Fabrication and Characterization of InZnO TFTs Grown on Transparent Conductive Oxide Substrate by DC Sputtering Technique

Moath N. Hussain
Jasim M. Abdul-Jabbar

[1] *Department of Electronic and Communications Engineering, College of Engineering, University of Basrah, Basrah, Iraq*

In this work, depletion-mode transistors were made of InZnO thin films prepared and grown on transparent conductive substrates by DC sputtering technique. The SiO_2-In_2O_3-ZnO system and N_2 plasma incorporated InZnO film were grown to get a better controllability of the carrier concentration during the film growth. Hydrogen plasma and oxygen plasma effects on the TCO films and the TFTs were investigated. Devices were simulated in a device model to extract the parasitic parameters. The depletion-mode TFTs have been fabricated successfully on glass by using InZnO films as the channel layers.

Keywords: InZnO films, Thin film transistor, TCOs, DC sputtering
Received: 22 December 2009, **Revised**: 04 February 2010, **Accepted**: 11 February 2010

1. Introduction

Flexible electronics is emerging rapidly [1,2]. Theses devices have the advantages such as low profile, light weight, small size, and better performance. In displays, thin film transistors (TFTs) are used as switching components in the active-matrix over a large area. Currently, liquid crystal displays (LCDs) mostly use amorphous Si as the channel.in TFTs. However, due to the low mobility ($<1cm^2/Vs$) and high process temperature (350°C), amorphous Si-TFTs are not available for high resolution displays on cheap plastic substrates. Organic TFTs have very low mobility ($<1cm^2/Vs$) and may have reliability concerns [3]. Oxide-based TFTs have at least 1 order higher mobility ($10\sim50cm^2/Vs$) [4] than amorphous Si-TFTs and organic TFTs and can be deposited at room temperature. The high mobility of oxide-based TFTs, make them available for high resolution displays and can integrate switching TFTs in the active-matrix and driver-integrated circuits (driver ICs) on the same plastic substrate, which can reduce cost and provide a more compact display. Besides, oxide-based TFTs have other advantages such as room temperature deposition, higher transparency, better smoothness, etc. [5]. The oxide-based TFTs have a great potential to realize a roll-to-roll display. If this technology can be realized, it may not only replace the current amorphous Si-TFTs for LCDs, but will also create new applications on various sets such as heads-up, windshield, electronic books or light weight computers for soldiers in the battle field and eventually change the whole display industry.

In this study, we fabricated TFTs by sputtering InZnO and InGaZnO on hard (glass) and flexible (plastic) transparent substrates. Depletion mode and enhancement mode field effect transistors will be fabricated. The study will include device designs, materials tuning, process developments, device characterization, device simulation, device reliability test, and device circuit demonstration. The study will cover the whole course of the device development.

TCOs are composed of post-transition metal oxides with outer major quantum number nγ4. These TCOs exhibit n-type carriers [6]. Oxygen vacancies dominate the carrier concentration in these TCO films. For these TCOs, the mobility is still close to that of the polycrystalline even in the amorphous material. It is very different fromα-Si, which has a extremely low mobility ($<1cm^2/Vs$) in amorphous type comparing to the several orders higher mobility in polycrystalline ($30\text{-}300cm^2/Vs$) or crystalline ($>1000cm^2/Vs$) [3]. Although there is more than one mechanism explaining the conduction behavior for these TCOs, the most widely accepted theory of carrier transport is the s orbitals overlapping of these transition metal atoms [6].

Many groups reported oxide based TFTs using InZnO, GaZnO, ZnO, SnO_2, In_2O_3 as channel layers fabricated on glass [7-10]. However, few of them are reported on organic flexible transparent substrates. In recent years, α-

 ISSN 1813-2065

Si TFTs have been fabricated a lot on organic substrate such as PET (polyethylene terephthalate) [11]. Recently, an enhancement mode TTFT using IGZO as the channel layer and Y_2O_3 as the gate dielectric fabricated on a PET substrate was reported [12-14]. The TFT has a field effect mobility of $10cm^2/Vs$, threshold voltage 1.2V, on-off ratio $>10^6$, subthreshold voltage swing ~0.2V/decade. It shows the TCO type TFTs have great potential to beat theα-Si TFTs (low mobility $<1cm^2/Vs$, high temperature 350°C) and organic TFTs (low mobility $<1cm^2/Vs$) [3] not only in electrical properties, but also in optical properties, ease of processing, and cost.

Currently, two different technologies are used to fabricate TFTs on plastics. The first one is to deposit films and do processes directly on the plastics [15]. The other one is to fabricate TFTs on rigid glass first, then etch off the substrate glass and paste the flexible plastics onto the TFTs [16]. The second one can avoid high temperature and stress caused by film deposition. However, our InZnO and InGaZnO TFTs are fabricated in a room temperature process, so we can use the direct process approach.

2. Experiment

We plan to fabricate the depletion mode TTFTs as shown in Fig. (1a). The gate dielectrics will be SiO_2, SiN_x or Sc_2O_3. Channel layers will be InZnO or InGaZnO. Device performance will be compared for different structures. Eventually, a fully transparent TFT will be fabricated on a flexible transparent substrate, PET.

We have already fabricated depletion mode thin film transistors using InZnO as the channel layer on glass substrates as depicted in Fig. (1b). This is the first report of depletion mode TFTs made of InZnO film in channel layer [17]. The InZnO films were deposited near room temperature by rf magnetron sputtering using 4in. diameter targets of In_2O_3 and ZnO [18]. The working pressure was varied from 2-15mTorr in a mixed ambient of O_2/Ar. The percentage of O_2 in the mixture was varied from 0-3%. At a percentage of 2.5%, we obtained films with carrier concentration of $\sim10^{18}cm^{-3}$ and electron mobility of $17cm^2.V^{-1}.s^{-1}$ obtained from Hall measurements. The partial pressure of oxygen during the sputter deposition was found to be the dominant factor controlling the conductivity of the films. The sputtering power on the targets was held constant at 125W, leading to compositions of the films measured by x-ray fluorescence spectroscopy of In/Zn=0.5 in atomic ratio. The typical thickness of the InZnO films deposited was 150nm, with a root mean square roughness of 0.4nm measured over a $10x10\mu m^2$ area by Atomic Force Microscopy. The films were amorphous as determined by x-ray diffraction and showed optical transmittance of ~80% in the visible range.

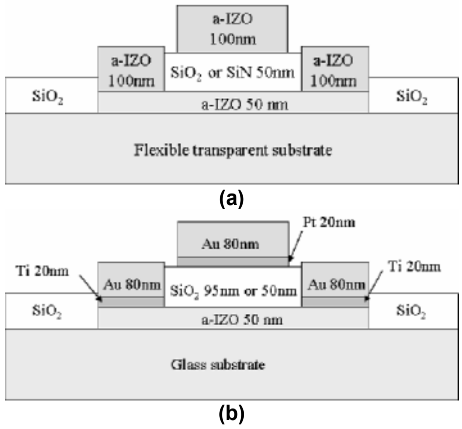

Fig. (1) (a) Schematics of the fully transparent D-Mode TFTs on flexible transparent substrate. (b) D-Mode TFTs on glass

As described in the previous section, the InZnO film was deposited in the sputtering machine with two targets, ZnO and In_2O_3, together with O_2 and Ar gas in the chamber. The O_2/Ar ratio decides the carrier concentration in the InZnO film. Here we plan to use N_2/O_2/Ar gas mixture to deposit InZnO film. The reasons to use N_2 is because in the plasma, N_2 will convert to N_2^+, which may replace O and bond with In. This was investigated in forming p-type ZnO [19]. We know the carriers in the InZnO result from the non-stoichiometry, which means the lack of oxygen allows some indium atoms that are not bonded with oxygen atoms to release electrons to the conduction band. That is why when the O_2/Ar ratio change during InZnO film deposition, the carrier concentration will also change. Higher O_2/Ar ratio leads to a decrease in the number of oxygen vacancies, which also means the carrier concentration decreases [18]. When removing one oxygen atom from the indium, one oxygen vacancy is created. In is a big atom and tends to lose electrons. Oxygen is a small atom and tends to get electrons from the In. ZnO acts as a stabilizer in the In_2O_3 matrix. That's why InZnO and GaZnO both have lower sensitivity of O_2/Ar ratio to carrier concentration than ZnO [10]. Since the oxygen has a higher electronegativity than nitrogen, oxygen can form a strong ionic bond with In. This means when removing or adding a certain amount of oxygen or nitrogen bonded with indium, oxygen will produce a larger change in carrier concentration than nitrogen. This means nitrogen can reduce the sensitivity of O_2/Ar ratio to carrier concentration. The second reason is, due to the previous reason, nitrogen may improve the device reliability. A reliability issue is one of the reasons why GaInZnO was developed [14]. We may provide another view to do the same thing by an easier method.

Ga_2O_3 introduced into the In_2O_3-ZnO system to form the InGaZnO was reported as providing a better stabilization in TFTs than InZnO [14]. Ga was chosen because it has an atomic radius close to In. The introduction of Ga into the InZnO reduces the electron concentration and mobility. The highest carrier concentration of InGaZnO is around $\sim 10^{19}cm^{-3}$ [12] which is smaller than that of InZnO ($\sim 10^{21}cm^{-3}$) [10]. The reduction in carrier concentration is not bad because for the channel layer, $10^{18}\sim 10^{16}cm^{-3}$ is enough for both depletion and enhancement mode TFTs. Although carrier concentration in InZnO can also be adjusted by O_2/Ar ratio, the carrier concentration change in the InZnO film is dramatic ranging from 10^{18} to $10^{16}cm^{-3}$ in a small O_2/Ar ratio region [18]. Ga not only reduces carrier concentration, but also reduces the sensitivity of the carrier concentration to the O_2/Ar ratio [10,12]. It is good for controlling the carrier concentration. However, in the mean time, the reduction in mobility is not welcome. It is interesting to introduce another oxide into the InZnO system to stabilize the oxide system and the mobility. The idea is to incorporate a smaller atom and in the mean time, oxide formed by this atom has E_g>3eV. SiO_2 fits these requirements. Si can easily bond with oxygen to reduce sensitivity of the carrier concentration to the O_2/Ar ratio during film deposition. Also, due to the smaller radius of Si than Ga, In atoms still can keep their s orbitals overlapped. This means the mobility may not be degraded too much.

Due to the different interfaces that may form between InZnO and various dielectrics, it is necessary to use different dielectrics such as SiO_2, SiN, and Sc_2O_3 as the gate dielectrics in the TFTs and compare the device performance.

O_2 plasma can obviously decrease the surface carrier concentration of the InZnO film due to the annihilation of the oxygen vacancies. This might help to reduce the surface leakage and then improve on/off ratio if the surface leakage dominates the leakage current, especially for the depletion mode FET. H^+ was reported to be implanted into the CdO-CeO_2 film and act as a shallow donor [20]. We believe that H_2 plasma can also create a donor in InZnO film. One very interesting experiment is that to be easier to control the carrier concentration by hydrogen plasma if we introduce hydrogen into an InZnO film, which had been deposited under a high O_2/Ar ratio. Due to the very small size of the hydrogen, it should not reduce the hall mobility of the InZnO film because it will not inhibit the overlap of the 5s orbitals of In.

After we successfully fabricate the D-mode FETs, we can start to make a ring oscillator using these TFTs. The reliability test will include (i) current stress in room temperature and high temperature (ii) thermal shock and bending test. These tests will be applied to the TCO films and devices on both glass and PET. The device will also be measured for the s parameters and be simulated to extract the parasitic parameters of the D-mode FETs. We have already performed the simulation for the D-mode InZnO TFTs, which will be mentioned in the latter section. TFTs made of InZnO, InGaZnO will be compared and discussed.

An Agilent 4156 parameter analyzer and Agilent E8361 network analyzer will be used to characterize the device dc and rf performance, respectively.

3. Results and Discussion

Top-gate-type TFTs using a-InZnO channels and 50nm or 95nm thick SiO_2 gate insulators deposited by plasma enhanced chemical vapor deposition were fabricated as shown schematically in Fig. (1a). Figure (2) shows the top-view of the TFT. The gate dimension is 36μm×100μm. The InZnO film deposited in 2.5% O_2/Ar ratio has a carrier concentration about $10^{18}cm^{-3}$ [18]. The whole process was done without heating the substrates, making the entire process consistent with typical continuous-use temperatures of commercial plastic films for electronic devices.

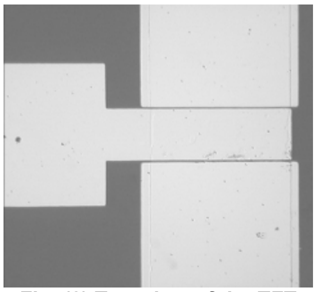

Fig. (2) Top-view of the TFT

Figure (3) shows I_{DS}-V_{DS} characteristics from InZnO transistors with 50nm thick SiO_2 gate dielectric. The transistor operates in depletion-mode with an appreciable drain current at zero gate voltage and exhibits excellent drain current saturation.

Figure (4) shows I_{DS} and g_m as a function of V_{GS} for a device with 50nm SiO_2 gate. The sub-threshold voltage swing was 1.9V/decade and the device had a threshold voltage of -6.5V.The latter is the gate voltage at the onset of the initial sharp increase in current in log(I_D)-V_{GS} characteristics. The drain current on-to-off ratio was $>10^6$. These results are competitive with past results on TFTs using room temperature sputter deposited amorphous $InGaZnO_4$ as the channel

 ISSN 1813-2065

material [5]. The field-effect mobility was of ~4.5cm^2.V^{-1}.s^{-1}.

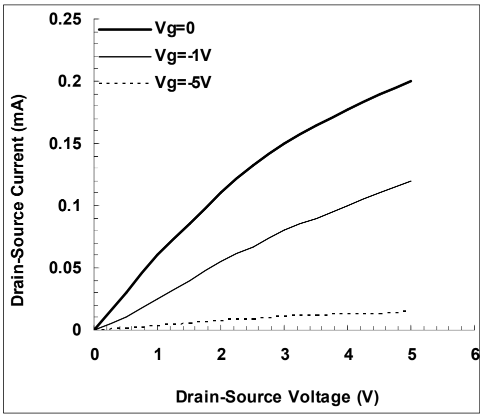

Fig. (3) I_{DS}-V_{DS} characteristics from InZnO transistors with 50nm thick SiO_2 gate dielectric

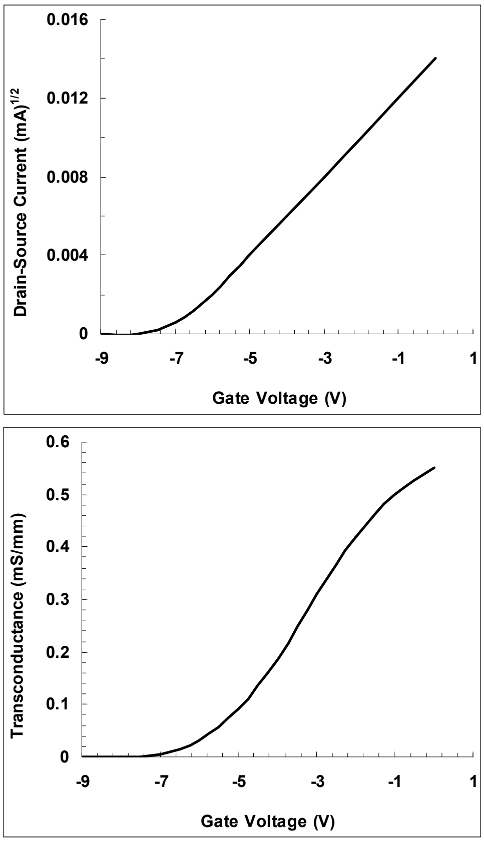

Fig. (4) Drain-source current (I_{DS}) and transconductance (g_m) as a function of V_{GS} for a device with 50nm SiO_2 gate

The gate I-V characteristics from devices with two different gate dielectric thicknesses are shown in Fig. (5). The leakage current is very small, in the 10^{-10}A range, for both gate thicknesses and demonstrates that the low temperature deposition process produces acceptable quality SiO_2 for TFT applications. The threshold voltage was decreased to -5.5V for the thicker dielectric and the slope of the sub-threshold voltage swing was 0.87V/decade for the 95nm thick dielectric.

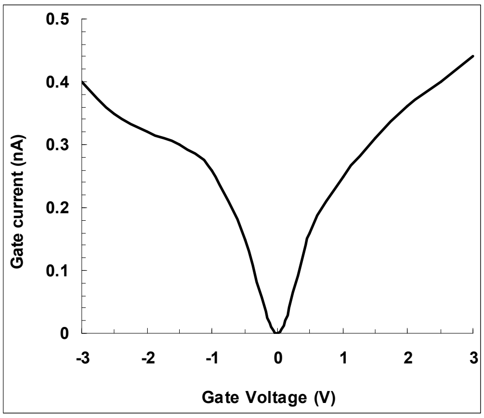

Fig. (5) The gate leakage current characteristics of the devices with two different gate dielectric thicknesses

Top-gate TFTs using 50nm of α-InZnO channels and 12.5nm-thick SiN_x gate insulators deposited by chemical vapor deposition (CVD) were fabricated as shown similarly in Fig. (1b). The gate dimension is 1µm×200µm. The SiN_x layer was deposited without heating the substrates. In addition, the SiN_x gate dielectric provided superior stability of device performance relative to SiO_2 deposited under the same conditions [17]. Specific contact resistance and sheet resistance from the linear transmission line measurements were $7\times10^{-5}\Omega.cm^2$ and 0.9MΩ/sq, respectively. Figure (6) shows typical drain current versus drain voltage, I_{DS}-V_{DS}, characteristics from the InZnO transistors.

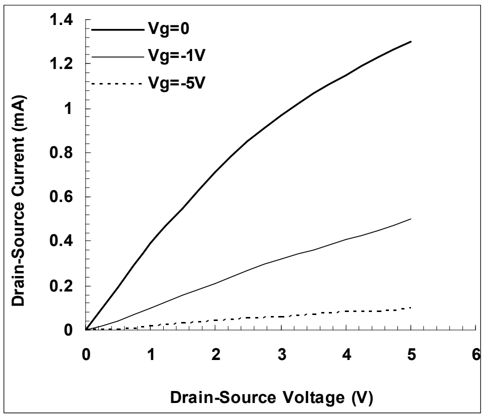

Fig. (6) Typical drain current versus drain voltage, I_{DS}-V_{DS}, characteristics from the InZnO transistors

Figure (7) shows drain current, I_{DS}, and transconductance, g_m, as a function of V_{GS} for an InZnO TFT. A maximum transconductance of 7.5mS/mm was obtained at I_{DS}=1.35mA, V_g=0V and V_d=5V. This is the highest transconductance ever reported for InZnO based TFTs. The transistor has a low threshold voltage of -2.5V. The drain current on-to-off ratio was >10^5. The gate leakage is about $10^{-10}A \sim 10^{-11}A$. The field-effect mobility is $14.5 cm^2.V^{-1}.s^{-1}$.

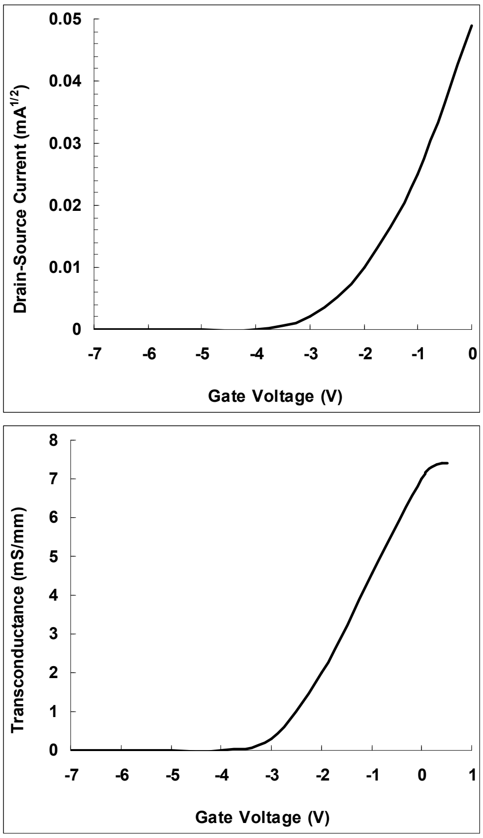

Fig. (7) drain current (I_{DS}) and transconductance (g_m) as a function of V_{GS} for an InZnO TFT

The measured s-parameters, estimated h_{21} and unilateral power gain of a typical InZnO TFT are illustrated in Fig. (8) and Fig. (9), respectively. The TFT was biased at drain and gate voltage of 3V and 0V, respectively during the s-parameter measurements. Unity gain cut-off frequency and maximum frequency of oscillation of 180MHz and 155MHz, respectively, were achieved.

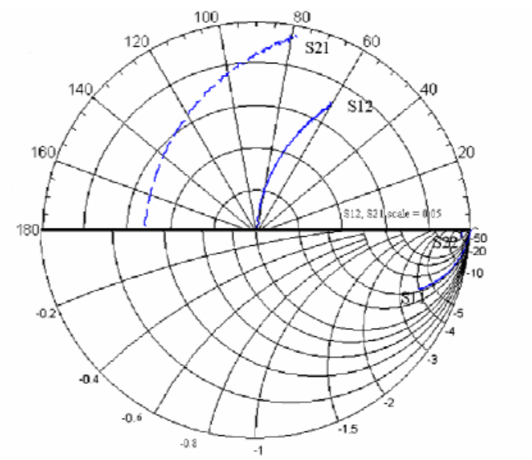

Fig. (8) The measured s-parameters of a typical InZnO TFT

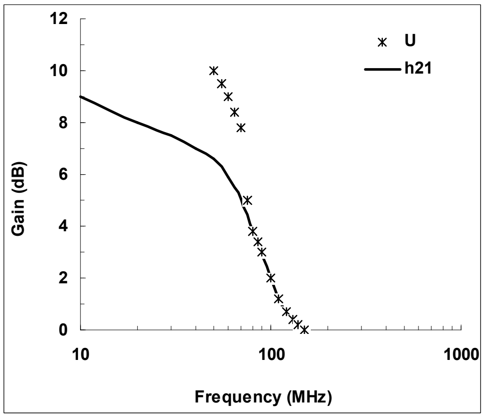

Fig. (9) The estimated (h_{21}) and unilateral power gain (U) of a typical InZnO TFT

A simplified equivalent T-model for the InZnO TFT, as shown in Fig. (10), was used to extract the device parameters. The extracted device parameters are listed in Table (1). The extracted source and drain resistance were consistent with the estimated resistance based on the transmission line measurements and drain I-V characteristics. The simulated intrinsic transconductance was very close to the measured extrinsic transconductance. The low cut-off frequency of the InZnO was limited by the fairly long transit time, 16ps, low transconductance, and high parasitic resistances, which were results of the low mobility and saturation velocity of the α-InZnO channel layer. However, this MHz-range switching performance is sufficient for many display applications.

An amorphous or polycrystalline Si:H layer as the channel have been commonly used for most conventional TFTs in display applications. The standard Si-based TFTs have drawbacks such as light sensitivity, light-induced degradation and low field effect mobility ($<1cm^2/Vs$) [3]. Therefore, Si:H TFT devices reduce the efficiency of light transmittance and brightness. Besides, both amorphous and polycrystalline Si:H TFTs require relatively high process temperatures (350°C and 450°C, respectively) [3] making it difficult to fabricate these TFTs on plastics. One of the methods to increase the efficiency and avoid high temperature is to use amorphous transparent oxides for the channels and electrodes, and fabricate TFTs at room temperature. Table (1) shows the major differences among α-InZnO, α-Si, and polycrystalline Si. Obviously, α-InZnO has the advantages of high field effect mobility, high transparency, room temperature compatible processing, large area deposition by sputtering, plastics substrate available, and is a cheaper process [3].

 ISSN 1813-2065

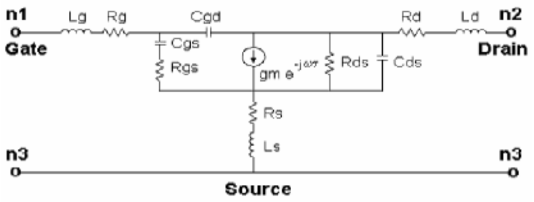

Fig. (10) A simplified equivalent T-model for the InZnO TFT

Table (1) Materials for TFTs used in display applications

Film type	**α-InZnO Amorphous**	**α-Si Amorphous**	**Poly-Si Polycrystalline**
Field effect mobility ($cm^2V^{-1}s^{-1}$)	10-50	0.5-1	30-300
Process temperature (°C)	20	350	450
Transparency (%)	>80	<20	<20
Substrate	Glass plastics	Low cost glass	Quartz

4. Conclusion

In this proposal, InZnO and InGaZnO were used as channel layers to fabricate depletion-mode TFTs and ring oscillators on glass and flexible transparent substrate (PET). The SiO_2-In_2O_3-ZnO system and N_2 plasma incorporated InZnO film were grown to get a better controllability of the carrier concentration during the film growth. Hydrogen plasma and oxygen plasma effects on the TCO films and the TFTs were investigated. The device reliability were tested to compare the effects from different TCO films and process treatments. Devices were simulated in a device model to extract the parasitic parameters. Devices were characterized in DC performance. The depletion-mode TFTs have been fabricated successfully on glass by using InZnO films as the channel layers.

References

[1] K.J. Allen, *Proc. IEEE*, 93 (2005) 1394.
[2] K. Jain *et al.*, *Proc. IEEE*, 93 (2005) 1500.
[3] Y. Sun and J.A. Rogers, *Adv. Mater.*, 19 (2007) 1897.
[4] H.C. Pan *et al.*, *J. Vac. Sci. Technol.*, A 23 (2005) 1187.
[5] T. Sasabayashi *et al.*, *Thin Solid Films*, 445 (2003) 219.
[6] M. Orita *et al.*, *Phil. Mag. B*, 81 (2001) 501.
[7] N.L. Dehuff *et al.*, *J. Appl. Phys.*, 97 (2005) 064505.
[8] R.E. Presley *et al.*, *J. Phys. D: Appl. Phys.*, 37 (2004) 2810.
[9] Dhananjay and C.W. Chu, *Appl. Phys. Lett.*, 91 (2007) 132111.
[10] R. Martins *et al.*, *J. Appl. Phys.*, 101 (2007) 044505.
[11] A. Sazonov and C. McArthur, *J. Vac. Sci. Technol.*, A 22 (2004) 2052.
[12] H. Hosono, *J. Non-Cryst. Solids*, 352 (2006) 851.
[13] K. Nomura *et al.*, *Jpn. J. Appl. Phys.*, 45 (2006) 4303.
[14] T. Kamiya *et al.*, *J. Electroceram.*, 17 (2006) 267.
[15] M.J. Lee, C.P. Judge and S.W. Wright, *Solid-State Electronics*, 44 (2000) 1431.
[16] K. Takechi *et al.*, *IEEE. Trans. Semi. Manuf.*, 18 (2005) 384.
[17] Y.-L. Wang *et al.*, *Appl. Phys. Lett.*, 90 (2007) 1.
[18] W. Lim *et al.*, *Electrochem. Solid-State Lett.*, 10 (2007) H267.
[19] C.L. Perkins *et al.*, *J. Appl. Phys.*, 97 (2005) 034907.
[20] S. Narushima *et al.*, *J. Non-Cryst. Solids*, 374 (2000) 313.

