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Coplanar homojunction a-InGaZnO thin film transistor fabricated using ultraviolet irradiation

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We have developed a new technique to fabricate coplanar homojunction structure a-IGZO thin film transistors (TFTs) by adopting selective ultraviolet (UV) irradiation in the n+ source/drain regions of an a-IGZO layer through a patterned photoresist mask. In order to apply this technique for coplanar homojunction a-IGZO TFTs, we systematically studied the effect of dual wavelength (185 nm and 254 nm) UV irradiation time on the conductivity of a-IGZO films. Various materials were evaluated to find one that provided proper shielding against UV irradiation. The resistivity of the a-IGZO film drastically decreased from an as-deposited value of 2.71×10^{6} Ω·cm to 3.76×10^{-5} Ω·cm after UV irradiation. The lowest resistivity obtained in this study is similar to that of ITO transparent electrodes and is about 2 orders of magnitude lower than the values obtained to date. Coplanar homojunction a-IGZO TFTs were successfully fabricated by introducing an optimized process that included UV irradiation through a patterned photoresist UV mask. The saturation mobility (μ_{sat}), threshold voltage (V_{th}), sub-threshold swing (SS), and on/off current ratio (I_{on}/I_{off}) were measured to be 6.7 cm^2/V·s, 7.3 V, 0.21 V/decade, and ~10^9, respectively. Moreover, we showed that the UV irradiation technique provided both a low contact resistance due to the high conductivity in the source/drain region and a small channel length modulation due to non-thermal doping behavior. We believe that this UV irradiation process is a useful technique because it is simple and results in outstanding electrical properties.

Introduction

Amorphous InGaZnO (a-IGZO) TFTs have attracted attention for the application in active-matrix liquid crystal displays and active-matrix organic light emitting diode displays due to their high mobility, low sub-threshold swing, low leakage current and good large-area uniformity in comparison with amorphous silicon TFTs. A bottom gate structure has been widely employed for a-IGZO TFTs.[1-4] However, the bottom gate structure has a high parasitic capacitance including gate-to-drain and gate-to-source due to overlap between the gate and source/drain electrodes. These parasitic capacitances eventually lead to signal resistance-capacitance (RC) delay in the TFT backplane of high-resolution large-area displays.

In order to overcome this problem, many research groups have studied coplanar structured a-IGZO TFTs, which can minimize the overlap between the gate and the source/drain electrodes.[5-8] Authors of these reports proposed the formation of an n^+-doped a-IGZO film on the source/drain contact regions by selective exposure to Ar, He, and H_2 plasma ambient.[5,9,10] High conductivity can also be achieved by hydrogen diffusion into the a-IGZO film during plasma enhanced chemical vapor deposition (PECVD) of silicon nitride (SiN_x) or silicon oxide (SiO_x), which provide an etch stopper layer or a passivation layer.[11] However, the n^+ doping process using plasma treatment is rather complicated, and channel region may become narrow because hydrogen diffuses to channel region during the process due to high diffusivity.[10] The effect of UV irradiation on the conductivity of a-IGZO films was investigated in a previous report. In that report, a-IGZO TFTs with a dual active layer were fabricated by inserting an embedded conductive layer using photo-chemical doping of the a-IGZO film by UV irradiation. The photo-chemical n^+-doped a-IGZO channel showed an increase in carrier concentration of ~10^{18} cm^{-3} from the background level of 10^{16} cm^{-3}, and the overall characteristics of the TFT were improved as well.[12]

In this study, we investigated the effect of UV irradiation time on the resistivity of a-IGZO films and evaluated shielding materials for selective doping in the a-IGZO active layer. Then, we optimized a simple photo-chemical doping technique to fabricate coplanar homojunction a-IGZO TFTs. In addition to the superior electrical characteristics of a-IGZO TFTs fabricated using the UV irradiation process, we also demonstrated the advantage of the selective UV irradiation method over the other methods by estimating the contact resistance (R_{sd}) and channel length modulation (△L) using a transmission line method (TLM).

Experimental

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In order to evaluate the effect of UV irradiation time on conductivity of IGZO film, we varied the irradiation time from 1 to 3hr. We also evaluated candidate masking material such as SiO_x, AlO_x and negative and positive photoresist (hereafter, denoted as NPR and PPR, respectively). Finally, we fabricated a coplanar homojunction a-IGZO TFTs employing the UV irradiation process as shown schematics in Figure 1. 100 nm-thick Mo layer was deposited as the gate electrode by direct current (DC) sputtering with a DC power of 80W and working pressure of 4 mTorr in an Ar ambient. These gate electrodes were patterned by using photolithography and a wet etching process. SiN_x and SiO_2 were sequentially deposited by plasma enhanced chemical vapor deposition (PECVD) at 250°C to form a SiN_x (100 nm)/SiO_2 (40 nm) bi-layer as a gate insulator. Then, a 50 nm-thick a-IGZO (In:Ga:Zn=1:1:1 mol ratio) layer was deposited at room temperature by radio frequency (RF) sputtering with a RF power of 40 W at a working pressure of 5 mTorr using a gas with a Ar : O_2 = 90 : 10 mix ratio. After the a-IGZO active layer was patterned by photolithography and wet etching, a nitrogen annealing process was performed in a furnace for 1 hr at 300°C. To form the n^+ a-IGZO source/drain region, a 1.8 μm-thick patterned positive photo-resist (PPR) was used as a UV masking layer. Then, the sample was exposed to UV light with a fixed intensity of 10.8 mW/cm^2 for 3 hrs. A typical UV cleaning apparatus was used to provide the UV irradiation at wavelengths of 185 and 254 nm. Finally, a 100 nm-thick layer of Mo was deposited using DC sputtering, and the source and drain electrodes were patterned using a lift-off method. The electrical properties of UV treated a-IGZO films and coplanar homojunction a-IGZO TFTs were evaluated by current–voltage (I–V) measurements performed using an Agilent E5270B parameter analyzer.

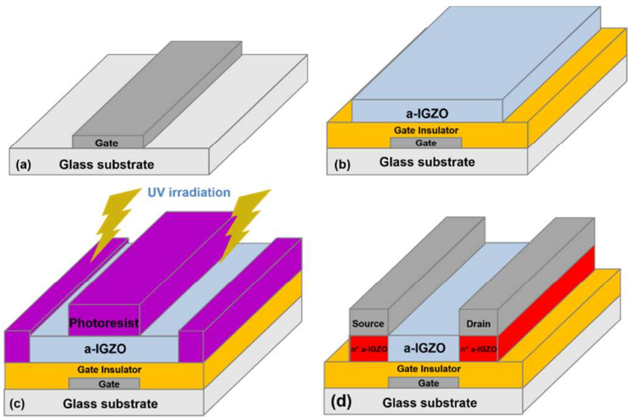

Fig. 1. A schematic representation of the fabrication process for coplanar homojunction a-IGZO TFTs: (a) gate metal deposition and patterning, (b) gate insulator and a-IGZO film deposition and patterning, (c) PR UV mask layer patterning followed by UV irradiation to form an n^+ a-IGZO region, and (d) source and drain formation using a lift-off method. The channel width (W) and length (L) are 160 μm and 40 μm, respectively.

Results and discussion

Figure 2 shows the resistivity of the a-IGZO film as a function of UV irradiation time. The resistivity of the as-deposited a-IGZO film was 2.71×10^6 Ω·cm. The resistivity drastically dropped over the first 2 hrs and then levelled off thereafter. The resistivity (3.76×10^{-5} Ω·cm) obtained after UV irradiation for 3 hrs is similar to that of ITO transparent electrodes (10^{-4} to 10^{-5} Ω·cm).

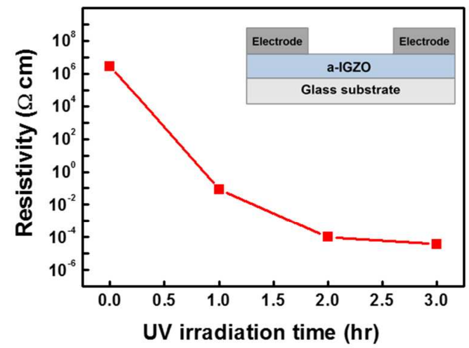

Fig. 2. Resistivity of a-IGZO films as a function of UV irradiation time. The resistivity of the as-deposited a-IGZO film was as high as 2.71×10^6 Ω•cm. After UV-irradiation for 3 hrs, the resistivity of the a-IGZO film dropped to 3.76×10^{-5} Ω•cm, which is similar to the level of typical transparent ITO electrodes (10^{-4}~10^{-5}Ω•cm).

Many research groups have introduced various plasma treatment techniques and diffusion of hydrogen or fluorine into a-IGZO film using a PECVD process to decrease the resistivity.[6,10,13,14] As shown in Table 1, the resistivity obtained by UV irradiation is significantly lower than those achieved for plasma-based n+ a-IGZO formation techniques previously reported. In the plasma-related techniques, the resistivity of a-IGZO films was all in the range of 10^{-3} Ω·cm. The resistivities obtained from direct plasma treatment with Ar[9], H_2[10], and He[5] were 2.93×10^{-3} Ω·cm, 4.8×10^{-3} Ω·cm and 2.79×10^{-3} Ω·cm, respectively, while the resistivity obtained from hydrogen diffusion during SiN_x[11] deposition by PECVD process was 6.20×10^{-3} Ω·cm. Previous investigators have claimed that plasma treatment with H_2, He, or Ar creates oxygen vacancies via bond breaking between metal and oxygen in a-IGZO.[7,9,10,16]

In our previous study, we fabricated a-IGZO TFT with high mobility by "permanent photo-chemical doping" via UV irradiation. The UV irradiation is known to break metal-oxide bonds and generate the charged oxygen vacancy such as V_o^+ and V_o^{2+} from V_o neutral vacancy in oxide semiconductor. These phenomenon provide free electrons in oxide semiconductor, which leads to increase of carrier concentration[12,17]. This UV irradiation technique is attractive because it is performed at room temperature in air ambient using

Table 1. Comparison of resistivity (Ω•cm) of n^+ a-IGZO films formed using various n^+ doping methods.

Method	Resistivity (Ω cm)	Ref.
SiN_x:H	6.20×10^{-3}	[11]
H_2 plasma treatment	4.8×10^{-3}	[10]
Ar plasma treatment	2.93×10^{-3}	[9]
He plasma treatment	2.79×10^{-3}	[5]
UV irradiation for 3hrs	3.76×10^{-5}	this work

commercially available UV cleaning equipment. Moreover, the line-of-sight nature of the UV exposure is advantageous for fabrication of coplanar homojunction TFTs that require accurate dimensional control.

In contrast, the definition of the n^+ region during fabrication of coplanar TFTs is not easy in some of the plasma treatment techniques due to the diffusion of the chemical species.

A proper masking material is required in order to define the source/drain region in a coplanar homojunction TFT. We evaluated candidate masking materials including SiO_x, AlO_x and negative and positive photoresist (i.e., NPR and PPR, respectively). The thicknesses were 100 nm, 100 nm and 1.8 µm, respectively, which were chosen based on the typical values used in conventional TFT fabrication processes. After the UV shielding layer was deposited onto the a-IGZO layer, the sample was exposed to UV light for 3hrs, which was followed by measurement of the resulting resistivity (Figure 3). The 100 nm thick SiO_x stacked a-IGZO film showed a resistivity of 1.41×10^{-4} Ω·cm after UV exposure; this resistivity is almost the same as that of unshielded a-IGZO after UV irradiation (3.76×10^{-5} Ω·cm). The resistivity was measured to be 1.63×10^{-1} Ω·cm for the AlO_x layer after UV exposure. Even though this value is about three orders of magnitude higher than that of the SiO_x stacked a-IGZO film, the AlO_x layer is still transparent to UV irradiation. Interestingly, the resistivities of PPR and NPR stacked a-IGZO films turned out to be 5.62×10^5 Ω·cm and 4.09×10^5 Ω·cm, respectively, after UV exposure. These values are close to the resistivity of the as-deposited a-IGZO film (2.71×10^6 Ω·cm). Therefore, a simple process of selective UV irradiation through a patterned PR shielding layer can be effective in the fabrication of coplanar homojunction a-IGZO TFTs.

Figure 4 shows the transfer characteristics of the a-IGZO TFTs without and with n+-doped a-IGZO source/drain (S/D) regions formed by UV irradiation for 3hrs. All the processes were carried out identically for these two samples except for the selective UV irradiation of the source/drain areas. Several important parameters of the a-IGZO TFT such as saturation mobility (μ_{sat}), threshold voltage (V_{th}), subthreshold swing (SS) and on/off current ratio were compared at room temperature (298 K). The non-UV treated a-IGZO TFT exhibited a μ_{sat} of 0.6 cm^2/V·s, V_{th} of 15.0 V, SS value of 0.90 V/decade, and on/off current ratio of ~10^8. These inferior electrical properties were mainly attributed to the high contact resistance between the S/D and the active layer in the a-IGZO TFT.

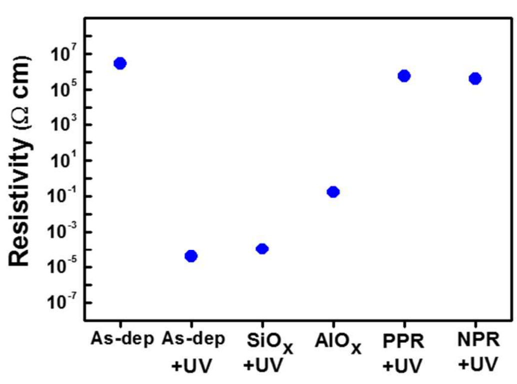

Fig. 3. Resistivity of a-IGZO films after UV irradiation through various UV shielding materials. UV light was irradiated for 3hrs after formation of a shielding layer with SiO_2 (100 nm), Al_2O_3 (100 nm), and PR (1.8 µm PPR, NPR) on an a-IGZO thin film.

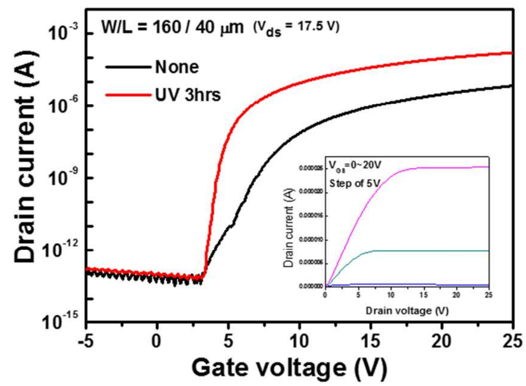

Fig. 4. Transfer characteristics of coplanar homojunction a-IGZO TFTs without and with n+ doping by UV irradiation of the source/drain region for 3 hrs. The channel width and length were fixed at 160 µm and 40 µm, respectively. The inset shows output characteristics of the a-IGZO TFT, which do not show any current crowding.

On the other hand, the a-IGZO TFT with an a-IGZO S/D region n+-doped by UV irradiation showed enhanced electrical properties; specifically, the μ_{sat}, V_{th}, SS, and on/off current ratio were 6.7 cm^2/V·s, 7.3 V, 0.21 V/decade, and ~10^9, respectively. There was a 10 fold increase in the saturation mobility upon UV exposure. These data confirmed that the UV irradiation of the source/drain regions effectively reduced the contact resistance in the a-IGZO TFT. The inset in Figure 4 provides the output characteristics of the a-IGZO TFT, which shows clear linear regions and no current crowding. The n^+-doped a-IGZO TFT also showed a low contact resistance.[18]

To extract the contact resistance of the a-IGZO TFT, we measured the total resistance (R_{TOT}) variation as a function of channel length in the range from 10µm to 80µm at a fixed channel width of 160 µm. The applied gate voltage (V_{gs}) was varied from 15 to 20 V at the drain voltage (V_d) of 0.1 V (Figure 5). The a-IGZO TFT was operated in enhancement mode ($V_{th} > 0$ V), and all the channels were turned on for an accurate measurement of the resistance. The contact resistance of the source/drain (R_{sd}) and the channel length modulation (ΔL) were extracted by using the transmission line method (TLM). When Vds << Vgs-Vth, the total resistance can be expressed by Equation (1):[10,15,19]

$$R_{TOT} = \frac{V_{DS}}{I_{DS}} = \frac{L-\Delta L}{\mu_{FE} C_{ox} W (V_{GS}-V_{TH})} + R_{SD} \quad (1)$$

Where, R_{TOT} is the total resistance of the TFTs, μ_{fe} is the field effect mobility, C_{ox} is the gate insulator capacitance per unit area, W is the channel width, V_{th} is the threshold voltage, L-ΔL is the effective channel length, and R_{sd} is the contact resistance of the source/drain. The threshold voltage was obtained from the transfer characteristics. The TLM plot of a-IGZO TFT in Figure 5 shows the linear dependence of R_{TOT} on the channel length at a V_{gs} of 15-20 V. R_{sd} and ΔL were extracted from the intersection point, and the values of R_{sd} and ΔL were 1.7 kΩ and 0.4 µm, respectively. Multiplication of the channel width (160 µm) by R_{sd} gives the width-normalized R_{sd} (R_{sd}W), which was 27 Ω·cm in this study.

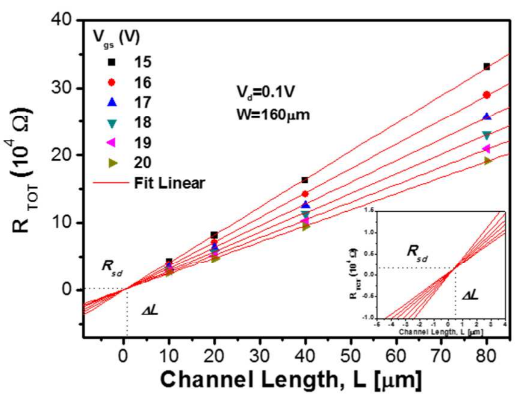

Fig. 5. Contact resistance of the coplanar homojunction a-IGZO TFTs with UV irradiated source/drain region was estimated by the transmission line method (TLM). The inset presents a magnified view in the small channel length region.

Table 2. Comparison of resistivity (Ω•cm) of n^+ a-IGZO films formed using various n^+ doping methods.

	ΔL (µm)	R_{sd}W (Ω cm)	Ref.
SiN_x:H	1.5	34	[11]
SiN_x:H	1.6	51	[13]
SiN_x:H	1.57	33.6	[14]
H_2 plasma treatment	-	75.5	[10]
Ar plasma treatment	-	128	[15]
H_2 plasma treatment	-	75	[15]
UV irradiation	0.4	27	this work

R_{sd}W is a suitable way to compare contact resistance with various n^+ doping methods because it is independent of the TFT channel width and length. The estimated ΔL and R_{sd}W values in our samples and other previously reported results are listed in table 2 for comparison. In comparison with the plasma treatment methods or the hydrogen diffusion technique, the UV irradiation method shows both a very small ΔL and a low value of R_{sd}W. This comparison demonstrates that the UV irradiation method provides precise doping control in the source/drain regions in coplanar homojunction a-IGZO TFTs with n^+-doped a-IGZO. Based on these data, we believe that UV irradiation is a very useful and cost-effective way to fabricate a-IGZO TFTs with coplanar homojuction.

Conclusions

In this research, we investigated the effect of UV irradiation on the resistivity of a-IGZO films. The resistivity of a-IGZO films drastically decreased from of 2.71 × 10^6 Ω·cm to ~10^{-5} Ω·cm after 2 hrs of UV irradiation and then almost saturated. Such a low resistivity is comparable to ITO transparent electrodes and is about 2 orders of magnitude lower than the resistivities of other reported n+ formation methods such as Ar, H_2, and He plasma treatment or the hydrogen diffusion method.

A suitable masking material for UV shielding must be chosen in order to employ the UV irradiation technique to fabricate coplanar homojunction TFTs. Among a number of shielding materials including AlO_x, SiO_x, and negative or positive photo-resist, the photo-resist layer turned out to be the most effective in masking UV light. Utilizing an optimized UV irradiation time and a patterned PR mask, we successfully fabricated coplanar homojunction a-IGZO TFTs. The a-IGZO TFT exhibited good electrical properties. The saturation mobility (μ_{sat}), threshold voltage (V_{th}), subthreshold swing (S/S), and I_{on}/I_{off} ratio were 6.7 cm^2/V·s, 7.3 V, 0.21 V/decade, and ~10^9, respectively. In addition, the channel length modulation, ΔL, was calculated to be 0.4 µm, which is much smaller than the ΔL values obtained using the other doping techniques. The excellent performance of the a-IGZO TFTs was attributed to the nature of UV irradiation, which does not involve significant lateral diffusion. Consequently, we believe that the application of UV irradiation through a patterned PR mask can be a useful technique to enhance the performance of coplanar a-IGZO TFTs for high-resolution displays.

Acknowledgements

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Notes and references

1 K. Nomura, H. Ohta, K. Ueda, T. Kamiya, M. Hirano and H. Hosono, Science, 2003, 300, 1269-1272.
2 H. Yabuta, M. Sano, K. Abe, T. Aiba, T. Den, H. Kumomi, K. Nomura, T. Kamiya and H. Hosono, Applied Physics Letters, 2006, 89, 112123
3 J.-S. Park, Journal of Electroceramics, 2012, 28, 74-79
4 E. Fortunato, P. Barquinha and R. Martins, Advanced materials, 2012, 24, 2945-2986.
5 H.-y. Jeong, B.-y. Lee, Y.-j. Lee, J.-i. Lee, M.-s. Yang, I.-b. Kang, M. Mativenga and J. Jang, Applied Physics Letters, 2014, 104, 022115
6 J. Jiang, M. Furuta and D. Wang, Electron Device Letters, IEEE, 2014, 35, 933-935
7 R. Chen, W. Zhou, M. Zhang, M. Wong and H. S. Kwok, Electron Device Letters, IEEE, 2013, 34, 60-62.
8 J. Yeon Kwon and J. Kyeong Jeong, Semiconductor Science and Technology, 2015, 30, 024002.
9 J.-S. Park, J. K. Jeong, Y.-G. Mo, H. D. Kim and S.-I. Kim, Applied Physics Letters, 2007, 90, 262106.
10 D. Ahn, H. S. Shin, G. H. Kim, J.-S. Park and H. J. Kim, Japanese Journal of Applied Physics, 2009, 48, 03B019.
11 A. Sato, K. Abe, R. Hayashi, H. Kumomi, K. Nomura, T. Kamiya, M. Hirano and H. Hosono, Applied Physics Letters, 2009, 94, 133502.
12 H. Seo, Y.-J. Cho, J. Kim, S. M.bobade, K.-Y. Park, J. Lee and D.-K. Choi, Applied Physics Letters, 2010, 96, 222101.
13 A. Sato, M. Shimada, K. Abe, R. Hayashi, H. Kumomi, K. Nomura, T. Kamiya, M. Hirano and H. Hosono, Thin Solid Films, 2009, 518, 1309-1313.
14 G. Baek, K. Abe, H. Kumomi and J. Kanicki, Japanese Journal of Applied Physics, 2013, 52, 03BB05.
15 B. Du Ahn, H. S. Shin, H. J. Kim, J.-S. Park and J. K. Jeong, Applied Physics Letters, 2008, 93, 203506.

16 J.-H. Bang, H.-S. Uhm, W. Kim and J.-S. Park, Thin Solid Films, 2010, 519, 1568-1572.
17 S.J. Lim, J.M. Kim, D. Kim, C. Lee, J.S. Park and H. Kim, Electrochemical and Solid-State Letters, 2010, 13, H151-H154
18 T. C. Fung, C. S. Chuang, K. Nomura, H. P. D. Shieh, H. Hosono and J. Kanicki, Journal of Information Display, 2008, 9, 21-29.
19 E. M. C. Fortunato, L. s. M. N. Pereira, P. M. C. Barquinha, A. M. Botelho do Rego, G. a. Gonçalves, A. Vilà, J. R. Morante and R. F. P. Martins, Applied Physics Letters, 2008, 92, 222103.

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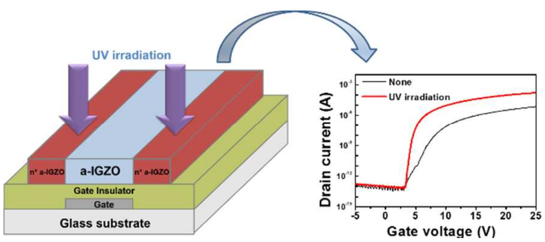
Colour Graphic:



Novelty of the work:

A novel technique for formation of thermally-stable IGZO homojunction with highly conductivity by UV light irradiation