Stability Behavior of Self-Aligned Coplanar a-IGZO Thin Film Transistors Fabricated by Deep Ultraviolet Irradiation

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We fabricated self-aligned coplanar amorphous indium-gallium-zinc-oxide (a-IGZO) TFTs and defined the source/drain region using deep ultraviolet (DUV) irradiation. For our TFTs, source/drain regions were well defined to designed dimensions and contact resistance was low value. The electrical properties of the device show field-effect mobility (μFE) of 13.2 cm2/V·s, subthreshold swing (S/sof) of 0.32 V/decade, threshold voltage (Vth) of 3.2 V, and on/off ratio of 8.8 × 106, respectively. In addition, the reduced channel length (ΔL) and width-normalized contact resistance (RSDW) were 1.08 μm and 87.5 Ω cm, respectively. Stability behavior of self-aligned coplanar a-IGZO TFT fabricated by DUV irradiation was investigated under negative bias stress (NBS), negative bias illumination stress (NBIS), positive bias stress (PBS), and positive bias temperature stress (PBTS). After the stress under NBS, NBIS, PBS, and PBTS, the A Vth values of −0.3 V, −0.8 V, 1.2 V, and 1.3 V were measured, respectively. Additionally, the electrical characteristics of the n+ doping region by DUV irradiation were not degraded under any of the stress conditions.

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Amorphous oxide semiconductors (AOS) have been intensively studied as promising materials for active layer of thin film transistors (TFTs) because of their low off-current, high mobility, and good switching properties compared to amorphous silicon (a-Si)-based TFTs. Among the many oxide TFTs, amorphous In-Ga-Zn-O (a-IGZO) TFTs have been commercialized as backplanes of organic light emission display (OLED) TVs due to their high mobility.1,2 Oxide TFTs with conventional bottom-gate structures such as back channel etch (BCE) and etch-stopper layer (ESL) structure have been widely applied in display back-plane. However, these structures have high parasitic capacitance induced by overlap between gate and source/drain electrodes.3 This parasitic capacitance can generate a voltage drop, which results in brightness non-uniformity, flickering, and image lagging in flat panel displays (FPDs). Self-aligned coplanar structured TFTs are candidate next-generation FPDs because overlap between gate and source/drain electrodes can be minimized, reducing parasitic capacitance.4,5 In previous research, we reported self-aligned coplanar a-IGZO top gate TFTs with various DUV irradiation energies.6 The n+ doping techniques using DUV irradiation is a very simple process. In addition, the self-aligned coplanar TFTs fabricated by DUV irradiation have attractive results for reduced channel length (ΔL) and width-normalized contact resistance (RSDW) compared to other n+ doping methods.6–9 We observed that the electrical properties of n+ regions were stable at elevated temperatures. However, to use these self-aligned TFTs fabricated by DUV irradiation as backplanes for OLEDs, the behavior of TFT stability under various stress conditions needs to be studied. In a self-aligned coplanar structure, the electrical characteristics of the n+ doping region formed by diffusion of hydrogen or/and oxygen deficiency could be degraded under stress conditions. Additionally, the n+ doping region in the intrinsic channel layer (undoped channel layer) could affect the device stability of oxide TFTs during stress. For these reasons, it is important to evaluate changes in electrical properties of the n+ doping region of self-aligned coplanar oxide TFTs under various stress conditions.10 However, the effect of stress on the n+ doping region of self-aligned coplanar oxide TFTs has not been considered in previous studies.

In this study, therefore, we investigated the stability behavior of self-aligned coplanar a-IGZO TFTs fabricated by DUV irradiation under negative bias stress (NBS), negative bias illumination stress (NBIS), positive bias stress (PBS), and positive bias temperature stress (PBTS). Additionally, we evaluated the stability of the n+ doping region by DUV irradiation in self-aligned coplanar a-IGZO TFTs by comparing the switching properties of TFTs before and after stress. We also studied the effect of n+ doping region in intrinsic channel layer on the device stability of self-aligned coplanar a-IGZO TFTs.

Experimental
A 30-nm-thick Al2O3 buffer layer was deposited by atomic layer deposition (ALD) on soda-lime glass. Then, a-IGZO (In: Ga: Zn = 1 : 1 : 1 mol %) was deposited by radio frequency (RF) sputtering at an Ar: O2 ratio of 7: 3 at room temperature and patterned by photolithography. A 100-nm-thick SiO2 layer as a gate insulator was deposited by plasma-enhanced chemical vapor deposition (PECVD). Source/drain contact holes were formed by reactive ion etching (RIE). Next, annealing was performed at 350 °C for 1 hour in N2 ambient. A 100-nm-thick Mo layer was deposited as a gate electrode by direct-current (DC) sputtering at room temperature and patterned by photolithography. As shown in Figure 1, the gate mask pattern acted as a DUV shield layer to define the source/drain regions for selective DUV irradiation (wavelengths of 185 nm and 244 nm) of the source/drain regions. Source/drain regions were n+ doped by DUV irradiation at an energy of 30 J/cm2. DUV irradiation energy is calculated as the product of irradiation time (s) and DUV intensity (mW/cm2). DUV intensity was measured using an EIT PP2-L-U UV POWERPUCK II. Finally, a 100-nm-thick Mo layer was deposited using DC sputtering and formed a source/drain electrode by a lift-off process. The electrical characteristics of the self-aligned coplanar TFTs were measured with an HP Agilent ES270B analyzer. Finally, the amount of hydrogen in a-IGZO thin film was analyzed using time-of-flight secondary mass spectrometry (TOF-SIMS).

Results and Discussion
A Figure 2 shows the resistivity of a-IGZO film as a function of DUV irradiation energy. The resistivity of the film drastically decreased from 9.4 × 105 Ω cm (as-deposited) to 6.6 × 103 Ω cm (DUV energy of 30 J/cm2) as DUV irradiation energy increased. This result indicates that DUV irradiation is an effective technique to n+ doping for a-IGZO film. It is well known that oxygen deficiency is associated with shallow donor dopants because oxygen deficiency provides free electrons in the bulk of oxide semiconductors.11 Additionally, hydrogen in oxide semiconductors is regarded as an electron source because it has two donor-like states: substitutional (H0\textsuperscript{+}) and interstitial (H\textsuperscript{+}) site.12,13 For these reasons, the oxygen deficiency creation and

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Figure 1. Schematic process flowchart for a self-aligned coplanar top gate a-IGZO TFT with source/drain regions formed by DUV irradiation energy of 30 J/cm².

Figure 2. The resistivity of a-IGZO thin film according to DUV irradiation energy. Resistivity decreased from $9.4 \times 10^7$ Ω cm to $6.6 \times 10^{-3}$ as DUV irradiation energy increased.

hydrogen incorporation in oxide semiconductors decreases the resistivity of oxide semiconductors.

In previous studies, we demonstrated a change in oxygen deficiency in a-IGZO film before and after DUV irradiation by analyzing X-ray photoelectron spectroscopy (XPS). After DUV irradiation, oxygen deficiencies increased in a-IGZO thin film compared to as-deposited a-IGZO thin film. This DUV irradiation-induced increase in oxygen deficiencies in a-IGZO thin film suggested an increase in carrier concentration in a-IGZO thin films. Consequently, oxygen deficiency creation is one of the reasons for decrease resistivity of a-IGZO thin films.

To confirm hydrogen incorporation into a-IGZO film by DUV irradiation, we analyzed the hydrogen and hydroxyl group contents in bulk of a-IGZO film before and after DUV irradiation using time-of-flight secondary mass spectrometry (TOF-SIMS). Figures 3a and 3b show a TOF-SIMS depth profile of hydrogen and hydroxyl group species in bulk of a-IGZO film before and after DUV irradiation energy of 30 J/cm², respectively. After the DUV irradiation, the concentration of hydrogen and hydroxyl groups in a-IGZO film increased.

As described in Figure 3c, hydrogen radicals can be generated by photochemical water dissociation during DUV irradiation, and

Figure 3. TOF-SIMS depth profile of (a) hydrogen and (b) hydroxyl group concentrations in a-IGZO film before and after DUV irradiation energy of 30 J/cm². The hydrogen and hydroxyl group peaks increased after DUV irradiation. (c) Scheme of photochemical dissociation caused by DUV irradiation.
these radicals can be incorporated into a-IGZO film.14–16 The water molecule bond dissociation energy is known to be 497.1 kJ/mol or 5.1 eV.17 The energies of DUV light of 185 and 254 nm wavelength are 6.7 and 4.9 eV, respectively. Therefore, 185 nm wavelength DUV is likely to decompose the water molecules into H and OH radicals. As a result, the hydrogen can donate electrons in the a-IGZO thin film because it has two donor-like state such as Ho+ and Hi+ site. Therefore, the hydrogen induced by DUV irradiation is another reason why a decrease in resistivity was observed in the DUV-irradiated a-IGZO thin films.

Figures 4a and 4b show the transfer and output characteristics of a self-aligned coplanar a-IGZO TFT irradiated with DUV energy of 30 J/cm². The output characteristics showed a clear linear region without current crowding at a low drain voltage, which indicates good contact between the source/drain region and contact metal. The electrical properties of the device show field-effect mobility (µFE) of 13.2 cm²/Vs, subthreshold swing (SS) of 0.32 V/decade, threshold voltage (Vth) of 3.2 V, and on/off ratio of $8.8 \times 10^8$ and these values are reasonably good compared with the other reported experimental results for self-aligned coplanar a-IGZO TFTs.6,8,10,18,19

To determine the device stability of self-aligned coplanar a-IGZO TFTs with DUV irradiation, we evaluated stability behavior of the device under negative bias stress (NBS), negative bias illumination stress (NBIS), positive bias stress (PBS), and positive bias temperature stress (PBTS) conditions. Figure 5 shows the transfer characteristics of TFTs as a function of time under NBS, NBIS, PBS, and PBTS conditions. Figures 5a and 5b show representative transfer characteristics of TFTs as a function of time under NBS and NBIS conditions, respectively. Devices were evaluated in air ambient using a gate bias of $V_{GS} = -20$ V and illumination of 3000 lux for a total stress time of 3600 s. No significant changes in the switching properties of the TFT were observed after NBS. However, NBIS resulted in a negative Vth shift of $-0.6$ V, attributed to (i) hole trapping at the interface between the a-IGZO active layer and gate insulator, (ii) hole injection into the gate insulator, and (iii) photo-ionization from a neutral oxygen deficiency (Vo) to a charged oxygen deficiency (Vo2+ ) state.20,21

In the photo-ionization model, the $V_{th}$ deep state near the valence band maximum could be converted to $V_{th}$ near the conduction band minimum, which provided two free electrons to the a-IGZO film. Compared with the hole trapping and injection models, the photo-ionization model appears to play a major role in determining the stability of TFTs under NBIS because there were no significant changes in switching properties in the NBS condition. Figures 5c and 5d show representative transfer characteristics of TFTs as a function of PBS and PBTS times. Devices were stressed under the following conditions: $V_{GS}$ of $+20$ V and temperature of 60 °C for 3600 s. Positive $V_{th}$ shifts of 1.2 V and 1.3 V were observed after PBS and PBTS, respectively. Instability in response to PBS and PBTS has been attributed...
Figure 6. Comparison of electrical characteristics of self-aligned coplanar a-IGZO TFTs with DUV irradiation as a function of (a) NBS, (b) NBIS, (c) PBS, and (d) PBTS times. The $\mu_{FE}$ and S/S factor were not degraded after NBS, NBIS, PBS, and PBTS.

...to (i) electron trapping at the interface between the a-IGZO active layer and gate insulator, (ii) electron injection into the gate insulator, and (iii) creation of acceptor-like defect states. When compared to the results about instability of the devices under PBS and PBTS conditions, it exhibited negligible variation in term of $V_{th}$ shift. This result indicates that there is no additional temperature effect on the instability of the TFTs.

It is also important to investigate the stability of the n+ doping region under various stress conditions because the electrical properties of the n+ doping region affect the switching properties of self-aligned coplanar TFTs. Figure 6 shows the electrical characteristics of the TFTs as a function of stress times under NBS, NBIS, PBS, and PBTS conditions. In the all stress conditions, it did not show noteworthy change in $\mu_{FE}$ and SS before and after stress. These results indicate that the n+ doping regions formed by DUV photochemical hydrogen doping process were not affected by bias, illumination, or temperature stress.

In the self-aligned coplanar structures, it has a reduced channel length ($\Delta L$) region at the edge of the intrinsic channel layer (undoped channel layer) due to the source/drain n+ doping process. In general, hydrogen impurities can affect the device stability of oxide TFTs under thermal stress, which leads to a negative $V_{th}$ shift. This is because of hydrogen diffusion from an adjacent layer such as the buffer layer, gate insulator, or passivation layer to a-IGZO film. As mentioned above, hydrogen species in the a-IGZO film increased after DUV irradiation. Therefore, we investigated the effect of the $\Delta L$ region in the intrinsic channel layer on the device stability of TFTs under thermal stress condition. The $\Delta L$ values of TFTs were calculated by the transmission line method (TLM). Figure 7a shows total resistance as a function of channel length. Intrinsic channel lengths were varied from 10 $\mu$m to 80 $\mu$m at a fixed channel width of 50 $\mu$m, while the applied gate voltage was varied from 5 V to 10 V at a drain voltage of 0.1 V. The extracted values of $\Delta L$ and width-normalized contact resistance ($R_{w}$) were 1.08 $\mu$m and 87.5 $\Omega cm$, respectively. These values are very promising compared to those obtained using other n+ doping techniques. Figure 7b shows the proportions of the $\Delta L$ region in intrinsic channel layers of various lengths. The $\Delta L$ region proportions in 80, 40, 20, and 10 $\mu$m intrinsic channels were 1.4%, 2.7%, 5.4%, and 10.8%, respectively. These results indicate that the proportion of hydrogen doped region in the intrinsic channel layer increased as the length of the intrinsic channel layer decreased. Therefore, this result means that proportion of hydrogen doped region in intrinsic channel layer increases as decrease length of intrinsic channel layer.

To investigate the effect of the $\Delta L$ region on device stability, we evaluated the intrinsic channel length dependency of $\Delta V_{th}$ under PBTS. Figure 8 shows the device stabilities of TFTs with channel lengths of 80, 40, 20, and 10 $\mu$m at a fixed channel width of 50 $\mu$m under PBTS condition. After the stress, the $V_{th}$ shifted in the positive direction in all TFTs; the $\Delta V_{th}$ values were 1.2 V, 1.3 V, 1.2 V, and 1.2 V for TFTs with channel lengths of 80, 40, 20, and 10 $\mu$m, respectively. This result indicates that the hydrogen doped region did not affect the device stability of self-aligned coplanar a-IGZO TFTs during PBTS. Therefore, it implies that the origin of $V_{th}$ shift of our devices were attributed to intrinsic channel layer, gate insulator, and channel layer/gate insulator interface. Consequently, we can conclude that the DUV n+ doping technique has a merit in aspect of $\Delta V_{th}$ and $R_{w}$ values than those obtained using other n+ doping techniques. The self-aligned coplanar a-IGZO TFTs showed reasonable stability under NBS, NBIS, PBS, and PBTS conditions, and the electrical characteristics of the n+ dop-
The n⁺ doping region formed by DUV irradiation were maintained during bias, illumination, and temperature stress. Additionally, the n⁺ doping region in the intrinsic channel layer did not affect the instability under PBTS.

**Conclusions**

In this paper, we investigated the effect of DUV irradiation on the resistivity of a-IGZO thin film. The resistivity of a-IGZO thin film decreased from $9.4 \times 10^7 \Omega \text{cm}$ to $6.6 \times 10^{-3} \Omega \text{cm}$ after application of 30 J/cm² of DUV irradiation. From the TOF-SIMS analysis, we confirmed the hydrogen incorporation in a-IGZO thin film is one of the mechanism for DUV n⁺ doping technique. We used DUV n⁺ doping to form a source/drain region in self-aligned coplanar a-IGZO TFTs and evaluated the stability of the resulting devices under NBS, NBIS, PBS, and PBTS. After the stress, the device shows good stability behavior under all of the stress conditions. Additionally, the n⁺ doping region formed by DUV irradiation did not affect switching properties of the self-aligned coplanar a-IGZO TFT during PBTS. For these reasons, this simple and cost-effective DUV n⁺ doping technique is very useful to define source/drain region in self-aligned coplanar oxide TFT for next generation OLED backplanes.

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