Chapter 6 Conclusions and Further Recommendations

6.1 Conclusions

In this thesis, sol-gel-derived Mg and Zr doped ZnO thin films and thin film transistors were proposed. The material and physical properties of Mg and Zr doped ZnO thin films are thoroughly discussed. In addition, the effects of Mg and Zr dopants on the electrical performance of $Zn_{(1-x)}M_xO$ thin film transistors are also comprehensively investigated. Finally, the $(Ba,Sr)TiO_3$ high-k gate insulators are utilized to improve the electrical characteristics of $Zn_{0.97}Zr_{0.03}O$-TFTs. The main results of these studies are summarized as below:

In Chapter 3, sol-gel-derived n-type $Zn_{(1-x)}Mg_xO$ (x= 0~0.45) thin films and thin-film transistors (TFTs) with active channel layers made of the films are presented. The Mg doping effectively increased the optical transparency, grain size, and densities of charge carriers, donors, and grain-boundary trap states of the films. The donor level of the ZnO films is found to be 0.27 eV below the conduction band. It is identified with the previously reported deep-level defect L_2, either an oxygen vacancy or the zinc interstitial. The depletion region in the grains increased with amount of Mg doping and resulted in almost depleted grains in the active channel layers at x = 0.2, where the TFT showed an enhancement mode and an on/off ratio of 10^6. The estimated solubility of MgO in ZnO is around x = 0.25, at which a minor precipitate of the MgO phase presumably begin to precipitate on the grain boundaries. That resulted in a saturated charge carrier concentration and degraded TFT performance.

In Chapter 4, we found that the crystallinity of sol-gel derived $Zn_{(1-x)}Zr_xO$ thin films degraded with more Zr dopant, and the grain size and surface roughness also decreased with higher x values of $Zn_{(1-x)}Zr_xO$ thin films. The off-state current of $Zn_{(1-x)}Zr_xO$-TFTs was dramatically suppressed due to the reduction of carrier concentration in $Zn_{(1-x)}Zr_xO$ active channel layers with more Zr additive. It was also demonstrated that the carrier concentration of sol-gel derived ZnO films could be diminished by doping Zr ions instead of high temperature annealing. The reduction of carrier concentration might result from the decrease of grain size. The optimized I_{OFF} and on/off current ratio of $Zn_{(1-x)}Zr_xO$ thin films where x = 0.03 were 3.24×10^{-13} A/μm and 8.89×10^6, respectively.

In Chapter 5, we investigated the electrical performance improvements of sol-gel derived $Zn_{0.97}Zr_{0.03}O$-TFTs incorporating high-*k* BST as gate insulators. Due to the (110) preferred orientation provided by BRO bottom electrodes, the dielectric constant enhancement and leakage current restraint of BST films were observed. By using BST gate insulators in $Zn_{0.97}Zr_{0.03}O$-TFTs, the high gate capacitances reduced the operation voltage of the devices. Inasmuch as BST gate dielectrics represented superior interface trap density, the electrical performance including mobility, threshold voltage and subthreshold slope of $Zn_{0.97}Zr_{0.03}O$-TFTs were significantly improved. The optimized mobility, threshold voltage and subthreshold slope of $Zn_{0.97}Zr_{0.03}O$-TFTs consisted of BST gate insulator deposited at 300°C with a ε_r of 151 were 1.40 cm^2/Vs, 1.45 V and 0.61

V/dec, respectively.

6.2 Further Recommendations

There are some interesting topics for further study.

(1) As described in Chapter 3 and 4, the Mg and Zr additives successfully suppress the off-state current and increase the current modulation of the $Zn_{(1-x)}M_xO$-TFTs. However, the annealing temperature of more than 400°C is still too high for display process. One of the ways to lower the annealing temperatures is to attempt another sol-gel precursor system. It would be an interesting topic to lower the annealing temperature of the $Zn_{(1-x)}M_xO$-TFTs.

(2) In the studies of silicon-based TFTs, the recrystallization processes such as solid state, laser annealing, metal induced, and metal-induced lateral crystallization enhance the crystalline of the semiconductor and thus improve the electrical performance of the devices. Some further studies of sol-gel-derived $Zn_{(1-x)}M_xO$-TFTs could be done by introducing the recrystallization processes mentioned above.

(3) The $(Ba,Sr)TiO_3$ high-*k* gate insulators improve the electrical characteristics, as described in Chapter 5, as a result of their higher dielectric constants and lower interface trap densities than that of SiO_2. However, there are some other high-*k* candidates exhibit excellent performance, such as HfO_2, ZrO_2, and Ta_2O_5. A further study of attempting another high-*k* gate insulators to improve the electrical characteristics is suggested.

Publication List

Journal Papers:

1. Jen Hao Lee, Pang Lin, Cheng Chung Lee, Jia Chong Ho and Yu Wu Wang, Sol-Gel-Derived $Zn_{(1-x)}Mg_xO$ Thin Films Used as Active Channel Layer of Thin-Film Transistors, *Jpn. J. Appl. Phys.*, **44**, No. 7A (2005)
2. Jen Hao Lee, Pang Lin, Jia Chong Ho and Cheng Chung Lee, Chemical Solution Deposition of $Zn_{(1-x)}Zr_xO$ Thin Films as Active Channel Layers of Thin Film Transistors, *Electrochem. Solid-State Lett.*, **9** G117 (2006)
3. Jen Hao Lee, Pang Lin, Jia Chong Ho and Cheng Chung Lee, Low-Voltage $Zn_{0.97}Zr_{0.03}O$ Thin-Film Transistors Incorporating High-*k* $(Ba,Sr)TiO_3$ Gate Insulators Deposited on (110) $BaRuO_3$ Gate Electrodes, *Electrochem. Solid-State Lett.*, **9** G292 (2006)

Conference Papers:

1. Kuang Chung Chen, Chia Fu Chen, Jen Hao Lee, Chian Liang Hwang, and Yu Yang Chang, Low-temperature CVD growth of carbon nanotube for Field Emission Application, The International Conference on Metallurgical Coating and Thin Films, ICMCTF 2006, DP-10.
2. Yi Kai Wang, Tarng Shiang Hu, Liang Ying Huang, Tsung Hsien Lin, Jing Yi Yan, Cheng Chung Hsieh, Wei Ling Lin, Hsiang Yuan Cheng, Yu Yuan Shen, Jen Hao Lee, Yu Wu Wang, Ming Chun Hsiao, Jia Chong Ho and Cheng Chung Lee, Electrical Properties of Pentacene Based Organic Thin–film Transistor (OTFT) on Flexible Substrate, Annual Flexible Displays & Microelectronics Conference 2006, Session 5.1

Patents:

1. 李仁豪、何家充、李正中、林鵬、李鈞道、王右武，”薄膜電晶體元件主動層之半導體材料與其製作方法” (Method and material for forming active layer of thin film transistor), 中華民國專利證號 I221341
2. Jia Chong Ho, Jen Hao Lee, Cheng Chung Lee, Yu Wu Wang, Chun Tao Lee, and Pang Lin, “Compound Semiconductor Material and Method for Forming An Active Layer of A Thin Film Transistor Device”,美國專利審查中