substrate. This is similar to hole trapped oxygen vacancy. There has been a report that the transition level can be raised above the conduction band edge and can act as a shallow donor if oxygen vacancy captures hole [9]. If this scenario is consistent with our result, the concentration of the free carrier in the active layer can increase under the negative gate bias stress and the transfer curve can shift in the negative direction. The larger shift of the transfer curve of IGZO A TFT, which is considered to contain more oxygen vacancies due to lower Ga content, can be explained by the above mechanism.

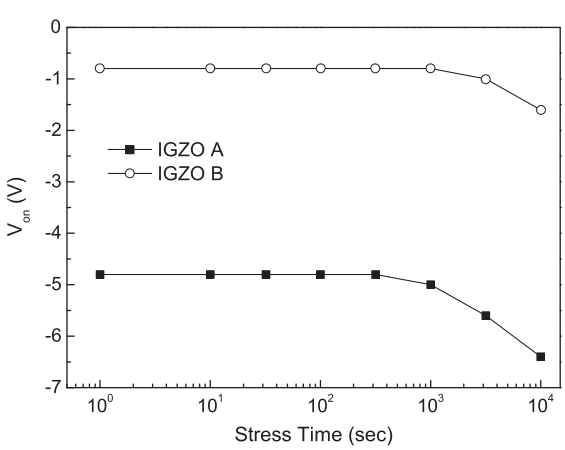

Fig. 4. Time dependence of the variation of V_{on} under the +20 V gate bias stress at 340 K stress.

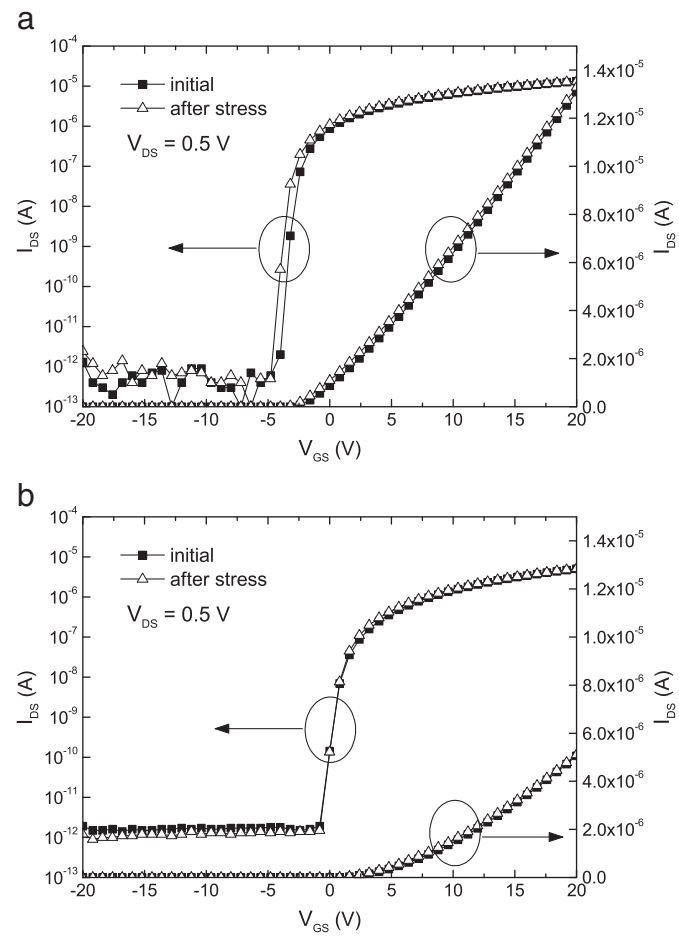

Fig. 5. Transfer characteristics of IGZO TFTs before and after −20 V gate bias stress at 340 K (a) IGZO A TFT, and (b) IGZO B TFT.

4. Conclusion

In this work, the electrical characteristics and the stability of a-IGZO TFTs fabricated by r.f. magnetron sputtering with the variance in the compositional ratio of the sputtering target were presented. IGZO A TFT, of which the Ga content was lower than that of IGZO B TFT, showed higher driving current and higher field effect mobility. However, it contained more free carriers in the active layer. In view of the stability, IGZO B TFT, of which the Ga content was higher, showed more stable performance against the bias stress. Difference in the stability between the two devices could be explained by the role of the Ga component which acts as a strong oxygen binder.

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