

The Field-Emission Characteristics of Aluminum-Doped and Silver Doped Zinc Oxide Nanorods

陳信樟、李世鴻

E-mail: 386727@mail.dyu.edu.tw

ABSTRACT

In this study, aluminum-doped zinc oxide (ZnO) and silver-doped zinc oxide nanorods were grown by a hydrothermal method and the effect of varying the doping concentration on the field emission characteristics of the synthesized ZnO nanorods were studied. The growth procedure of ZnO nanorods is first spin-coating a seeding layer on silicon substrates, followed by the growth in the mixed solution of zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$), hexamethylenetetramine ($C_6H_{12}N_4$), and aluminum nitrate ($Al(NO_3)_3 \cdot 9H_2O$) or silver nitrate ($AgNO_3$) at 90°C for 2 hours. The ratio of volume concentration of zinc nitrate hexahydrate to hexamethylenetetramine is 1:1. The purpose of aluminum nitrate and silver nitrate was to supply dopant atoms and the volume concentration was varied from 0.2% to 4% (i.e. 0.0000M to 0.0008M). Field-emission scanning electron microscopy (FE-SEM), field-emission tunneling electron spectroscopy (FE-TEM), energy dispersive spectrometer (EDS), X-ray diffraction (XRD) were used to investigate the surface morphology, chemical compositions, and microstructure of aluminum-doped ZnO and silver-doped ZnO nanorods, the electrical properties were determined by Hall effect measurement, and the field emission characteristics of ZnO nanorods were measured in high vacuum. As found by EDS results, dopant atoms such as aluminum (Al) or silver (Ag) have been successfully incorporated into the crystalline structure of ZnO nanorods, and the conductivity, the concentration and mobility of majority carrier of ZnO nanorods have been modified accordingly. As can be seen in SEM results, the surface morphology of ZnO nanorods can be affected by impurity doping. It is found from XRD and FE-TEM results that the ZnO nanorods are of hexagonal wurtzite structure with [0001] as the most preferential direction of growth. It is also found that the Al-doped ZnO nanorods grown with 2% aluminum nitrate have the largest field emission current 127.78 ($\mu A/cm^2$); while silver doped ZnO nanorods of field emission maximum is 77.5 ($\mu A/cm^2$). In this study, it is demonstrated that the field emission characteristics of the ZnO nanorods can be effectively enhanced by doping impurities.

Keywords : zinc oxide (ZnO)、doping、field emission

Table of Contents

封面內頁 簽名頁 中文摘要	iii	英文摘要	iii
.	v	誌謝	vii
.	viii	圖目錄	xi
.	xv	表目錄	xi
.	xv	第一章 緒論 1.1 氧化鋅的歷史與簡介	1
.	3	第二章 氧化鋅理論原理與文獻回顧 2.1 氧化鋅簡介	5
.	5	2.2 氧化鋅的應用之相關文獻	6
.	8	2.3 以水熱法製備氧化鋅奈米柱相關文獻	8
.	11	2.4 水熱法製備摻雜鋁氧化鋅奈米柱之導電特性	11
.	14	2.5 水熱法製備p型氧化鋅奈米柱之光電特性	14
.	14	第三章 理論與研究方法 3.1 電子場發射之原理	19
.	22	3.2 氧化鋅奈米柱的成長機制	22
.	24	3.3 氧化鋅的製備方法	24
.	24	3.3.1 水熱法	24
.	25	3.3.2 鋅蒸氣氧化法	25
.	26	3.3.3 化學氣相沉積法(CVD)	26
.	27	3.3.4 溶膠 凝膠法	27
.	29	3.3.5 模板法	29
.	29	3.4 實驗步驟與流程	29
.	29	3.4.1 實驗流程	29
.	31	3.4.2 實驗基材與化學藥品	31
.	31	3.4.3 基板清洗	31
.	34	3.4.4 旋塗種子層	31
.	34	3.4.5 成長摻雜之氧化鋅奈米柱	34
.	35	3.5 實驗儀器與原理	35
.	35	3.5.1 場發射掃描式電子顯微鏡	35
.	36	3.5.2 能量散佈分析儀	36
.	38	3.5.3 X光繞射儀	38
.	39	3.5.4 場發射穿透式電子顯微鏡	39
.	41	3.5.5 場發射量測裝置與量測步驟	41
.	42	3.5.6 霍爾效應量測裝置與原理	42
.	47	第四章 實驗結果與討論 4.1 摻雜鋁對氧化鋅奈米柱的研究與討論	47
.	47	4.1.1 摻雜鋁氧化鋅奈米柱之FE-SEM分析	47
.	55	4.1.2 摻雜鋁氧化鋅奈米柱的成份分析(EDS分析)	55
.	56	4.1.3 摻雜鋁氧化鋅奈米柱的霍爾效應量測分析	56
.	59	4.1.4 摻雜鋁氧化鋅奈米柱電子場發射特性	59
.	64	4.2 摻雜銀對氧化鋅奈米柱的研究與討論	64
.	64	4.2.1 摻雜銀氧化鋅奈米柱之FE-SEM分析	64
.	64	4.2.2 摻雜銀氧化鋅奈米柱的成份分析(EDS分析)	64
.	71	4.2.3 摻雜銀氧化鋅奈米柱的霍爾效應量測分析	71
.	74	4.2.4 摻雜銀氧化鋅奈米柱電子場發射特性	74
.	74	4.3 摻雜後氧化	

銻奈米柱的結晶方向分析與晶格繞射分析	79	第五章 結論
83 參考文獻	85	圖目錄 圖2-1
SEM上視圖顯示, ZnO奈米線被曝光定義的圖形	10	圖2-2 SEM上視圖顯示, 樣品均以90°C成長8小時, (a) 無種子層拋光Si基板; (b) 2 nm奈米金種子層; (c) 5 nm金薄膜; (d) 10 nm的ZnO奈米粒子
10	圖2-3 奈米線的電子場發射。短奈米線(0.2 μm)為成長2小時, 直徑為60 nm。長奈米線(1.3 μm)為成長8小時, 直徑為10 nm到20 nm	
11	圖2-4 不同濃度硝酸鋁所成長之ZnO奈米柱之X光繞射圖。(a) 0; (b) 0.5%; (c) 1.0%; (d) 1.5%; (e) 2.0%; (f) 3.0%	13
13	圖2-5 不同濃度硝酸鋁所成長之ZnO奈米柱之SEM圖。(a) 0; (b) 0.5%; (c) 1.0%; (d) 1.5%; (e) 2.0%; (f) 3.0%	13
14	圖2-6 不同濃度硝酸鋁所成長之ZnO奈米柱之導電率曲線圖	14
16	圖2-7 未摻雜和摻雜的ZnO奈米柱的XRD比較圖	16
17	圖2-8 為奈米柱SEM圖, (a)和(b)未摻雜之氧化銻; (c)和(d)摻雜3%的鉀的氧化銻; (e)和(f)摻雜3%的銀的氧化銻	17
18	圖2-9 奈米柱退火前後的電流-電壓曲線圖。(a)未經退火的曲線圖(b)經過Ar/H ₂ (95/5)%, 在500 °C下退火一小時	18
19	圖3-1 金屬-真空界面之電子場發射示意圖	19
23	圖3-2 理想化的氧化銻晶體在[0001]的界面結構圖像	23
25	圖3-3 銻蒸氣氣化法製備氧化銻四針狀鬚結構圖	25
26	圖3-4 化學氣相沉積示意圖	26
30	圖3-5 實驗流程圖	30
37	圖3-6 場發射掃描式電子顯微鏡(附EDS)	37
38	圖3-7 高解析X光繞射儀	38
40	圖3-8 場發射穿透式電子顯微鏡(附EDS)	40
41	圖3-9 場發射量測裝置	41
43	圖3-10 霍爾效應量測載子濃度之示意圖	43
45	圖3-11 各形狀的van der Pauw霍爾效應量測試片: (a)不規則形狀, (b)圓形, (c)四葉形, (d)方形, (e)矩形, (f)十字形	45
46	圖3-12 霍爾效應量測裝置	46
51	圖4-1 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之3K倍上視圖, 硝酸鋁濃度分別為: (a) 無摻雜, (b) 0.2%, (c) 1%, (d) 1.5%, (e) 2%, (f) 4%	51
52	圖4-2 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之30K倍上視圖, 硝酸鋁濃度分別為: (a) 無摻雜, (b) 0.2%, (c) 1%, (d) 1.5%, (e) 2%, (f) 4%	52
53	圖4-3 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之100K倍上視圖, 硝酸鋁濃度分別為: (a) 無摻雜, (b) 0.2%, (c) 1%, (d) 1.5%, (e) 2%, (f) 4%	53
54	圖4-4 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之20K倍剖面圖, 硝酸鋁濃度分別為: (a) 無摻雜, (b) 0.2%, (c) 1%, (d) 1.5%, (e) 2%, (f) 4%	54
57	圖4-5 4-5 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之導電率曲線圖	57
58	圖4-6 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之載子遷移率曲線圖	58
58	圖4-7 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之載子濃度曲線圖	58
62	圖4-8 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之電流密度與施加電場曲線圖(J-E圖)	62
63	圖4-9 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之最大電流密度比較圖	63
63	圖4-10 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之相對Fowler-Nordheim (F-N)圖	63
64	圖4-11 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之相對應高電場Fowler-Nordheim (F-N)曲線圖	64
67	圖4-12 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之3K倍上視圖, 摻雜濃度分別為: (a) 無摻雜、(b) 0.2%、(c) 1%、(d) 1.5%、(e) 2%、(f) 4%	67
68	圖4-13 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之30K倍上視圖, 摻雜濃度分別為: (a) 無摻雜、(b) 0.2%、(c) 1%、(d) 1.5%、(e) 2%、(f) 4%	68
69	圖4-14 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之100K倍的上視圖, 摻雜濃度分別為: (a) 無摻雜、(b) 0.2%、(c) 1%、(d) 1.5%、(e) 2%、(f) 4%	69
70	圖4-15 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之20K倍的剖面圖, 摻雜濃度分別為: (a) 無摻雜、(b) 0.2%、(c) 1%、(d) 1.5%、(e) 2%、(f) 4%	70
72	圖4-16 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之導電率曲線圖	72
73	圖4-17 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之載子遷移率曲線圖	73
73	圖4-18 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之載子濃度曲線圖	73
77	圖4-19 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之電流密度與施加電場曲線圖(J-E圖)	77
77	圖4-20 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之最大電流密度比較圖	77
78	圖4-21 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之相對的Fowler-Nordheim (F-N)圖	78
78	圖4-22 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之相對應的高電場Fowler-Nordheim (F-N)曲線圖	78
81	圖4-23 摻雜不同元素的ZnO奈米柱之XRD頻譜圖	81
81	圖4-24 XRD晶體頻譜資料庫(1997 JCPDS-ICDD:36-1451)	81
82	圖4-25 摻雜雜質後ZnO奈米柱之FE-TEM影像: (a) 摻雜鋁ZnO奈米柱之高倍解析影像、(b) 摻雜鋁ZnO奈米柱之電子繞射圖、(c) 摻雜銀之高倍解析影像、(d) 摻雜銀ZnO奈米柱之電子繞射圖	82
32	表目錄 表3-1 本實驗製備之基材	32
32	表3-2 本實驗製備之化學試劑	32
55	表4-1 不同濃度硝酸鋁所成長之摻雜鋁ZnO的直徑、高度及密度比較表	55
55	表4-2 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之成份比較表	55
59	表4-3 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之霍爾效應量測之體積濃度原始數據	59
61	表4-4 不同濃度硝酸鋁所成長之摻雜鋁ZnO奈米柱之高電場F-N圖斜率及場增強因子	61
66	表4-5 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱的直徑、高度及密度比較表	66
71	表4-6 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之成份比較表	71
71	表4-7 不同濃度硝酸銀所成長之摻雜銀ZnO奈米柱之	71

REFERENCES

- [1]L. Spanhel and M. A. Anderson, Semiconductor clusters in the sol-gel process: quantized aggregation, gelation, and crystal growth in concentrated ZnO colloids, *J. Am. Chem. Soc.*, 113 (1991) 2826.
- [2]L. Vayssieres, K. Keis, S. E. Lindquist and A. Hagfeldt, Purpose-built anisotropic metal oxide material: 3D highly oriented microrod array of ZnO, *J. Phys. Chem. B*, 105 (2001) 3350.
- [3]L. Vayssieres, K. Keis, A Hagfeldt and S. E. Lindquist, Three-dimensional array of highly oriented crystalline ZnO microtubes, *Chem. Mater.*, 13 (2001) 4395.
- [4]L. Vayssieres, Growth of arrayed nanorods and nanowires of ZnO from aqueous solutions, *Adv. Mater.*, 15 (2003) 464.
- [5]L. E. Greene, M. Law, J. Goldberger, F. Kim, J. C. Johnson, Y. Zhang, R. J. Saykally and P. Yang, Low-temperature wafer-scale production of ZnO nanowire arrays, *Angew. Chem. Int. Ed.*, 42 (2003) 3031.
- [6]Y. Tak and K. Yong, Controlled growth of well-aligned ZnO nanorod array using a novel solution method, *J. Phys. Chem. B*, 109 (2005) 19263.
- [7]H. D. Sun, T. Makino, Y. Segawa, M. Kawasaki, A. Ohtomo, K. Tamura and H. Koinuma, Enhancement of exciton binding energies in ZnO/ZnMgO multiquantum wells, *J. Appl. Phys.*, 91 (2002) 1993-1997.
- [8]C. G. Van de Walle, D. B. Laks, G. F. Neumark and S. T. Pantelides, First-principles calculations of solubilities and doping limits: Li, Na, and N in ZnSe, *Phys. Rev. B*, 47(15) (1993) 9425.
- [9]H. von Wenckstern, R. Pickenhain, H. Schmidt, M. Brandt, G. Biehne, M. Lorenz and M. Grundmann, Deep acceptor states in ZnO single crystals, *Appl. Phys. Lett.*, 89(9) (2006) 092122.
- [10]W. I. Park, D. H. Kim, S. W. Jung and G. Yi, Metalorganic vapor-phase epitaxial growth of vertically well-aligned ZnO nanorods, *Appl. Phys. Lett.*, 80 (2002) 4232.
- [11]張均豪, 「以溶膠凝膠法製備氧化鋅奈米結構於半導體型氣體感測器之應用」, 國立臺灣師範大學機電科技學系碩士論文, 2008年。
- [12]J. Y. Lee, Y. S. Choi, J. H. Kim, M. O. Park and S. Im, Optimizing n-ZnO/p-Si heterojunctions for photodiode applications, *Thin Solid Films*, 403 (2002) 553.
- [13]Z. W. Pan, Z. R. Dai and Z. L. Wang, Nanobelts of semiconducting oxides, *Science*, 291 (2001) 1947.
- [14]Y. C. Kong, D. P. Yu, B. Zhang, W. Fang and S. Q. Feng, Ultraviolet-emitting ZnO nanowires synthesized by a physical vapor deposition approach, *Appl. Phys. Lett.*, 78 (2001) 407.
- [15]C. L. Wu, Li Chang, H. G. Chen, C. W. Lin, T. F. Chang, Y. C. Chao and J. K. Yan, Growth and characterization of chemical-vapor-deposited zinc oxide nanorods, *Thin Solid Films*, 498 (2006) 137.
- [16]Q. Li, V. Kumar, Y. Li, H. Zhang, T. J. Marks and R. P. H. Chang, Fabrication of ZnO nanorods and nanotubes in aqueous solutions, *Chem. Mater.*, 17 (2005) 1001.
- [17]魏竹瑜, 「水熱法成長摻雜氧化鋅奈米柱之研究」, 國立虎尾科技大學光電與材料科技研究所碩士論文, 2010年。
- [18]G. Zhang, Q. Zhang, Y. Pei and L. Chen, Field emission from nonaligned zinc oxide nanowires, *Vacuum*, 77(1) (2004) 53-56.
- [19]H. L. Hartnagel, A. K. Jain and C. Jagadish, *Semiconducting transparent thin films*, Institute of Physics Publication, (1998) 17.
- [20]A. Wei, W. Sun, C. X. Xu, Z. L. Dong, Y. Yang, S. T. Tan and W. Hung, Growth mechanism of tubular ZnO formed in aqueous solution, *Nanotechnology*, 17 (2006) 1740.
- [21]W. J. Li, E. W. Shi, W. Z. Zhong and Z. W. Yin, Growth mechanism and growth habit of oxide crystals, *J. Cryst. Growth*, 186-196 (1999) 203.
- [22]Y. S. Choi, J. W. Kang, D. K. Hwang and S. J. Park, Recent advances in ZnO-based light-emitting diodes, *IEEE Trans. Electron Dev.*, 57(1) (2010) 26-41.
- [23]黃建綸, 「PN型氧化鋅奈米結構之研究」, 國立清華大學碩士論文, 2010年。
- [24]潘韋志, 「氧化鋅六角奈米柱場發射性質之研究」, 大葉大學電機工程學系碩士班碩士論文, 2012年。
- [25]M. Law, L. E. Greene, J. C. Johnson, R. J. Saykally and P. Yang, Nanowire dye-sensitized solar cells, *Nat. Mater.*, 4 (2005) 455-459.
- [26]K. Kakiuchi, E. Hosono and S. J. Fujihara, Enhanced photoelectrochemical performance of ZnO electrodes sensitized with N-719, *J. Photochem. Photobio. A. Chem.*, 179 (2006) 81-86.
- [27]E. Neshataeva, T. Kummell, G. Bacher and A. Ebbers, All-inorganic light emitting device based on ZnO nanoparticles, *Appl. Phys. Lett.*, 94 (2009) 091115.
- [28]J. B. Cui, C. P. Daghljan, U. J. Gibson, R. Pusche, P. Geithner and L. Ley, Low-temperature growth and field emission of ZnO nanowire arrays, *Appl. Phys.*, 97 (2005) 044315.
- [29]Suping Huang, Qi Xiao, Hao Zhou, Dan Wang and Wenjuan Jiang, Hydrothermal synthesis and conductive properties of Al-doped ZnO rod-like whiskers, *J. Alloys Comp.*, 486 (2009) L24 – L26.

- [30] M. H. Yoon, S. H. Lee, H. L. Park, H. K. Kim and M. S. Jang, Solid solubility limits of Ga and Al in ZnO, *J. Mater. Sci. Lett.*, 21 (2002) 1703.
- [31] B. Joseph, P. K. Manoj and V. K. Vaidyan, Studies on the structural, electrical and optical properties of Al-doped ZnO thin films prepared by chemical spray deposition, *Ceram. Int.*, 32 (2006) 487.
- [32] R. Thangavel and Yia-Chung Chang, Investigations on structural, optical and electrical properties of p-type ZnO nanorods using hydrothermal method, *Thin Solid Films*, 520 (2012) 2589-2593.
- [33] J. S. Huang, C. F. Lin, Influences of ZnO sol-gel thin film characteristics on ZnO nanowire arrays prepared at low temperature using all solution based processing, *J. Appl. Phys.*, 103 (2008) 014304.
- [34] R. Gomer, *Field Emission and Field Ionization*, Harvard University Press, Cambridge, MA (1961).
- [35] R. H. Fowler and L. Nordheim, Electron emission in intense electric fields, *Proc. Roy. Soc. Ser. A*, 119 (1928) 173.
- [36] C. Y. Lee, T. Y. Tseng, S. Y. Li and P. Lin, Single-crystalline $Mg_xZn_{1-x}O$ ($0 \leq x \leq 0.25$) nanowires on glass substrates obtained by a hydrothermal method: growth, structure and electrical characteristics, *Nanotechnology*, 16 (2005) 1105.
- [37] K. Govender, D. S. Boyle, P. B. Kenway and P. O' Brien, Understanding the factors that govern the deposition and morphology of thin films of ZnO from aqueous solution, *J. Mater. Chem.*, 14 (2004) 2575.
- [38] W. J. Li, E. W. Shi, W. Z. Zhong and Z. W. Yin, Growth mechanism and growth habit of oxide crystals, *J. Cryst. Growth*, 203 (1999) 186.
- [39] Z. Zhou, W. Peng, S. Ke and H. Deng, Tetrapod-shaped ZnO whisker and its composites, *J. Mater. Process. Technol.*, 89 (1999) 415.
- [40] M. Satoh, N. Tanaka, Y. Ueda, S. Ohshio and H. Saitoh, Epitaxial growth of zinc oxide whiskers by chemical-vapor deposition under atmosphere pressure, *Jpn. J. Appl. Phys.*, 38 (1999) L586.
- [41] P. Yang, H. Yan, S. Mao, R. Russo, J. Johnson, R. J. Saykally, N. Morris, J. Pham, R. He and H. -J. Choi, Controlled growth of ZnO nanowires and their optical properties, *Adv. Funct. Mater.*, 12(5) (2002) 323.
- [42] M. J. Zheng, L. D. Zhang, G. H. Li and W. Z. Shen, Fabrication and optical properties of large-scale uniform zinc oxide nanowire arrays by one-step electrochemical deposition technique, *Chem. Phys. Lett.*, 363 (2002) 123.
- [43] M. H. Hwang, Room-temperature ultraviolet nanowires nanolasers, *Science*, 292 (2001) 1897.
- [44] Y. W. Wang, L. D. Zhang, G. Z. Wang, X. S. Peng, Z. Q. Chu and C. H. Liang, Catalytic growth of semiconducting zinc oxide nanowires and their photoluminescence properties, *J. Cryst. Growth*, 234 (2002) 171.
- [45] L. Vayssieres, K. Keis, A. Hagfeldt and S. E. Lindquist, Three-dimensional array of highly oriented crystalline ZnO microtubes, *Chem. Mater.*, 13 (2001) 4395.
- [46] J. Q. Hu, Synthesis of uniform hexagonal prismatic ZnO whiskers, *Chem. Mater.*, 14 (2002) 1216.
- [47] Y. C. Wang, I. C. Leu and M. H. Hon, Preparation of nano-sized ZnO arrays by electrophoretic deposition, *Electrochem. Solid-State Lett.*, 5(4) (2002) C53.
- [48] R. F. Service, Will UV lasers beat the blues, *Science*, 895 (1997) 276.
- [49] R. A. Laudise and A. A. Ballman, Hydrothermal synthesis of zinc oxide and zinc sulfide, *J. Phys. Chem.*, 64(5) (1960) 688.
- [50] H. Ohta, M. Orita, M. Hirano and H. Hosono, Fabrication and characterization of ultraviolet-emitting diodes composed of transparent p-n heterojunction, p-SrCu₂O₂ and n-ZnO, *J. Appl. Phys.*, 89(10) (2001) 5720-5725.
- [51] H. Kawazoe, M. Tasukawa, H. Hyodo, M. Kurita, H. Yanagi and H. Hosono, P-type electrical conduction intransparent thin films of CuAlO₂, *Nature (London)*, 389 (1997) 939-942.
- [52] A. Kudo, H. Yanagi, H. Hosono and H. Kawazoe, SrCu₂O₂: A p-type conductive oxide with wide band gap, *Appl. Phys. Lett.*, 73(2) (1998) 220-222.
- [53] Y. R. Ryu, W. J. Kim and H. W. White, Fabrication of homostructural ZnO p-n junctions, *J. Cryst. Growth*, 219 (2000) 419-422.
- [54] H. Nagayama, H. Honda and H. Kawahara, Preparation of photocatalyst doped TiO₂ with liquid phase deposition, *J. Electrochem. Soc.*, 135 (1998) 2013.
- [55] 郭旭祥, 「ZnO:Al薄膜氣體感測器之研究」, 國立成功大學材料科學及工程學系碩士論文, 2000年。
- [56] 鄭聖賢, 「氧化鋅奈米線成長技術研究及特性探討」, 國立成功大學電機工程系研究所碩士論文, 2004年。
- [57] C. J. Brinker and G. Scherer, *Sol-Gel Science*, Academic Press, New York, 1990.
- [58] 蔣孝撤, 「溶凝膠製作與應用專輯」。化工, 第46卷第5期, 民88年, 12-15頁。
- [59] H. Nagayama, H. Honda and H. Kawahara, A new process for silica coating, *J. Electrochem. Soc.*, 135 (1988) 2013.
- [60] S. Deki, Y. Aoi, O. Hiroi and A. Kajinami, Titanium (IV) oxide thin films prepared from aqueous solution, *Chem. Lett.*, 25 (1996) 433-434.
- [61] 陳隆建, 「發光二極體之原理與製程」, 2006年8月一版, 全華科技圖書股份有限公司。
- [62] Jinping Liu, Xintang Huang, Yuanyuan Li, K. M. Sulieman, Xiang He and Fenglou Sun, Facile and large-scale production of ZnO/Zn-Al layered double hydroxide hierarchical heterostructures, *J. Phys. Chem. B*, 110 (2006) 21865-21872.
- [63] Donald A. Neamen 著, 楊賜麟譯, 「半導體物理與元件」, 2009年8月初版三刷, 麥格羅 希爾國際股份有限公司台灣分公司。
- [64] S. L. S. Jacoby, J. S. Kowalik and J. T. Pizzo, Iterative methods for nonlinear optimization problems, Prentice Hall, Inc., Englewood Cliffs, New Jersey, ISBN:0-13-508199-X, pp. 79-83 (1972).
- [65] R. H. Fowler and L. W. Nordheim, Electron emission in intense electric fields, *Proc. Royal Soc. London*, 119 (1928) 173-181.

- [66]吳明憲，「摻雜銻之p-type氧化鋅薄膜特性分析」，國立臺北科技大學光電工程系碩士班碩士學位論文，2008年。
- [67]陳皇欽，「超奈米微晶鑽石薄膜之微結構及電子場發射特性之研究」，淡江大學物理學系博士班博士論文，2010年。
- [68]黃琇澤，「以反應濺鍍法製備氧化鋅薄膜與摻雜鋁之研究」，國立中山大學材料科學與工程研究所碩士論文，2003年。
- [69]張坤榮，「摻雜鋁於氧化鋅透明導電膜之光特性與電特性研究」，國立中央大學光電科學研究所碩士論文，2004年。