Characteristics of IGZO TFT Prepared by Atmospheric Pressure Plasma Jet Using PE-ALD Al_2O_3 Gate Dielectric

Chien-Hung Wu, Kow-Ming Chang, Sung-Hung Huang, I-Chung Deng, Chin-Jyi Wu, Wei-Han Chiang, and Chia-Chiang Chang

***Abstract*—This letter proposes a novel atmospheric pressure plasma jet (APPJ) method for indium–gallium–zinc-oxide (IGZO) deposition and use of the plasma-enhanced atomic layer deposition (PE-ALD) Al_2O_3 as gate dielectric. A nonvacuum and simple APPJ system was demonstrated for channel material deposition. High-transmittance nanocrystalline IGZO thin films were obtained. Excellent electrical characteristics were achieved, including a low V_T of 0.71 V, a small subthreshold swing of 276 mV/dec, a mobility of 8.39 $\mathrm{cm^2/(V \cdot s)}$, and a large $I_{\mathrm{on}}/I_{\mathrm{off}}$ ratio of 1×10^8.**

***Index Terms*—Al_2O_3, atmospheric pressure plasma jet (APPJ), indium–gallium–zinc oxide (IGZO), nonvacuum, plasma-enhanced atomic layer deposition (PE-ALD).**

I. Introduction

RECENTLY, indium–gallium–zinc oxide (IGZO) was widely studied for active-channel material and exhibited high potential in active matrix organic light-emitting diode and active matrix liquid crystal display applications [1], [2]. The superior properties of IGZO thin films includes wide band gap, high transparency, and high mobility, even in the amorphous phase [3]. To prepare IGZO thin films, various deposition methods were developed, including radio-frequency/direct-current magnetron sputtering [4], pulsed laser deposition [5], and solution process [6], [7]. Most active-channel layers are fabricated using conventional vacuum techniques because vacuum-processed devices exhibit excellent performance and reliability. However, a nonvacuum process offers competitive advantages, such as low cost, high throughput, and excellent suitability for large-area applications. Atmospheric pressure plasma jet (APPJ) is a recent technology in plasma processing applications [8], [9] and is used in several industrial applications, such as surface modification, etching, cleaning, and thin-film coating [10]. Considerable progress has been achieved in atmospheric pressure plasma technology for thin-film coating, and several thin-film coatings were demonstrated, including SiO_2 [10], ZnO [11], and IZO [12]. The main benefit of APPJ is the high potential for inline production without an expensive and complex vacuum system. To our knowledge, this is the first report of an IGZO thin-film transistor (TFT) achieved using APPJ. Furthermore, the high-k Al_2O_3 is a promising gate dielectric because of its low leakage current and excellent compatibility with the IGZO thin film [13]. The plasma-enhanced atomic layer deposition (PE-ALD) method was assumed to increase reactivity, reduce impurities, widen the process window, and increase the film density compared with conventional atomic layer deposition [14]. In this letter, an environmentally friendly water-based solution precursor was used to deposit the IGZO active layer, and we achieved superior performance of IGZO TFT compared with other nonvacuum process.

II. Experimental Details

Trimethylaluminum (TMA) was used as the precursors, and oxygen plasma reactants were used as the oxidants. The inductively coupled plasma source with an operating power of 300 W was used, and the substrate temperature was maintained at 250 °C during the deposition process. First, the PE-ALD 30-nm-thick Al_2O_3 gate dielectric was directly deposited on heavily doped n-type Si wafers, which served as the gate electrode. Indium nitrate $(\mathrm{In(NO_3)_2})$, gallium nitrate $(\mathrm{Ga(NO_3)_2})$, and zinc nitrate $(\mathrm{Zn(NO_3)_2})$ were used as the precursor, and pure deionized water was used as solvent. The concentration of the IGZO solution was 0.2 M with an atomic ratio of In:Ga:Zn $= 1:1:1$. Subsequently, the 40-nm-thick IGZO thin films were deposited on the $\mathrm{Al_2O_3/n+}$ Si at a substrate temperature of 200 °C by APPJ. Details of the APPJ apparatus are shown in our previously published work [12]. After deposition, the as-deposited IGZO films were placed into a furnace and subsequently thermally annealed for 30 min at 500 °C in nitrogen ambient to improve the quality of the IGZO film. The pattern on the IGZO thin film was obtained by conventional photolithography and wet etching by using HCl:H_2O $(1:200)$. Finally, 100-nm-thick Al source/drain layers were patterned by liftoff technique. The channel width W and length L were 200 and 20 μm, respectively. The Al/$\mathrm{Al_2O_3/n+}$ Si capacitors were also fabricated to analyze the dielectric properties.

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TABLE I
ELECTRICAL PROPERTIES OF IGZO TFTS ANNEALED IN DIFFERENT TEMPERATURES

Post Annealing	V_T (V)	Mobility (cm^2/V-s)	SS (V/dec.)	I_{on}/I_{off} ratio
As-deposited	-	-	-	8.99×10^1
300 °C for 30min	-0.571	2.60	1.60	1.88×10^8
400 °C for 30min	0.938	3.43	1.69	7.63×10^7
500 °C for 30min	6.74	10.31	1.54	3.28×10^8

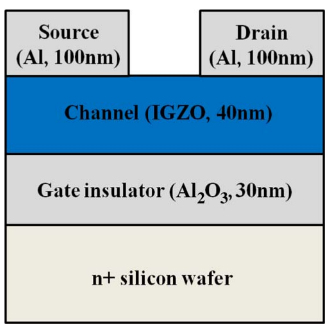

Fig. 1. Schematic cross view of the bottom-gate/top-contact IGZO TFT.

III. RESULTS AND DISCUSSION

In order to find the optimized postannealing temperature of the IGZO thin film, the effect of the postannealing temperature on the IGZO TFT with thermal SiO_2 gate dielectric was measured, as shown in Table I. The as-deposited sample shows high conductivity and poor switching properties. The high carrier concentration may be due to oxygen vacancies and H species. The postannealing is necessary to repair the defects and reduce the carrier concentration. After 300 °C annealing, the IGZO shows the depletion-mode operation and the low mobility. On the other hand, the 500 °C sample (optimized temperature condition) operates in the enhancement mode and exhibit higher mobility compared with the 300 °C sample.

A schematic cross view of the bottom-gate/top-contact IGZO TFT is shown in Fig. 1. Fig. 2 shows the optical transmission spectra of IGZO films deposited on glass. The average transmittance in the visible region is higher than 85%. The optical band gap was estimated by extrapolating the square of absorption coefficient versus the photon energy curve [15]. The optical band gap of 3.39 eV indicates that the IGZO thin film is transparent in visible light. The inset graph shows the grazing incidence X-ray diffraction pattern and demonstrates a weak broad (008) peak [16], indicating the formation of a nanocrystalline phase. The C–V and J–V characteristics of the $Al/Al_2O_3/n+$ gate capacitor are shown in Fig. 3. The measured capacitance density of 2.15 fF/μm^2 produced a capacitance equivalent thickness of 16 nm and a high-k value of 7.29. The PE-ALD gate dielectric exhibits a low $C-V$ hysteresis of 8 mV and a low leakage current of 1.62×10^{-8} A/cm^2 at 1 MV/cm. Fig. 4 shows the

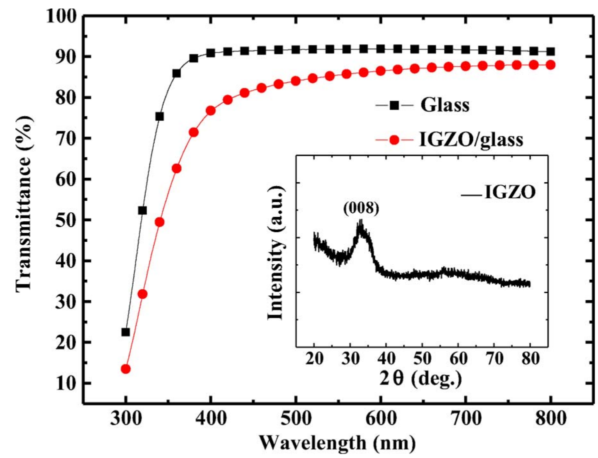

Fig. 2. Optical transmission spectra and GIXRD patterns of IGZO films.

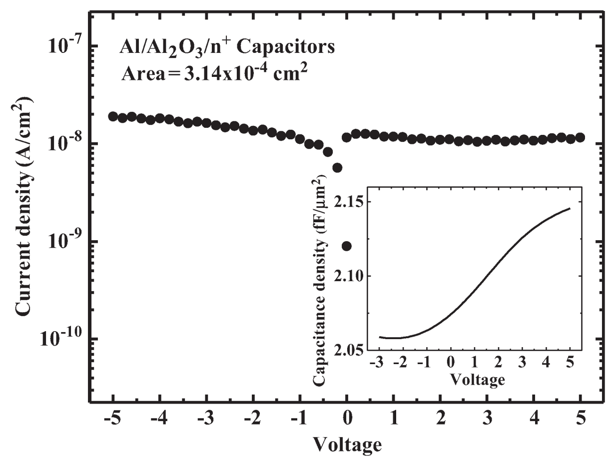

Fig. 3. J–V and (inset graph) C–V characteristics of the $Al/Al_2O_3/n+$ capacitors.

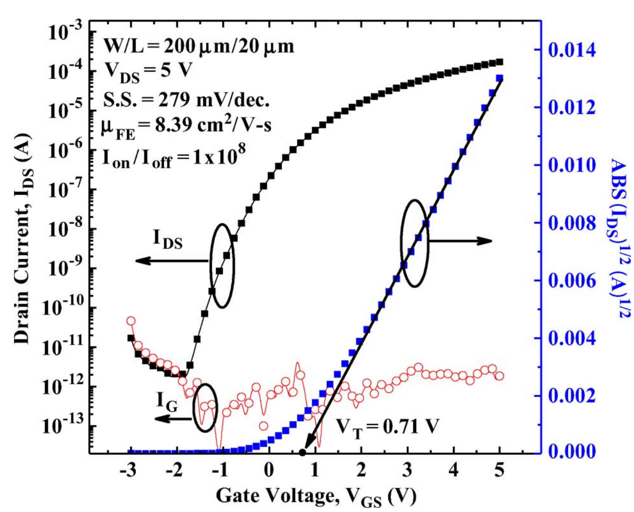

Fig. 4. Transfer characteristics (I_D–V_G) of the IGZO TFT with PE-ALD Al_2O_3 gate dielectric.

transfer characteristics (I_D–V_G) of the PE-ALD Al_2O_3/IGZO TFT. The field-effect mobility μ_{FE} and the threshold voltage V_T were extracted from the $I_{DS1/2}$ versus V_{GS} plot. This device exhibited a low SS of 276 mV/dec, a V_T of 0.71 V, an

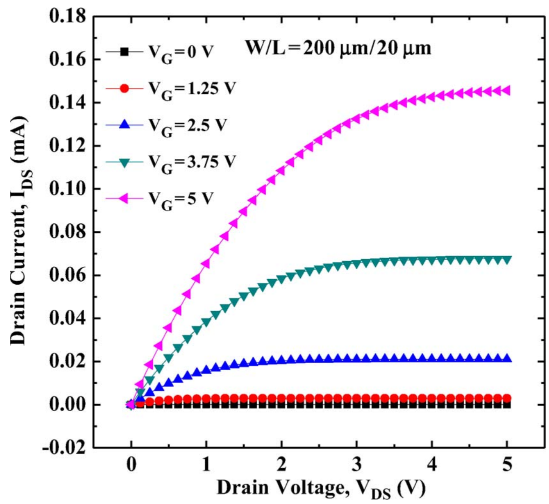

Fig. 5. Output characteristics ($I_D V_D$) of the IGZO TFT with PE-ALD Al_2O_3 gate dielectric.

TABLE II
COMPARISON OF IGZO TFTS DEPOSITED BY NONVACUUM PROCESS

Fabrication method	Post treatment	V_T (V)	Mobility (cm^2/V-s)	SS (V/dec.)	I_{on}/I_{off} ratio
APPJ This Work	500 °C for 30min	0.71	8.39	0.276	1×10^8
Spin coating [17]	laser annealing	-	7.65	-	$2.88X10^7$
Spin coating [7]	500 °C for 1h	2	2	1.5	$>10^7$
Ink-jet printing [18]	500 °C for 1 h	1	1.41	0.38	4.3×10^7
Spin coating [6]	95 °C for 10min	0.9	2.3	-	$>10^6$

excellent $\mu_{\rm FE}$ of 8.39 $\rm cm^2/(V \cdot s)$, and an $I_{\rm on}/I_{\rm off}$ as high as 1.0×10^8. A low V_T and a low SS were attributed to the high capacitor density and are suitable for low-voltage operations. Fig. 5 shows the output characteristics ($I_D V_G$) of the IGZO TFT. The IGZO TFT operates in the enhancement mode and exhibits excellent linear/saturation behavior. We compared important device parameters of the IGZO TFT deposited by the nonvacuum process, as shown in Table II. The performance of our IGZO TFT is comparable with that of other devices. Our device exhibited excellent performance compared with the solution process and may obtain a high-quality IGZO thin film deposited by APPJ.

IV. CONCLUSION

In summary, we have demonstrated IGZO thin films prepared by nonvacuum APPJ and characterized the IGZO TFT by using the PE-ALD Al_2O_3 as the gate dielectric. The IGZO thin films exhibited a high transmittance with a nanocrystalline phase. The PE-ALD Al_2O_3/IGZO TFT demonstrated excellent electrical characteristics, including a low V_T of 0.71 V, a small subthreshold swing of 276 mV/dec, a mobility of 8.39 $\rm cm^2/(V \cdot s)$, and a large $I_{\rm on}/I_{\rm off}$ ratio of 1×10^8. This device is suitable for low-cost and low-operation voltage applications.

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