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Mobility enhancement in amorphous InGaZnO thin-film transistors by Ar plasma treatment

Jung Han Kang,1 Edward Namkyu Cho,1 Chang Eun Kim,2 Min-Jung Lee,3 Su Jeong Lee,3 Jae-Min Myoung,3 and Ilgu Yun1,3(a)

1Department of Electrical and Electronic Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, South Korea
2LG Display Co. Ltd., 1007 Deogeun-ri, Wollong-myeon, Paju-si, Gyeonggi-do 413-811, South Korea
3Department of Materials Science and Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, South Korea

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The effects of Ar plasma treatment on the back-channel of amorphous InGaZnO (a-IGZO) thin-film transistors are investigated. A decrease in metallic ion-oxygen bonding in the Ar plasma-treated a-IGZO channel layer was observed by X-ray photoelectron spectroscopy (XPS) depth profile analysis. An increase in the channel charge carrier concentration is estimated from the increased oxygen vacancy atomic ratio using XPS curve decomposition analysis. The plasma-treated area of the a-IGZO back-channel is varied with a photoresist screening layer with a varied open window length ($L_p$). From the $L_p$-dependent channel resistance analysis, a carrier concentration-dependent field-effect mobility enhancement is observed. © 2013 AIP Publishing LLC

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Amorphous InGaZnO (a-IGZO) thin-film transistors (TFTs) have received much attention as a potential alternative material in future display applications due to its high mobility, room-temperature processibility, and large area uniformity. Recently, it has been shown that improvements to stability and performance of a-IGZO TFTs can be achieved by plasma treatment on an insulator or channel layer. In particular, mobility enhancements by plasma treatment of the source and drain channel regions have been reported as a result of a reduction in contact resistance. However, plasma treatment of the back channel region has rarely been investigated. In this paper, channel carrier concentration-modulated performance characteristics were investigated by varying the open window length of the channel layer using a protective photo resist (PR) layer during plasma treatment.

A-IGZO TFTs were fabricated with a conventional staggered inverted bottom gate structure. A 500 nm thick SiO$_2$ gate dielectric was grown on a p-type silicon substrate with thermal oxidation; a 30 nm thick a-IGZO channel layer was then deposited by RF sputtering at room temperature (RT). The deposition was performed in an O$_2$/Ar gas flow of 5/45 sccm at a working pressure of 5 Torr with an Ar flow rate of 100 sccm, 300 W of RF power, and a working pressure of 0.4 Torr. The electrical characteristics were measured using a Keithley 236 source measurement unit (SMU). Performance parameters such as threshold voltage ($V_T$) and subthreshold swing (SS) were extracted by reading the gate voltage ($V_C$) at a drain current of $I_D = 10$ nA$\times$L/W and SS = $(dlog(I_D))/dV_C$ $^{-1}$, respectively. X-ray photoelectron spectroscopy (XPS) depth profiles of the plasma-treated and untreated a-IGZO active layers were obtained with Ar ion etching (ion beam: 1 kV, 1.4 A) at a filtered Al K$_\alpha$ source ($h\nu = 1486.6$ eV) (Thermo VG, UK).

Fig. 2(a) shows the chemical composition of plasma-treated and untreated a-IGZO active layers with increasing etch time. Both the channel layers are estimated to have similar thicknesses by looking at the depth at which the metallic ions are reduced (In 3d, Ga 2p, and Zn 2p peaks) and the Si 2p peak rises (etch rate was approximately 0.2 nm/s). The plasma-treated channel layer shows a reduced atomic ratio of oxygen (O 1s) and increased metallic ion atomic ratios compared to the untreated channel layer. This seems due to the dissociation of oxygen atoms from metal cations under energetic Ar ion bombardment during the plasma treatment. Based on this previous research, it is assumed that Ar ion with high kinetic energy penetrates and discharges into depth direction which can be estimated from the decreased O 1s throughout the plasma-treated channel layer. Thus, to investigate the depth composition of O 1s, we performed Gaussian curve fit on XPS profiles at a certain depth.

The O 1s peak is decomposed into three components with binding energies of 530.3, 531.0, and 532.3 eV (lattice oxygen, oxygen vacancies, and -OH hydroxide oxygen atoms, respectively) as shown in Figs. 2(b) and 2(c). The
decomposed curve fit of the plasma-treated channel layer’s O 1s peak shows an increase in the atomic ratio of oxygen vacancies compared to that of the untreated channel layer. Due to indications in the literature that the carrier concentration is strongly correlated to oxygen deficiency, the increased oxygen vacancy atomic ratio indicates an increase in channel carrier concentration.6–8 Oxygen vacancies increase because Ar plasma treatment disrupts metallic ion-oxygen bonding.5,9

Fig. 3 shows the variation in transfer characteristics with changes in $L_p$. Since the plasma treatment area is proportional to $L_p$, the turn-on voltage ($V_{ON}$), which is defined as a value of $V_G$ where $I_D$ starts to increase sharply in the logarithmic plot of a transfer curve, shifts from $-9$ V to $-14.5$ V as $L_p$ increases. This is due to an increase in channel carrier concentration from $1.29 \times 10^{17}$ to $2.08 \times 10^{17}$ cm$^{-3}$ (about 61% increase), estimated using the following equation:10,11

$$N_{ch} = C_i V_{ON} / q t_{ch}, \quad (1)$$

where $N_{ch}$, $C_i$, $q$, and $t_{ch}$ are the channel carrier concentration, the insulator capacitance per unit area ($\sim 6.9 \times 10^{-9}$ F/cm$^2$), the electronic charge, and the channel thickness, respectively.

The dependence of carrier concentration on $L_p$ was evaluated using the following equation, based on two assumptions: (1) carrier concentration is uniformly distributed in the plasma-treated and untreated regions in Fig. 1; (2) the same calculation area product of $W \times t_{ch}$ is applicable to both plasma-treated and untreated material

$$N_{ch} = N_{ch,untreat} \times (L - L_p) + N_{ch,plasma} \times L_p \quad (L), \quad (2)$$

where $N_{ch,plasma}$ and $N_{ch,untreated}$ are the carrier concentrations of the plasma-treated and untreated regions, respectively. From Eq. (2), $N_{ch}$ is linear with a positive slope with increasing $L_p$ because $N_{ch,untreat} = N_{ch} (L_p = 0 \, \mu m)$ from Eqs. (1) and (2) is constant and $N_{ch,plasma} > N_{ch,untreated}$ from the previous XPS analysis result.

In order to verify the effects of plasma treatment on the operational properties of a-IGZO, the driving voltage ($V_G-V_T$)-dependent channel resistance of untreated channels ($r_{ch,untreat}$) was extracted using the transmission line method (TLM) on an untreated test set with various $L$.12 Fig. 4 (inset) shows the total resistance ($R_T$) response to various $L_p$. The plasma-treated channel resistance ($r_{ch,plasma}$) was extracted from the modified $R_T$ equation as the following equations:12

$$r_{ch} = \frac{C_i V_{ON}}{q t_{ch}}, \quad (1)$$

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Lp

net mobility of a-IGZO TFTs increases with reduced resistance from the transfer characteristics. As Lp was

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where

was varied using an open PR screening layer with varied open window length on the a-IGZO back-channel surface. The plasma-treated a-IGZO channel layer exhibited a reduction in oxygen vacancies compared to the untreated channel indicating the increase of carrier concentration, which is consistent with the results of transfer characteristic. Therefore, Ar plasma treatment of the back-channel enhanced its mobility by decreasing channel resistance.

In Eq. (3), rch was assumed to be made up of rch plasma and rch untreated connected in series, as shown in Fig. 1. The rch plasma were extracted by applying Eq. (4) on inset of Fig. 4 and the previously extracted rch untreated. The extracted rch plasma shows a reduced resistance compared to rch untreated, as shown in Fig. 4. This is due to the carrier concentration-dependent mobility characteristics indicating that the mobility increases with increasing carrier concentration and therefore the resistivity decreases.13 The Rf decreased with increasing Lp because rch plasma - rch untreated < 0. Thus, the net mobility of a-IGZO TFTs increases with Lp due to reduced rch as shown in Fig. 5 (Inset of Fig. 5 shows an example of Lp-dependent VON and \( \mu_{FE} \) characteristics at \( V_{G-V_T} = 20 \) V).

In this paper, the effects of Ar plasma treatment on the back-channel of a-IGZO TFTs were investigated. Plasma-treated a-IGZO channel layer exhibited a reduction in oxygen atomic ratio from XPS depth profile. The plasma-treated open window length on the a-IGZO back-channel surface was varied using an open PR screening layer with varied Lp lengths. We have analyzed Lp dependent VON and channel resistance from the transfer characteristics. As Lp was increased, the VON shifted negative due to an increase in channel carrier concentration. The channel resistance showed a relationship inversely proportional with Lp. The analysis of the depth profile using curve fitting showed an increase in oxygen vacancies compared to the untreated channel layer indicating the increase of carrier concentration, which is consistent with the results of transfer characteristic. Therefore, Ar plasma treatment of the back-channel enhanced its mobility by decreasing channel resistance.

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