AIP | Applied Physics Letters

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Citation: Applied Physics Letters **98**, 052102 (2011); doi: 10.1063/1.3551537
View online: http://dx.doi.org/10.1063/1.3551537
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/98/5?ver=pdfcov
Published by the AIP Publishing

Nitrogenated amorphous InGaZnO thin film transistor

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(Received 22 October 2010; accepted 12 January 2011; published online 31 January 2011)

This work presents the electrical characteristics of the nitrogenated amorphous InGaZnO thin film transistor (a-IGZO:N TFT). The a-IGZO:N film acting as a channel layer of a thin film transistor (TFT) device was prepared by dc reactive sputter with a nitrogen and argon gas mixture at room temperature. Experimental results show that the *in situ* nitrogen incorporation to IGZO film can properly adjust the threshold voltage and enhance the ambient stability of a TFT device. Furthermore, the a-IGZO:N TFT has a 44% increase in the carrier mobility and electrical reliability and uniformity also progress obviously while comparing with those not implementing a nitrogen doping process. © *2011 American Institute of Physics*. [doi:10.1063/1.3551537]

As the development of flat panel displays grows rapidly, thin film transistor (TFT) technologies have been widely used as switching devices or peripheral drivers in active-matrix liquid crystal displays (AM-LCDs). However, the conventional amorphous silicon acting as the channel layer in a TFT device faces its development limitation due to its physical drawback properties. For this reason, the TFT device with amorphous oxide semiconductors (AOSs) recently attracts lots of attention due to its high mobility, low temperature deposition, and transmission advantages.[1,2] Among several promising AOS materials, amorphous indium (In), gallium (Ga), zinc (Zn) oxide (a-IGZO) is one of the most glaring candidates.[3–5] The a-IGZO film has electrons as majority carriers, which is mainly affected by the oxygen vacancies and oxygen interstitials during deposition processes.[6,7] The ion bonding structure makes the a-IGZO TFT exhibit high field-effect carrier mobility even in the amorphous phase.[6] Even if the a-IGZO TFT owns many superior characteristics, the sensitivity to atmosphere is a extremely critical issue for the a-IGZO TFT application.[8,9] The environment-dependent metastability was attributed to oxygen adsorption/desorption reactions to the backchannel of the a-IGZO TFT device. The random reactions between the ambient air and the a-IGZO backchannel layer cannot only change the oxygen vacancies in the a-IGZO film but result in a threshold voltage shift with days going by and even device uniformity problems.[9–11] In addition to isolating the a-IGZO layer from exposure to the atmosphere, the electrical stability and uniformity of the a-IGZO film can be improved by the optimization of the chemical stoichiometry or adjusting oxygen content inherently. In this work, we proposed an *in situ* nitrogen doping method during a-IGZO film preparation to properly substitute the nitrogen for the inactive oxygen in the a-IGZO film. The effects of nitrogen incorporation on the ambient stability and electrical performance of the a-IGZO:N TFTs are also investigated comprehensively.

The TFT device was chosen as an inverted staggered structure and fabricated on the silicon wafer substrate. First, a n^+ heavily doped silicon substrate acting as a gate electrode was thermally grown a 100-nm-thick thermal oxide in a thermal furnace at 650 °C. The active channel layer of a 50-nm-thick a-IGZO layer was formed by dc reactive sputtering with a power of 100 W at room temperature. The target for the a-IGZO film deposition was an IGZO pellet with the component ratio of 1:1:1:4 (In:Ga:Zn:O). In addition to argon (Ar) gas with a flow rate of 10 SCCM (SCCM denotes cubic centimeter per minute at STP), nitrogen gas (N_2) was *in situ* injected to the deposition chamber at the flow rate ranging from 0 to 2 SCCM during the sputtering process under a total pressure of about 5×10^{-3} torr. This resultant nitrogenated amorphous IGZO (a-IGZO:N) active island was also defined through a shadow mask process. A 50-nm-thick indium tin oxide (ITO) layer was then sputter-deposited and patterned to form source/drain electrodes. Sequentially, all samples were thermally annealed at 350 °C for 1 h. Material analysis techniques such as high resolution X-ray diffractometer (XRD) spectra, X-ray photoelectron spectrometer (XPS), and Rutherford backscattering spectrometry (RBS) were utilized to analyze the crystallinity and compositions of the a-IGZO:N films. All electrical measurements were carried out by using the electrical analyzer Keithley 4200. As for the study on the ambient stability of TFT devices, all specimens were stayed in ambient atmosphere and measured every two days, then ended up on the seventh day periodically. The measurement conditions for device reliability were applying the gate bias to the a-IGZO:N TFTs with an electrical field of 1 MV/cm for 10^4 s at room temperature.

First, a 100-nm-thick blanket a-IGZO:N layer with different nitrogen concentrations was deposited separately on Corning Eagle 2000 glass substrates for the transparency measurement. Experimental results show that the transparency of the a-IGZO:N films is high and all are in the range of $94 \pm 1\%$ at a 550 nm measuring wavelength. Also, XRD spectra indicated that these IGZO:N films were still in the amorphous phase, even after the 350 °C postannealing process (not shown). Figure 1 shows the XPS spectra of a-IGZO:N thin films for the analysis of the chemical nitrogen bonding. The bonding energy of Ga Auger line at 397 eV is observed in the a-IGZO film. As N_2 gas is *in situ* introduced to the a-IGZO sputter-deposition process, the a-IGZO:N film

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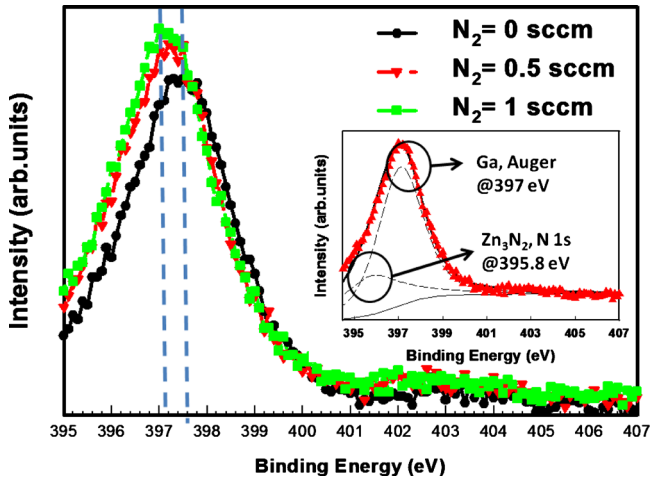

FIG. 1. (Color online) The X-ray photoelectron spectrometer (XPS) spectra of the nitrogenated amorphous IGZO (a-IGZO:N) with N_2 gas flow rates of 0, 0.5, and 1 SCCM (SCCM denotes cubic centimeter per minute at STP), respectively. The inset presents the composition of Ga Auger at 397.4 eV and the N1s of Zn_3N_2 at 395.8 eV.

was formed. The signal peak of N1s originated from Zn_3N_2 bonds at 395.8 eV appears in the a-IGZO:N film and the resulting XPS binding energy shifts left. The comparison between Ga Auger at 397 eV and N1s at 395.8 eV is shown in the inset of Fig. 1. These peak positions clearly differ from N1s in GaN (397.3 and 397.8 eV)[11] and InN (396.5 eV).[12] This indicates that the nitrogen species in the a-IGZO:N thin film has an electronic state similar to the one in Zn_3N_2. In order to investigate the uniformity of device characteristics, five different measuring points were sampled for each specimen. RBS analysis was also used to confirm the existence of nitrogen and quantify the atomic ratio of chemical compositions in the a-IGZO:N films. The In:Ga:Zn:O:N atomic ratios of the a-IGZO:N film deposited with the N_2 flow of 1 SCCM is 1:1:0.8:5.4:1.7, while the a-IGZO film without the nitrogen incorporation (i.e., the control sample) is 1:1:0.7:5.4:0, respectively. The transfer characteristic curves of a-IGZO:N TFTs are compared in Fig. 2(a), also with the corresponding device parameters shown in the inset. The channel length and channel width of the a-IGZO:N TFT device was 600 and 600 μm, respectively. It is clearly observed that the carrier mobility is increased, and the threshold voltage (V_{th}) and subthreshold swing (S.S) are decreased with increasing nitrogen concentration. Furthermore, all the TFT devices not implementing any backchannel passivation process were purposely exposed to the ambient atmosphere for one week, and their electrical characteristics were measured in different staying days. The time-dependent V_{th} shifts are shown in Fig. 2(b). Each error bar includes five different measuring results for each TFT device. Figure 2(b) shows that the average of V_{th} shifts for the a-IGZO TFTs is -2.23 V, while that is reduced to -0.90 V for the a-IGZO:N TFT with the N_2 flow of 1 SCCM. In addition to the decrease of V_{th} shift, the error bars representing the fluctuation of V_{th} shifts shrink as the nitrogen content increases. These results show that the electrical performance and device uniformity of a-IGZO TFTs can be improved obviously by the *in situ* N_2 doping technology. The nitrogen incorporation to the a-IGZO film with the N_2 flow rate of 1 SCCM is an optimum for TFT device characteristics in this work. The ambient stability of IGZO-based materials is strongly related to the distribution of oxygen vacancies during the film deposition.[9] The inactive oxygen from the a-IGZO backchannel region can react with the ambient atmosphere and causes a desorption reaction to form oxygen vacancies.[9,10] When the nitrogen is doped to the a-IGZO to form a-IGZO:N film, nitrogen atoms can partially replace the inactive oxygen atoms and reduce the oxygen desorption effect. Thus, the interaction between the a-IGZO:N backchannel layer and the atmosphere can be effectively reduced and the ambient stability of a-IGZO:N TFT device is enhanced consequently.[9] Figures 3(a) and 3(b) show the V_{th} shifts of the a-IGZO:N TFT devices under positive gate bias stress (PGBS) and negative gate bias stress (NGBS) for the time duration of 10^4 s, respectively. The V_{th} shift of the a-IGZO TFT device under PGBS is 6.96 V and that is -2.80 V for the NGBS case. In contrast, the V_{th} shift of the a-IGZO:N TFT device with the N_2 flow of 1 SCCM is reduced to 2.97 and -1.70 V, respectively, after the PGBS and NGBS. This also clearly indicates that the a-IGZO:N TFT device has a superior electrical reliability as compared with the a-IGZO TFT device. The bias-induced oxygen absorption/desorption behavior or molecules migration in the a-IGZO film has been addressed by previous studies.[1,13,14] When the PGBS was applied to the a-IGZO TFT in the atmosphere, a number of excess electrons would accumulate in the channel region and enhance the oxygen absorption from the ambient atmosphere. The absorbed oxygen and inactive oxygen (O_2) in the a-IGZO film can capture electrons and form negatively charged oxygen species ($O_{2(solid)}^-$) through

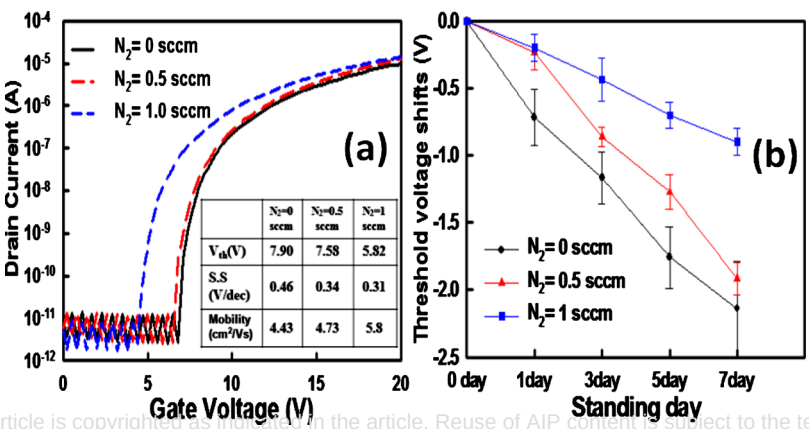

FIG. 2. (Color online) (a) The transfer characteristics (I_D-V_G) of a-IGZO:N TFTs with different nitrogen doping concentrations. The corresponding device parameters to the a-IGZO:N TFTs are shown in the inset, including threshold voltage (V_{th}), subthreshold swing (S.S), and carrier mobility (μ). (b) The V_{th} shifts of a-IGZO:N TFT devices staying at the ambient atmosphere for the time duration of 7 days. Each error bar includes five different measuring results for each TFT device.

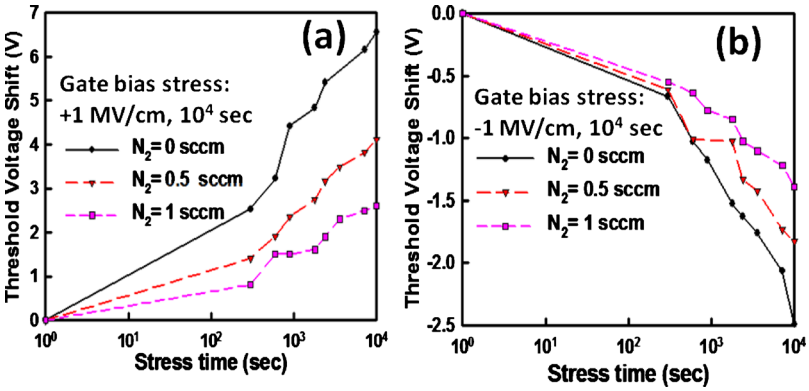

FIG. 3. (Color online) The electrical reliability of a-IGZO:N TFTs with different nitrogen doping concentrations under (a) the positive and (b) the negative gate bias stress. The gate bias stress conditions were 1 MV/cm for positive bias and −1 MV/cm for negative bias stress at room temperature for 10^4 s while source and drain electrodes were connected to the ground. The V_{th} shifts of the gate bias stressed a-IGZO:N TFTs dramatically decrease with the increase of nitrogen incorporation during the a-IGZO film deposition.

the reaction formula of $O_2+e^- \rightarrow O_{2(solid)}^-$. As the charge transfer process occurs, a depletion layer will be formed beneath the backchannel region and lead to an increase of V_{th}. It is thereby expected that the negatively charged oxygen species ($O_{2(solid)}^-$) on the surface will be desorbed upon the application of a negative gate bias, causing a decrease of V_{th}.[1,9,13] In this study, the bias-induced reaction of oxygen absorption/desorption can decline effectively as a result of the addition of nitrogen, which is insensitive to the ambient. Therefore, the electrical reliability of the a-IGZO:N TFT device is promoted as compared with the a-IGZO TFT without nitrogen doping process.

In summary, the amorphous IGZO:N material was produced to act as the channel layer of the TFT device by *in situ* nitrogen doping process during the IGZO sputter-deposition. Material analysis results showed the existence of a nitrogen element, and it can partially substitute for the inactive oxygen atom in the IGZO film. The ambient stability of the IGZO:N film was thereby enhanced by reducing the oxygen absorption/desorption reaction to the atmosphere. Experimental results showed that TFT device parameters such as threshold voltage, subthreshold swing, and carrier mobility were improved remarkably due to the nitrogen incorporation. In comparison with the a-IGZO TFT, the a-IGZO:N TFT also exhibited superior electrical reliability after the gate bias stress and good device uniformity under the ambient atmosphere. In this study, the proposed a-IGZO:N TFT certainly releases the issues encountered in the present IGZO TFT technology.

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