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THEORETICAL AND EXPERIMENTAL STUDIES OF CHARACTERISTICS OF ZnO TFTS

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Abstract

A study of the characteristics of bottom gate enhancement-mode thin film transistors (TFTs) based on zinc oxide (ZnO) as an active channel layer deposited by two different methods e.g, radio frequency magnetron sputtering (RF-sputtering) and sol-gel technique at room temperature is reported. The SiO_2 is used to serve as the gate dielectric insulating layer for both the TFTs. Simulation of these TFT is also carried out by using the commercial software ATLAS™ from Silvaco. The simulated results of the device were compared and contrasted with those measured experimentally. The experimental results are in fairly good agreement with those obtained from simulation. The difference in electrical behavior of the devices is attributed to different characteristics of the interface between the channel and dielectric layers.

Keywords: ZnO; Thin film transistor (TFT); Sol-gel; RF-sputtering; Bottom-gate; Simulation.

I. INTRODUCTION

ZnO is one of the most promising materials among various semiconducting metal-oxides, because of its range of electronic, optical, magnetic and chemical properties. ZnO is most widely used oxide semiconductor with applications ranging from medical, agriculture, ceramic, chemical to electronics and photonics [1, 2]. ZnO has been recognized in recent times as one of the most potential candidates for the next generation of transparent and flexible electronics for display systems in the form of transparent thin film transistors (TTFTs) [3-6]. The current technology based on amorphous or polycrystalline Si and organic semiconductors has severe electronic limitations due to low mobility ($\leq$ 1cm^2/V s) and inadequate light sensitivity. Currently it has been suggested that wurtzite structured ZnO thin films could be used as the active channel layer in TFTs because of its low cost, easy availability, high mobility and no environmental concerns. Furthermore, unlike Si TFTs and poly-Si TFTs, ZnO based TFTs are transparent in the visible region of the spectra and less visible light sensitive because of the large bandgap (3.4eV) of ZnO [7]. Another possible application involves use of ZnO TTFTs as transparent select-transistors in each pixel of an active-matrix liquid-crystal display (AMLCD) [8]. The important figures of merit that determine the performance of TFTs are the magnitude of the field effect mobility, threshold voltage, and the drain current on/off ratio. A high value of channel mobility ensures a higher drive current density and a faster switching speed of a TFT. Considerable effort has been made to achieve high field-effect mobility and to understand the mechanism of operation of TFTs in order to realize the key factors behind high performance and stability of these devices. In the recent past the field-effect mobility was reported to be ~25 cm^2/Vs in a polycrystalline channel layer [9, 10] and as high as ~70cm^2/Vs in a single-crystalline channel layer [11]. Ever increasing interest in the ZnO TFTs, has motivated the researchers to explore various techniques for growing ZnO films. These include RF-sputtering [3, 4] pulsed laser deposition (PLD) [12], spray pyrolysis [13], atomic layer deposition (ALD) [5], sol-gel [14, 15], thermal oxidation of Zn thin films [16] and chemical bath deposition [17]. Among these techniques sol-gel method has certain advantages, such as good reproducibility, simplicity, low cost, and high throughput that enable the fabrication of high-performance and low-cost electronics. In addition to these merits, it may also be possible to use sol-gel technique to realize high electron mobility

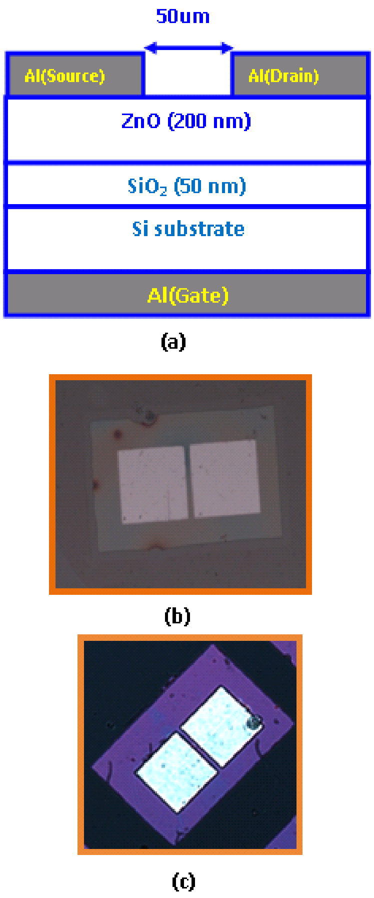


Figure 1: (a) The schematic structure and (b) & (c) Images of sol-gel and RF sputtered ZnO TFTs

TFTs using indium doped ZnO (IZO) as channel layer [18]. In view of these facts, there has been an increasing interest in the recent past to develop ZnO based TFTs that employ channel layers grown by sol-gel technique. To date sol-gel deposited ZnO TFT with mobility in the range from 0.020 cm^2/Vs to 1.29 cm^2/Vs have been demonstrated by various researchers [19, 20, 21]. For device applications of sol-gel grown ZnO TFTs, μ_{FE} is one of the parameters which requires improvement and higher values of μ_{FE} are highly desirable. In a TFT using polycrystalline ZnO films as channel layers, it has been understood that the *c*-axis crystal orientation [22, 23] and grain size [24, 25] of the channel layers affect μ_{FE} of carriers. This indicates that one key approach to improving carrier transport in TFTs is to obtain highly *c*-axis oriented films with large grain size. The information on how ZnO films (grown by different methods) influence the mobility μ_{FE} and hence the performance of TFTs is not available in the literature. In this paper, we investigated the characteristics of a suitable ZnO thin film for an active channel layer of ZnO TFT. It was found that different deposition techniques of ZnO layer produce different electrical properties for the final devices. Theoretical study of these above mentioned TFTs is also carried out by ATLAS simulator; these theoretical results were further compared with experimental results.

II. EXPERIMENTS

Fig.1 (a), (b) and (c) show the schematic structure of ZnO based bottom gate TFT and sol-gel and RF sputtered ZnO TFTs respectively. The devices were fabricated using p-type Si (100) (~380 µm thick with a resistivity of 2-7 Ωcm) as the substrate and, thermally grown 50 nm thick SiO_2 layer as the TFT gate dielectric. ZnO thin film was used as channel layer for both the TFTs. The ZnO thin films were deposited over these SiO_2/Si substrate samples, by two different methods via RF-sputtering and sol-gel methods. The SiO_2 surface was ultrasonically cleaned with acetone, isopropyl alcohol (IPA) and DI water sequentially before ZnO deposition. The details of ZnO thin film deposition parameters pertaining to sol-gel and RF sputtering techniques could be studied from elsewhere [3, 14].

After deposition of the ZnO thin film, source and drain electrodes were patterned using standard photolithography. The values of channel width and channel length for sol-gel derived ZnO TFTs and RF-sputtered ZnO TFTs were kept the same; W=200µm and L=50µm (i.e. W/L=4:1). Aluminum (Al) metal is used for source, drain and gate contacts. The thickness of Al metal was kept 90-100 nm for all electrodes.

III. CHARACTERIZATION

The surface topography of the sample such as the surface roughness, the grain size etc. are measured by using e-line scanning electron microscope (SEM) from Raith GmbH, Germany. The thickness and resistivity of the ZnO thin films were measured by Ellipsometer (Model: M2000U, USA)

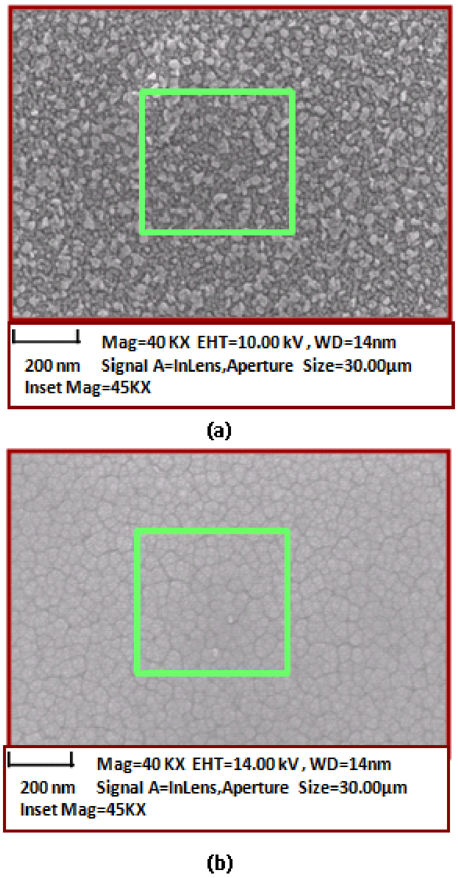


Figure 2: SEM images of sol-gel and RF sputtered ZnO thin films

and by four-probe measurement setup respectively. Optical properties of both ZnO films were measured by photoluminescence spectroscopy. Ellipsometer is used to measure for thickness of ZnO thin films. The *I–V* characteristics were measured by using HP Semiconductor Parameter Analyzer (SPA) from Hewlett-Packard (Model No. 4145 B, USA) at room temperature (300 K).

IV. RESULTS AND DISCUSSIONS

The crystal structure of the ZnO films was examined by SEM, which is shown in Figure 2 (a) and (b). The SEM images of both the ZnO films show that the film in each case is composed of closely packed hexagonal particles. The grain size of sol-gel deposited ZnO film ranges between 20 nm to 100 nm, while the grain size ranges between 10 nm to 20 nm for RF-sputtered ZnO films. The sizes of crystals were uniform for RF-sputtered ZnO films whereas they were not so throughout for sol-gel derived ZnO films. A few clusters were also found to be formed in sol-gel derived ZnO thin films. A qualitative investigation of the SEM image of sol-gel derived ZnO thin film reveals that the observed clusters consist of closely packed nanoparticles of smaller sizes (20 nm). The SEM images for RF-sputtered ZnO films reveal that a good homogeneous film across entire surface can be grown by this technique. The nanocrystalline structure of both the films has a special significance in the context of electrical characteristics of transistors based on these films. Grain size is understood to be directly correlated with device performance, because the grain boundaries act as a barrier to electron hopping [17, 26]. For example, in a thin film transistor (TFT) application, the active channel layer with larger grain size and less grain boundary is desirable in order to achieve high electron mobility [8]. The thickness of ZnO thin films was measured by Ellipsometer. The thickness of the film was found to be in the range of 200-300nm for both the ZnO films. The sheet resistance (R_{sh}) was measured by using a four-point probe setup. The value of resistivity is 2.04699E-1 Ω.cm and 6.20744E-3 Ω.cm for RF-sputtered and sol-gel ZnO thin films respectively. This optical property of the ZnO thin film can be exploited for the detection of optical signal in PL spectra. Fig. 6 presents the room temperature PL spectra of all the ZnO thin films. The shapes of all the spectra, similar to those reported by others, are dominated by strong near band edge UV emission. The UV emission peak originates from free exciton emission as shown by other researchers [27], and it can be seen from Fig. 3 that the peak intensity and peak position of the UV emission is different for sol-gel derived and RF-sputtered ZnO films. The PL spectra of RF-sputtered ZnO film exhibited a weak deep level emission along with near band edge (NBE) emission. The deep level emission in the PL spectra of RF-sputtered ZnO film can be attributed to both the native defects like oxygen vacancies and impurities unintentionally introduced during the film deposition. However, the exact origins of these emissions are not clearly understood yet [16, 27].

IV.1. Evaluation of Performance Parameters ZnO based TFT devices

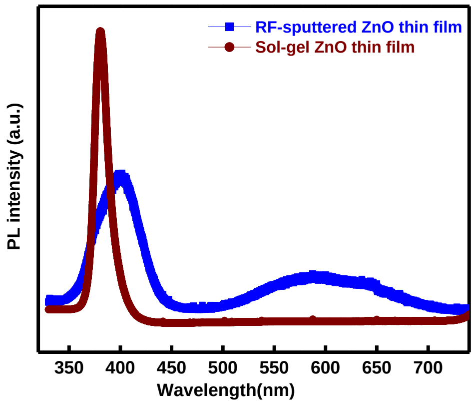
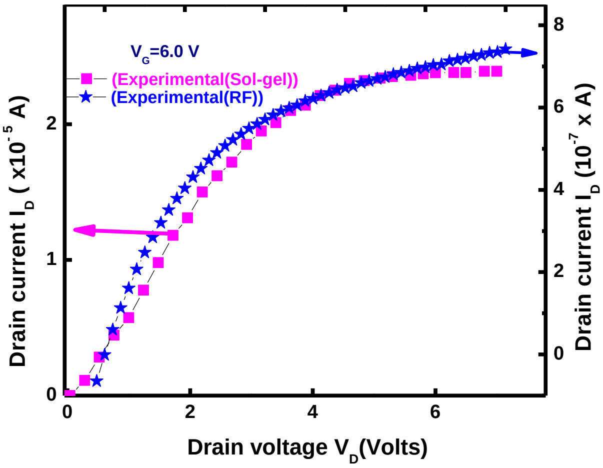


Figure 3: PL spectra of sol-gel and RF sputtered ZnO thin films.

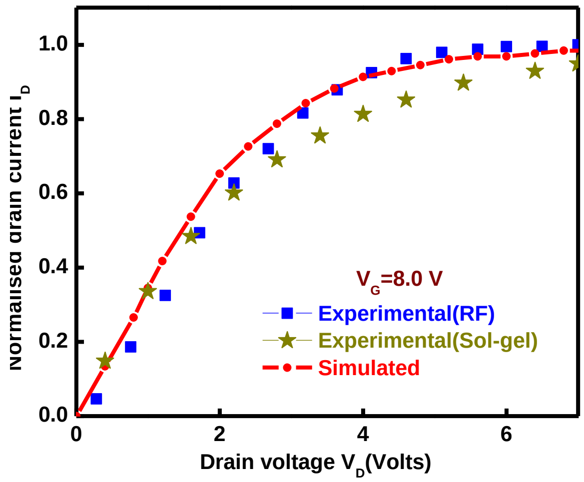
Thin film transistors fabricated by using ZnO film grown by two techniques were tested subsequently for electrical characterization. The measurements were performed at room temperature. The drain current versus drain voltage characteristics for various applied gate voltages for the TFTs grown by two different techniques are shown in Fig.4. Device performance is assessed through an analysis of the turn-on voltage (V_{ON}), drain current on-to-off ratio (I_{ON}/I_{OFF}), and incremental channel mobility (μ_{FE}). Hoffman [9] and Hong et al. [28] have defined V_{ON} as the gate voltage at which I_D begins to increase when plotted against V_{GS} on a logarithmic scale. It is clear from the Fig.4 that with the increase of source-to-drain voltage (V_{DS}) at a positive gate bias (V_G), the source-to-drain current (I_{DS}) increases markedly, confirming that the channel was n-type. The device operated in enhancement mode because very little amount of drain current flows at zero gate voltage. Pinch-off and current saturation are clearly observed. It is seen that the entire channel region could be depleted of electrons, which is desirable for most circuit applications. The I_D-V_G characteristics of the TFT can be approximated as [29]

$$I_{DS} = \left(\frac{C_i W \mu_{FE}}{2L}\right)(V_G - V_{th})^2 \; for (V_D \rangle V_G - V_{th}) \quad (1)$$

In this equation, C_i is the capacitance per unit area of the insulating layer, W and L are the channel



(a)



(b)

Figure 4: (a) Output characteristics (I_D-V_D) of sol-gel and RF sputtered ZnO based TFT,
(b) Comparison between experimental and simulated I_D-V_D characteristics of experimental and simulated results of sol-gel and RF sputtered ZnO based TFT.

width and length respectively ; V_D and V_G are the drain-source voltage and gate-source voltage respectively ;the field effect channel mobility is denoted by μ_{FE} .The transfer characteristics of sol-gel and RF-sputtered ZnO TFTs have been used to extract the values of mobility and threshold voltage, which are 11 cm^2/Vs, 1.3V and 0.6134 cm^2/Vs, 3.1V for sol-gel and RF sputtered ZnO

TFTs respectively. It is clear that the threshold voltage is positive showing that both the TFTs operate in the enhancement-mode (normally-off characteristics). In an enhancement-mode TFT device, the channel conductivity increases with positive gate bias voltage, which is preferable for a TFT being used as a switching device in electronics circuits because the power dissipation is minimized [30].

Further, it can be seen that even though the device structure (W: L) and thickness of oxide layer are identical for both the TFTs, the RF-sputtered ZnO TFT presents higher threshold voltage and lesser field effect mobility than that of the sol-gel derived ZnO TFT. Our ZnO channel layer deposited by RF sputtering at room temperature is likely to contain a higher density of point defects that may mainly consist of natural mid-gap acceptor states induced by Zn vacancies (single-charged) or O interstitials in ZnO as observed by others [31, 32]. The comparative less efficient electrical performance of the RF-sputtered ZnO TFT may also be due to the degradation of ZnO/SiO_2 interface and due to the higher resistivity of the RF-sputtered ZnO thin film in comparison to sol-gel derived ZnO thin film. Smaller grain size of RF-sputtered ZnO thin film may also be responsible for low mobility of the device.

IV.2. Study and Comparison of Experimental Results with Theoretically Simulated Results

The two-dimensional (2D) device simulator of ATLAS from Silvaco, Singapore was used to simulate the ZnO TFT structure. The parameters of ZnO were taken from literature [33]. All necessary material constants of ZnO have been collected from different sources [34, 35]. The simulation by ATLAS, involves solution of the Poisson's equation, continuity equation and carrier transportation equations in a coupled manner. Drift- Diffusion (DD) model of carrier transportation was utilized to simulate the structure from the available models (Drift-Diffusion (DD), Energy valance (EV) and Hydrodynamics (HD)) in ATLAS library. The experimental output characteristics of sol-gel and RF-sputtered TFT shows good agreement with ATLAS simulated results for V_G = 8.0 V. The variation of normalized drain current with the applied drain voltage is shown in Figure 6 for both the experimental measured data and the simulated results.

V. CONCLUSION

Bottom gate ZnO thin film transistors were fabricated by sol-gel and RF-magnetron sputtering with same structure and same thickness of the dielectric layer (SiO_2 film). Dense, high quality, polycrystalline ZnO films deposited by RF-sputtering and sol-gel method were used to form the channel of the TFTs. Electrical characteristics of these TFTs show that the performance ratings of the ZnO-TFT not only depend on the device structure but on the thin film deposition conditions as well. Enhancement-mode TFTs with sol-gel derived ZnO channels are found to exhibit better field effect mobility as compared to RF-sputtered TFTs. But the other parameters of both the TFTs are of the same order. The reason of low value of on/off ratio for both TFTs, is attributed to the degradation of ZnO/SiO_2 interface, smaller grain size and high resistivity of ZnO thin films in both the cases. The deposition condition for both kind of ZnO thin films need further optimization for getting improved performance of TFTs. Further, the simulation tool can be used to optimize predicted performance of sol–gel and RF-sputtered TFT for specific applications.

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References

[1] S. J. Pearton, D. P. Norton, K. Ip, Y.W. Heo, T. Steiner," Recent progress in processing and properties of ZnO" Prog. in Mat. Sci., **50** (2005) 293-295.

[2] S. Singh, P. Thiyagarajan, K. M. Kant, D. Anita, S. Thirupathiah, N. Rama, B. Tiwari, M. Kottaisamy and M. S. R. Rao, "**S**tructure, microstructure and physical properties of ZnO based materials in various forms: bulk, thin film and nano" J. of Phys. D: Appl. Phy., **40**, (2007) 6312-6316.

[3] S. Singh and P. Chakrabarti, "Simulation, Fabrication and Characterization of ZnO Based Thin Film Transistors Grown by Radio Frequency Magnetron Sputtering" J. of Nanosci. &Nanotech., **12**, (2012) 1880-1885.

[4] M.F.A. Alias, H.Kh. Alamy and R.M. Aljarrah, "The Role of Thickness on the Structural and Electrical Properties of Dc Magnetron Sputtered Nano Zno Thin Films," J. Elec. Dev., **14** (2012) 1178-1185.

[5] F. Chowdhury, "Influence of Thickness Variation on the Optical Properties of ZnO thin films prepared by thermal evaporation method," J. Elec. Dev.,**10** (2011) 448-455.
[6] S. Rajesh1, T. Ganesh2 and Francis P. Xavier, "Thickness dependent microstructure, optical and photo conducting properties of ZnO thin films prepared by spin coating process," J. Elec. Dev., **17** (2013) 1417-1422
[7] E. FortunatoT, P. Barquinha, A. Pimentel, A. Gonc¸alves, A. Marques, L. Pereira, R. Martins, "Recent advances in ZnO " TFTs" Thin Solid Films **487**, (2005) 205.
[8] T. Hirao, M. Furuta, H. Furuta, and T. Matsuda, T. Hiramatsu, H. Hokari, M. Yoshida, H. Ishii and M. Kakegawa, "Bottom-Gate Zinc Oxide Thin-Film Transistors (ZnO TFTs) for AM-LCDs" J. Soc. Inf. Display **15**, (2007) 17.
[9] R. L. Hoffman, "ZnO-channel thin-film transistors: Channel mobility" J. Appl. Phys. **95**, (2004) 5813.
[10] E.M.C. Fortunato, P.M.C. Barquinha, A.C.M.B.G. Pimentel, A.M.F. Gonvalves, "Wide-bandgap high-mobility ZnO thin-film transistors produced at room temperature" Appl. Phys. Lett. **85**, (2004) 2541.
[11] T.I. Suzuki, A. Ohtomo, A. Tsukazaki, F. Sato, J. Nishii, H. Ohno, M. Kawasaki, "Hall and Field-Effect Mobilities of Electrons Accumulated at a Lattice-Matched ZnO/$ScAlMgO_4$ Heterointerface"Adv.Mater. **16**, (2004) 1887.
[12] P. K. Shin, Y. Aya, T. Ikegami, K. Ebihara, "Application of pulsed laser deposited zinc oxide films to thin film transistor device" Thin Solid Films **516**, (2008) 3767.
[13] S. Sriram and A. Thayumanavan, "Optical and electrical properties of nitrogen doped ZnO thin films prepared by low cost spray pyrolysis technique," J. Elec. Dev., **15**, (2012) 1215-1224.
[14] S. Singh and P. Chakrabarti, "Simulation, Fabrication and Characterization of Sol–Gel Deposited ZnO Based Thin Film Transistors," Sci. Adv. Mat. **4** (2012) 199–203.
[15] Mounir Alhamed, Wael Abdullah, "Structural and optical properties of ZnO:Al films prepared by the sol–gel method," J. Elec. Dev., **7**, (2010) 246-252.
[16] S. Singh and P. Chakrabarti, "Optical Characterization of ZnO Thin Films Grown by Thermal Oxidation of Metallic Zinc," Adv. Sci., Engg. & Med., **5**, (2013) 1–6.
[17] H. C. Cheng, C. F. Chen, C. C. Lee, "Thin-film transistors with active layers of zinc oxide (ZnO) fabricated by low-temperature chemical bath method" Thin Solid Films **498**, (2006) 142.
[18] C. Y. Koo, K. Song, T. Jun, D. Kim, Y. Jeong, S. H. Kim, J. Ha and J. Moon, "Low Temperature Solution-Processed InZnO Thin-Film Transistors" J. Electrochem. Soc. **157**, (2010) J111.
[19] B. J. Norris, J. Anderson, J. F. Wager and D. A. Keszler, "Spin-coated zinc oxide transparent transistor" J. Phys. D: Appl. Phys. **36**, (2003) L105.
[20] D. Gupta, M. Anand, S. W. Ryu, Y. K. Choi and S. Yoo, "Nonvolatile memory based on sol-gel ZnO thin-film transistors with Ag nanoparticles embedded in the ZnO/gate insulator interface" Appl. Phys. Lett. **93**, (2008) 224106.
[21] G. Xiong, G. A. C. Jones, R. Rungsawang and D. Anderson, "Non-aqueous solution processed ZnO thin film transistors" Thin solid films **518**, (2010) 4019.
[22] B. S. Ong, C. Li, Y. Li, Y. Wu and R. Loutfy, "Stable, Solution-Processed, High-Mobility ZnO Thin-Film Transistors" J. Am. Chem. Soc. **129**, (2007) 2750.
[23] P. K. Nayak, J. Jang, C. Lee and Y. Hong, "Effects of Li doping on the performance and environmental stability of solution processed ZnO thin film transistors" Appl. Phys. Lett. **95**, (2009) 193503.
[24] K. Remashan, Y. S. Choi, S. J. Park and J. H. Jang, "Enhanced Performance of MOCVD ZnO TFTs on Glass Substrates with Nitrogen-Rich Silicon Nitride Gate Dielectric" Electrochem. Soc. **157**, (2010) H60.
[25] R. B. M. Cross, M. M. D. Souza, S. C. Deane and N. D. Young, "Investigating the stability of zinc oxide thin film transistors" Appl. Phys. Lett. **89**, 263513 (2006).
[26] I. A. Motaleb, N. Shetty, K. Leedy and R. Cortez, "Investigation of the drain current shift in ZnO thin film transistors" J. Appl. Phys. **109**, (2011) 014503.
[27] J.M. Myoung, W.H. Yoon, D.H. Lee, I. Yun, S.H. Bae, S.Y. Lee, "Effects of Thickness Variation on Properties of ZnO Thin Films Grown by Pulsed Laser Deposition" Jpn. J. Appl. Phys. **41**, (2002) 28.
[28] D. Hong, G. Yerubandi, H. Q. Chiang, M. C. Spiegelberg, J. F. Wager, "Electrical Modeling of Thin-Film Transistors" Crit. ReV. Solid-State Mater. **33**, (2008) 101.
[29] S. Masuda, K. Kitamura, Y. Okumura, S. Miyatake, "Transparent thin film transistors using ZnO as an active channel layer and their electrical properties" J. Appl. Phys. **93**, (2003) 1624.
[30] S. Im, B.J. Jin, S. Yi, "Ultraviolet emission and microstructural evolution in pulsed-laser-deposited ZnO films" Appl. Phys. Lett. **87**, (2000) 4558.
[31] J.Y. Lee, Y.S. Choi, J.H. Kim, M.O. Park, S. Im, "Optimizing n-ZnO/p-Si heterojunctions for photodiode applications" Thin Solid Films **553**, (2002) 403.
[32] F. M. Hossain, J. Nishii, S. Takagi, A. Ohtomo, T. Fukumura, H. Fujioka, H. Ohno, H. Koinuma and M. Kawasaki, "Modeling and simulation of polycrystalline ZnO thin-film transistors" *J. Appl. Phys.* **94**, (2003) 7768.
[33] D. Gupta, M. Katiyar and D. Gupta, "An analysis of the difference in behavior of top and bottom contact organic thin film transistors using device simulation" *Org. Electron.* **10**, (2009) 775.
[34] I. G. Hill, "Numerical simulations of contact resistance in organic thin-film transistors" Appl. Phys. Lett. **87**, (2005) 163505.