Metal oxide semiconductors have been widely investigated as an active channel in thin-film transistors (TFTs) for next-generation flat-panel displays (FPDs), owing to their outstanding electrical properties such as high-mobility, low-leakage current, steep subthreshold characteristics, and lower processing temperature as compared with amorphous Si TFTs. To achieve high-speed circuits, a self-aligned structure is essential since parasitic capacitances of gate-to-drain (CGD) and gate-to-source (CGS) reduce the operation speed of the TFT circuits. In addition, for an organic light emitting diode display, the CGD and CGS of the pixel selecting TFTs strongly influence the brightness uniformity of the display, because the parasitic capacitances influence the operation voltage of the pixel driving TFTs owing to the kickback/feedback voltage. There are several reports of the self-aligned In-Ga-Zn-O (IGZO) TFTs with highly conductive source and drain regions, which were formed by hydrogen diffusion from hydrogenated silicon nitride, selective exposure with H2, H2O, or He plasma,2-10 ion implantation of dopants,11-16 fluorine doping,14-16 excimer laser irradiation,17 and an Al reaction method.18,19 Among them, the plasma treatment is an easy and cost-effective method for forming an IGZO homojunction over a large-area substrate. Almost all previous research has used conventional capacitive coupled plasma (ICP) apparatus for the plasma treatments; however, both the ion density and ion energy depended on an input power. In contrast, an inductively coupled plasma (ICP) apparatus can control the ion density and ion energy individually by changing the source power and substrate bias power (Pb), respectively.

In this article, we investigated the influence of the substrate bias power during Ar- and He-plasma treatments on the electrical properties, carrier generation mechanism, and subgap states in an IGZO film. First, the effect of Pb on the electrical properties of IGZO films was evaluated by Hall effect measurements. Then, the carrier generation mechanism and origin of subgap states in IGZO were investigated by X-ray photoelectron spectroscopy with the AlKα X-ray source of 1487 eV (hereafter denoted as XPS) and the CrKα X-ray source of 5415 eV (hereafter denoted as hard XPS (HXPS)).20-22 The plasma-treated IGZO films were analyzed by both the surface sensitive XPS and bulk sensitive HXPS methods without an ion beam etching. Thus, the chemical states in IGZO could be obtained from the surface (XPS) and the bulk (HXPS) regions by eliminating the ion beam etching damage during conventional XPS depth analysis.

Experimental

A 45-nm-thick IGZO film was deposited at 160 °C on a glass substrate by DC magnetron sputtering from a ceramic In2Ga2Zn4O11 target (In:Ga:Zn = 1:1:1 mol%). The deposition pressure and Ar/O2 flow rate ratio were 1 Pa and 29.4/0.6 sccm (2% O2 in Ar + O2), respectively. The IGZO film was then exposed to either He or Ar plasma for one minute to modulate the carrier concentration in the IGZO film. During the ICP plasma treatment, the pressure was set at 5 Pa with either an Ar or He flow rate of 100 sccm. The ICP source power was maintained at 500 W, whereas the Pb was varied from 0 to 100 W to investigate the effect of the incident ion’s energy on carrier generation in the IGZO film. During the plasma treatments, the IGZO/glass substrate was held on a water-cooled (20 °C) substrate stage by an electrostatic chucking with helium gas cooling from the back side of the substrate; thus, the substrate temperature was kept below 120 °C.

The sheet carrier concentration (Nₛ) and Hall mobility (μₑ) of plasma-treated IGZO films were measured by DC-type Hall effect measurements using Van der Pauw geometry with Mo/AI electrodes. The XPS measurements were carried out at the incident angle (beam angle respect to sample surface) was 15 and 5 degrees for XPS and HXPS measurements, respectively, while a take-off angle (angle respect to sample surface) was set at 85 degrees for both the XPS and HXPS measurements. Since the escape depth of photoelectron depends on the excitation energy, the XPS provides an information at a depth of a few nanometers from the sample surface, whereas the HXPS had a deeper information depth than the XPS.20-22 The inelastic mean free paths (IMFP) in Ga2O3, In2O3, and ZnO were calculated to be 5.7, 6.4, and 6.5 nm, respectively, at a X-ray source with 5415 eV;22 therefore, the information depth of the HXPS was approximately 17–20 nm (3 times the IMFP).23

Results and Discussion

Electrical and optical properties of plasma-treated IGZO films.—Figure 1 shows the variation of (a) sheet resistance (Rₛ) and (b) Nₛ of the Ar- and He-plasma-treated IGZO films as a function of Pb during the plasma-treatment. The Rₛ and Nₛ of the as-deposited IGZO film were 1.8 × 10⁶ Ω/□ and 6.6 × 10¹¹ cm⁻², respectively. After the plasma treatment without Pb, the Rₛ of the Ar-plasma-treated IGZO film slightly decreased to 6.3 × 10⁴ Ω/□, whereas that of the He-plasma-treated IGZO film further decreased to 7.0 × 10³ Ω/□.
Figure 1. (a) $R_S$ and (b) $N_S$ and $\mu_H$ of He- and Ar-plasma treated IGZO films as a function of $P_B$. (c) The relationship between $\mu_H$ and $N_S$ of the Ar- and He-plasma-treated IGZO films.

$N_S$ of the He-plasma-treated IGZO film increased to $7.0 \times 10^{13}$ cm$^{-2}$, which was more than one order of magnitude higher than that of the Ar-plasma-treated IGZO film ($1.8 \times 10^{12}$ cm$^{-2}$). This result indicated that He-plasma treatment is more effective for the generation of free carriers in IGZO than Ar-plasma treatment without $P_B$, which agreed well with the previous report. When the applied $P_B$ was 100 W, the $R_S$ of the Ar-plasma-treated film decreased to $4.1 \times 10^3$ Ω/□, while that of the He-plasma-treated film further decreased to $1.6 \times 10^3$ Ω/□. The $N_S$ of the Ar-plasma-treated film increased to $1.4 \times 10^{14}$ cm$^{-2}$, while that of the He-plasma-treated film further increased to $3.5 \times 10^{14}$ cm$^{-2}$. It is worth noticing that the $R_S$ and $N_S$ of the Ar-plasma-treated films showed much larger $P_B$ dependence than those of the He-plasma-treated films although the He-plasma treatment generated much higher free carriers than the Ar-plasma treatment. Figure 1c shows the relationship between $\mu_H$ and $N_S$ of the plasma-treated IGZO films. The $\mu_H$ gradually increased with increasing $N_S$ and reached over $10$ cm$^2$·V$^{-1}$·s$^{-1}$, which is a comparable to the values reported from IGZO TFTs. Thus, the $\mu_H$ of IGZO films did not deteriorate when a $P_B$ of 100 W was applied.

Figures 2a and 2b show the transmittance and reflectance spectra of Ar- and He-plasma-treated IGZO films, respectively. The transmittance did not change significantly even when the $P_B$ of 100 W was applied. Figures 2c and 2d show the absorption coefficient ($\alpha$) of Ar- and He-plasma-treated IGZO films as a function of photon energy. After the Ar- and He-plasma treatments without $P_B$, no significant change in $\alpha$ was observed from the as-deposited film. After the plasma treatment at a $P_B$ of 50 W, subgap states were increased for both the Ar- and He-plasma-treated IGZO films. The $\alpha$ gradually increased with increasing $N_S$, and reached over $10$ cm$^{-1}$. The $\alpha$ is a comparable to the values reported from IGZO TFTs. Thus, the $\alpha$ of IGZO films did not deteriorate when a $P_B$ of 100 W was applied.

Carrier generation mechanism in He- and Ar-plasma-treated IGZO films without $P_B$.—First, the carrier generation mechanism in both the He- and Ar-plasma-treated IGZO without $P_B$ was investigated by XPS and HXPS. Figure 3 shows the XPS spectra of (a) In3d and (b) Zn2p obtained from He- and Ar-plasma-treated IGZO films without $P_B$. O1s spectra of (c) He- and (d) Ar-plasma-treated IGZO films without $P_B$. The dependence of the electrical and optical properties on $P_B$ suggests that the influence of $P_B$ on the carrier generation mechanism is different between Ar- and He-plasma treatments. Thus, the XPS and HXPS analyses were carried out for Ar- and He-plasma-treated IGZO films to investigate the carrier generation mechanism and origin of subgap states.
|                     | XPS                       | HXPS                      |
|---------------------|---------------------------|---------------------------|
|                     | M-O | V-O | O-H | M-O | V-O | O-H |
| as-deposited        | 80.1| 17.6| 2.3 | 90.2| 6.8 | 3.0 |
| He-plasma           |     |     |     |     |     |     |
| $P_b = 0$ W         | 62.8| 32.2| 5.0 | 80.9| 14.6| 4.5 |
| $P_b = 50$ W        | 56.9| 39.7| 3.4 | 70.3| 26.3| 3.4 |
| $P_b = 100$ W       | 59.3| 38.7| 2.0 | 67.1| 28.1| 4.8 |
| Ar-plasma           |     |     |     |     |     |     |
| $P_b = 0$ W         | 79.1| 18.7| 2.2 | 88.6| 8.9 | 2.5 |
| $P_b = 50$ W        | 76.0| 22.8| 1.2 | 89.5| 9.7 | 0.8 |
| $P_b = 100$ W       | 75.4| 23.5| 1.1 | 86.5| 11.4| 2.1 |

$P_b$. The XPS spectra of the as-deposited film are also shown as a reference. All spectra were normalized to the Ga2p spectrum because the Ga–O bond had the highest dissociation energy among the metal-oxygen (M–O) bonds in IGZO. No significant changes were observed in the In3d and Zn2p spectra before and after the plasma treatments. In contrast, as shown in Figs. 3c and 3d, a marked difference was observed in the O1s spectra before and after the He- and Ar-plasma treatments. After the plasma treatments, a shoulder appeared in the O1s spectra at approximately 1.2 eV higher than the M–O bond peak at 531.2 eV. The intensity of the shoulder in O1s spectra of the He-plasma-treated film was higher than that of the Ar-plasma-treated film. After Shirley’s background subtraction, the O1s spectrum was well fitted by three Gaussian–Lorentz curves. We assigned the lowest binding energy peak at 531.2 eV (O_L) to the M–O bonds, the medium binding energy peak at 532.4 eV (O_M) to the oxygen vacancies (V_O), and the highest binding energy peak at 533.2 eV (O_H) to the oxygen in the hydroxide.11,16 A similar analysis was also carried out for the O1s spectra obtained by HXPS. Table I summarizes the area ratio of M–O, V_O, and O_H of the as-deposited, He- and Ar-plasma-treated IGZO films evaluated by XPS and HXPS. From the XPS analysis, the area ratio of O_M slightly increased from 17.6% (as-deposited) to 18.7% after the Ar-plasma treatment, whereas it markedly increased to 32.2% after the He-plasma treatment. A similar trend was observed in the HXPS analysis. The XPS and HXPS analyses indicated that He-plasma treatment generates more V_O than Ar-plasma treatment, and the V_O is the main cause of free carriers in both the Ar- and He-plasma-treated IGZO films without $P_b$, which agreed well with the previous report.11

**Influence of $P_b$ on the carrier generation mechanism and origin of subgap states in He- and Ar-plasma-treated IGZO films.**—Next, we investigated the influence of $P_b$ on the carrier generation mechanism and origin of subgap states in the He- and Ar-plasma-treated IGZO films. Figures 4 and 5 show the O1s spectra of He- and Ar-plasma-treated IGZO films, respectively, with a $P_b$ of 0 and 100 W measured by XPS and HXPS. The area ratios of M–O, V_O, and O_H in the O1s spectra are also summarized in Table I. By increasing the $P_b$ from 0 to 100 W, the V_O ratio in the He-plasma-treated IGZO films increased from 32.2 to 38.7% by XPS analysis and from 14.6 to 28.1% by HXPS analysis. The V_O ratio in the Ar-plasma-treated IGZO films increased from 18.7 to 23.5% by XPS analysis and from 8.9 to 11.4% by HXPS analysis. The XPS results revealed that the $P_b$ of the He-plasma treatment generated much larger V_O at the surface of the IGZO film than that of the Ar-plasma treatment. The HXPS results clearly depicted that the generation depth of V_O increased with increasing $P_b$ of the He-plasma treatment. Since the incident energies of the He$^+$ and Ar$^+$ ions were mainly determined by the $P_b$, the lighter mass of the He$^+$ ion had a larger projected range than the Ar$^+$ ion. Thus, for the case of He-plasma treatment, the generation depth of the V_O and the total number of V_O increased with increasing $P_b$, which resulted in an increase of free carriers in the IGZO film. However, the

![Figure 4](https://example.com/figure4.png)

**Figure 4.** O1s spectra of He-plasma-treated IGZO with a $P_b$ of (a,c) 0 and (b,d) 100 W measured by (a,b) XPS and (c,d) HXPS.

Ns had much larger dependence on $P_b$ during Ar-plasma treatment than during He-plasma treatment as shown in Fig. 1b. The $P_b$ dependence of Ns in Ar-plasma-treated IGZO cannot be explained by only considering the V_O.

Figures 6 and 7 show the In3d and Zn2p spectra, respectively, of Ar-plasma-treated IGZO films with a $P_b$ of 0 and 100 W measured by XPS and HXPS. From the XPS measurements, we found that the
In3d and Zn2p spectra shifted to a lower binding energy when the \( P_B \) increased from 0 to 100 W. The shifted In3d and Zn2p spectra could be fitted by two Gaussian–Lorentz curves. In the In3d spectra shown in Fig. 6b, we attributed the main peak at 445.5 eV to the In\(^{3+}\) state in In\(_2\)O\(_3\), and the satellite peak at 444.9 eV to metallic In (In\(^{0}\)).\(^{24-27}\) In the Zn2p spectra shown in Fig. 7b, we attributed the main peak at 1022.6 eV to the Zn\(^{2+}\) state in ZnO, and the satellite peak at 1022.3 eV to metallic Zn (Zn\(^{0}\)).\(^{28,29}\) Table II summarizes the area ratio of In\(^{3+}\), Zn\(^{2+}\), In\(^{0}\), and Zn\(^{0}\) states in the He- and Ar-plasma-treated IGZO films measured by XPS and HXPS. The XPS analysis indicated that the In\(^{0}\) ratio at the IGZO surface was only 0.8 and 1.3% after the He- and Ar-plasma treatments, respectively, without \( P_B \). When the \( P_B \) was increased to 100 W, the In\(^{0}\) ratio drastically increased to 54.2% after the Ar-plasma treatment, whereas it slightly increased to 8.7% after the He-plasma treatment. In addition, HXPS analysis also depicted that the In\(^{0}\) ratio increased from 0.9 to 8.0% after the Ar-plasma treatment at a \( P_B \) of 100 W, whereas it was almost unchanged even after He-plasma treatment at a \( P_B \) of 100 W. The XPS analysis indicated that the Zn\(^{0}\) ratio at the IGZO surface was 2.1 and 0.7% after the He- and Ar-plasma treatments, respectively, without \( P_B \). When the \( P_B \) was increased to 100 W, the Zn\(^{0}\) ratio rapidly increased to 32.5% after the Ar-plasma treatment, whereas it was almost unchanged at 3.4% after the He-plasma treatment. The results shown in Figs. 6 and 7 indicate that the Ar-plasma treatment formed In\(^{0}\) and Zn\(^{0}\) states mostly at the IGZO surface as the \( P_B \) was increased. Free carriers in the Ar-plasma-treated IGZO film would be generated from the In\(^{0}\) and Zn\(^{0}\) states; thus, the \( N_s \) shown in Fig. 1b exhibited much stronger \( P_B \) dependence for the Ar-plasma treatment than for the He-plasma treatment.

Figure 8 shows the HXPS spectra within the bandgap region of the (a) He-plasma-treated and (b) Ar-plasma-treated IGZO films with various \( P_B \). As shown in Fig. 8a, subgap states were observed only near the Fermi level (\( E_F \)) for the as-deposited and the He-plasma-treated IGZO film without \( P_B \). It was reported that the subgap states in the IGZO were detected at the near valence band maximum (near-VBM) and near \( E_F \) when the film was analyzed by HXPS with a synchrotron X-ray source (7940 eV).\(^{30,31}\) Unfortunately, only the subgap states near the \( E_F \) could be detected for the as-deposited IGZO film by our laboratory-based HXPS owing to sensitivity limitations. However, the near-VBM states could be detected for the He-plasma-treated film.

### Table II. The area ratios of In–O, In–In, Zn–O, and Zn–Zn in He- and Ar-plasma-treated IGZO films at different \( P_B \) evaluated by XPS and HXPS.

| \( P_B \) (W) | XPS | HXPS |
|---|---|---|
| | In–O | In–In | Zn–O | Zn–Zn | In–O | In–In | Zn–O | Zn–Zn |
| as-deposited | 99.1 | 0.9 | 99.0 | 1.0 | 99.7 | 0.3 | 98.3 | 1.7 |
| He-plasma | | | | | | | | |
| \( P_B = 0 \) W | 99.2 | 0.8 | 97.9 | 2.1 | 99.3 | 0.7 | 98.3 | 1.7 |
| \( P_B = 50 \) W | 97.8 | 2.2 | 96.7 | 3.3 | 99.5 | 0.5 | 95.8 | 4.2 |
| \( P_B = 100 \) W | 91.3 | 8.7 | 96.6 | 3.4 | 99.2 | 0.8 | 98.1 | 1.9 |
| Ar-plasma | | | | | | | | |
| \( P_B = 0 \) W | 98.7 | 1.3 | 99.3 | 0.7 | 99.1 | 0.9 | 97.1 | 2.9 |
| \( P_B = 50 \) W | 67.0 | 33.0 | 61.6 | 38.4 | 89.3 | 10.7 | 95.9 | 4.1 |
| \( P_B = 100 \) W | 45.8 | 54.2 | 67.5 | 32.5 | 92.0 | 8.0 | 96.4 | 3.6 |

\[^{24-27}\] ECS Journal of Solid State Science and Technology, 6 (8) Q101-Q107 (2017)

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IGZO films when the $P_B$ of 50 and 100 W were applied. The near-VBM states were approximately 1.5–2.0 eV above from the VBM; their shape was very similar to the near-VBM states observed from a low-quality IGZO reported by Nomura et al.\textsuperscript{30,31} Based on the results shown in Fig. 4, the generation depth and total number of $V_O$ increased in the He-plasma-treated IGZO with increasing $P_B$. Thus, the near-VBM states in the He-plasma-treated IGZO films ($P_B$ of 50 and 100 W) mainly originated from oxygen vacancies. In contrast, near-VBM states were not detected for the Ar-plasma-treated IGZO films when the $P_B$ was less than 100 W. Although the near-VBM states were detected in the Ar-plasma-treated IGZO at a $P_B$ of 100 W, their shape was different to the He-plasma-treated films. The Ar-plasma-treated IGZO film at a $P_B$ of 100 W contained stepwise continuous states near conduction band minimum (near-CBM states) in addition to the near VBM states. Similar stepwise near CBM states were reported for IGZO films deposited in the pure-Ar (without O$_2$) gas.\textsuperscript{27} Our results shown in Figs. 5–7 depicted that the In$^+$ and Zn$^+$ states were formed at the surface of the Ar-plasma-treated IGZO film when the $P_B$ of 100 W was applied. In addition, the Vo ratio in the Ar-plasma-treated IGZO was much smaller than that in the He-plasma-treated IGZO; thus, the subgap states in the Ar-plasma-treated IGZO films would be originated from the metallic In$^+$ and Zn$^+$ states.

To further investigate the generation mechanism of the metallic In$^+$ and Zn$^+$ states, we evaluated the $P_B$ dependence of an IGZO etching rate. Figure 9 shows the IGZO etching rate as a function of $P_B$. For the He-plasma treatment, the IGZO etching rate was negligible (< 1 nm/min) even at a $P_B$ of 100 W, which indicated that the He-plasma did not etch the IGZO film. In contrast, for the Ar-plasma treatment, the IGZO etching rate clearly increased to approximately 6 nm/min when the $P_B$ was increased to 100 W. This result indicated that the heavy mass of the Ar$^+$ ions enhanced the re-sputtering of the IGZO film when the incident energy of the Ar$^+$ ions was increased. Unfortunately, we did not measure the potential of the IGZO surface (self-bias) during the plasma treatments because insulating glass was used as a substrate. However, the potential of the IGZO surface was deduced less than several hundred volts because a similar deposition rate (~6 nm/min) was obtained by DC sputtering of IGZO at a cathode voltage of ~450 V. In our previous research of ZnO sputtering,\textsuperscript{32} ZnO films were deposited from ceramic ZnO target using a mixed gas containing isotopic oxygen (O$^{18}$) and Ar as a sputtering gas to confirm the origin of the constituent oxygen in the ZnO film. Secondary ion mass spectroscopy results revealed that the O$^{18}$ ratio in the deposited ZnO film exceeded 80%, which indicated that the ZnO film was formed by chemical reaction of Zn and oxygen radicals at the target surface even when a ceramic ZnO target was used. In other words, a reduction of ZnO occurred and Zn$^{2+}$ ions were formed at the target surface during the ZnO sputtering. Thus, the generation mechanism of the metallic In$^+$ and Zn$^+$ states in the Ar-plasma-treated IGZO film can be considered as follows. During the Ar-plasma treatment with $P_B$, the high energy of the Ar$^+$ ions sputtered the IGZO film and reduced the Zn–O and In–O bonds to In$^+$ and Zn$^+$ states, because the dissociation energies of In–O (346 kJ/mol) and Zn–O (284 kJ/mol) bonds are smaller than that of the Ga–O (374 kJ/mol) bond.\textsuperscript{33} As a result of the increase of metallic In$^+$ and Zn$^+$ states at the IGZO surface, the $N_S$ showed a much larger $P_B$ dependence on the Ar-plasma treatment than on the He-plasma treatment, as shown in Fig. 1b.

**Bottom gate self-aligned IGZO TFT with source/drain regions formed by He- or Ar-plasma treatment with $P_B$.**—To apply the plasma treatment for source and drain (S/D) regions in a self-aligned IGZO TFT, the change in $R_S$ through thermal annealing was investigated. The annealing was carried out in N$_2$ ambient for 1 hour after deposition of a 200-nm-thick SiO$_x$ on the plasma-treated IGZO films since the S/D regions in TFT were covered by the SiO$_x$ interlayer as shown in Fig. 11.

Figure 10 shows the $R_S$ of the plasma-treated IGZO films covered by SiO$_x$ film as a function of annealing temperature ($T_a$). The $R_S$ of the film w/o plasma treatment reduced from $1.8 \times 10^3 \Omega \cdot \square$ to $3.9 \times 10^2 \Omega \cdot \square$ after the SiO$_x$ deposition. The decrease of the $R_S$ may have originated by hydrogen diffusion and/or formation of $V_O$ during the plasma-enhanced chemical vapor deposition (PE-CVD) of the SiO$_x$.\textsuperscript{34} The $R_S$ of the film w/o plasma treatment rapidly increased when the $T_a$ exceeded 250°C. The $R_S$ of the Ar-plasma-treated films with $P_B$ of 0 and 50 W exhibited similar tendency as the film w/o plasma treatment, whereas that with $P_B$ of 100 W was stable ($R_S = 3.1 \times 10^3 \Omega \cdot \square$) even after annealing at 350°C. Although the He-plasma-treated films showed lower $R_S$ than the Ar-plasma-treated films, the $R_S$ of the film with $P_B$ of 0 W when the $T_a$ exceeded 350°C.

In contrast, the $R_S$ of 9.8 × 10$^7$ and 7.9 × 10$^9$ Ω·□ were achieved by He-plasma treatments with $P_B$ of 50 and 100 W, respectively, even after annealing at 350°C. The result indicated that an appropri-
ate $P_B$ effectively suppressed an increase of the $R_S$ after annealing at 300–350°C. Thus, we fabricated bottom-gated and self-aligned IGZO TFTs with the S/D regions formed by Ar- and He-plasma treatments with $P_B$. Figure 11 shows a fabrication step of the IGZO TFT. First, a 50-nm-thick Cr gate electrode was formed on a 4-inch nonalkaline glass substrate. A 150-nm-thick SiO$_2$ gate insulator was deposited at 350°C by PE-CVD. A 45-nm-thick IGZO channel was deposited at 160°C by dc magnetron sputtering in the mixture of Ar$_2$O$_2$ (2% O$_2$) gases. A 200-nm-thick SiO$_2$, etching-stopper layer (ESL) was deposited by PE-CVD at 170°C. Then, the ESL was aligned by a backside-exposure method, using gate electrodes as a self-aligned mask, and was etched by dry-etching. The IGZO was then patterned into a channel by lithography and dry-etching, as shown in Fig. 11a. The source and drain (S/D) regions were formed by He- or Ar-plasma treatment with $P_B$ of 50 and 100 W. The TFT without plasma treatment was also made as a reference. After the plasma treatment of the S/D regions, a 200-nm-thick SiO$_2$ interlayer was deposited by PE-CVD at 220°C. The S/D electrodes were formed by Mo/Al/Mo. The TFT properties were measured in dark and ambient air after post annealing at 350°C for 1 hour in N$_2$ ambient.

Figure 12 shows transfer characteristics of the IGZO TFTs with (a) Ar- and (b) He-plasma-treated S/D regions. The IGZO TFT with S/D regions formed w/o plasma and with Ar-plasma treatment at a $P_B$ of 50 W showed low on-current, owing to a huge series resistance in the S/D regions. In contrast, the on-current of the TFTs with S/D regions formed by Ar-plasma treatment at a $P_B$ of 100 W and He-plasma treatment at $P_B$ of 50 and 100 W were drastically improved with $\mu_{FE}$ of around 9–10 cm$^2$ V$^{-1}$ s$^{-1}$. The on-current of the TFTs were well correlated with the $R_S$ of the plasma-treated films as shown in Fig. 10. Electrical properties of the TFTs were summarized in Table III. For the case of He-plasma treatment, subthreshold swing (S) slightly degraded as the $P_B$ increased from 50 to 100 W, which may be due to an ion bombardment damage through the ESL. The results indicated that an appropriate $P_B$ enhanced thermal stability of the S/D regions, and improved the TFT properties even after post-fabrication annealing at 350°C.

### Conclusions

In this study, we investigated the effects of the substrate bias power during Ar- and He-plasma treatments on the electrical properties of the IGZO films. The $N_V$ of the IGZO films increased from 6.6 $\times$ 10$^{11}$ cm$^{-2}$ (as-deposited) to 3.5 $\times$ 10$^{11}$ cm$^{-2}$ and 1.4 $\times$ 10$^{11}$ cm$^{-2}$ after He- and Ar-plasma treatments, respectively, with a $P_B$ of 100 W. No significant degradation of Hall mobility was observed after the plasma treatments even with a $P_B$ of 100 W. The application of $P_B$ during the plasma-treatment is an effective method to form homojunctions in an IGZO film. The carrier generation mechanism and origin of subgap states were also investigated by XPS and HXPS analyses. The generation of $V_O$ was the main cause of carrier generation in the He-plasma-treated IGZO films. The generation depth and total number of $V_O$ increased with increasing $P_B$, which resulted in an increase of free carriers in the He-plasma-treated IGZO film. As the $V_O$ increased, near-VBM states were observed in the He-plasma-treated IGZO films when the $P_B$ of more than 50 W was applied. Thus, the near-VBM states in the He-plasma-treated IGZO films mainly originated from $V_O$. On the other hand, the metallic In and Zn states were observed at the surface of the Ar-plasma-treated IGZO as $P_B$ increased. Although the near-VBM states were observed for the Ar-plasma-treated IGZO at a $P_B$ of 100 W, their shape was different to the He-plasma-treated IGZO film. The near-VBM states were observed in the Ar-plasma-treated IGZO film accompanied by stepwise continuous subgap states near CBM when the $P_B$ of 100 W was applied. Since the $V_O$ in the Ar-plasma-treated IGZO film was much lower than that in the He-plasma-treated film, the subgap states in the Ar-plasma-treated IGZO film would be originated from the metallic In and Zn states. We also demonstrated a bottom gate and self-aligned IGZO TFT with S/D regions formed by the plasma treatment with $P_B$. An appropriate $P_B$ significantly reduced a series resistance in the S/D regions and improved the TFT properties even after post-fabrication annealing at 350°C.

### Acknowledgment

This work was partly supported by JSPS KAKENHI grant Number 16K06309.

### Table III. Summary of the TFT properties.

| Plasma treating condition | $Ar\ P_B = 100\ W$ | $He\ P_B = 50\ W$ | $He\ P_B = 100\ W$ |
|---------------------------|---------------------|-------------------|-------------------|
| $\mu_{FE}$ [cm$^2$ V$^{-1}$ s$^{-1}$] | 9.3 | 9.9 | 11.3 |
| $S$ [V/dec.] (10–100 pA) | 0.40 | 0.46 | 0.54 |
| $V_g$ at $I_d = 1$ nA [V] | 1.42 | 2.01 | 2.36 |

Figure 11. Cross-sectional fabrication steps of bottom-gate and self-aligned IGZO TFT.

Figure 12. Transfer characteristics of IGZO TFTs (W/L = 66/12 μm) with the S/D regions formed by (a) Ar- and (b) He-plasma treatment with $P_B$ of 50 and 100 W.

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