SYNTHESIZE OF ALUMINUM ZINC OXIDE NANOWIRES FOR DYE SENSITIZED SOLAR CELL APPLICATION

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Dedicated to

My beloved family especially my wife and my son and my parent's soul. Thank you very much for being supportive, helpful and understanding.

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ABSTRACT

Zinc oxide nanowires (ZnO NWs) have evoked extensive attention in recent years because of their potential technological applications. Aluminum (Al-ZnO) doped ZnO NWs have been deposited onto indium tin oxide (ITO) glass substrate, by using sol-gel spin coating and hydrothermal methods. Al-ZnO NWs with the percentage of Al content up to 6% were annealed at 450–600 °C. The structural, electrical and optical properties of the samples were characterized with X-ray diffraction (XRD), Energy-dispersive X-ray (EDX) spectroscope, Field-emission scanning electron microscope (FE-SEM), atomic force microscope (AFM), and UV-Visible spectrophotometer and photoluminescence (PL) spectrometer. Meanwhile, the Al-ZnO NWs conductivity level was determined by Van der Pauw method. XRD analysis confirmed a single phase spinel structure with the crystallite size between 20-50 nm calculated using the Scherrer's formula. The highest main diffraction peak corresponding to the (002) orientation was due to the dominant phase of Al-ZnO at annealing temperature of 550 °C. The FE-SEM and AFM micrographs displayed the formation of well-defined and homogenous crystallite grains. The biggest grain size of 37 nm was observed for Al-ZnO NWs prepared with 6% Al concentration and annealed at 550 °C. The samples showed a high transmittance of more than 85% in the visible region, with energy band gap in the range of 3.25 to 3.35 eV. In addition, the electrical measurement result of the Al-ZnO NWs showed the lowest conductivity value of 2.49×10^{-4} S/cm with the activation energy E_a = 27 meV. A dye sensitized solar sell (DSSC) with this design showed a high short-circuit current density of 3.94 mA/cm^2 and open circuit voltage of 0.48 V. A DSSC with efficiency of 0.72% was achieved using this photo-anode.
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ABSTRAK

Dawai nano zink oksida (ZnO NWs) telah mendapat perhatian meluas dalam tahun kebelakangan ini kerana potensi yang tinggi dalam penggunaan teknologi. ZnO NWs berdop aluminum (Al-ZnO) telah dimendapkan ke atas substrat kaca indium Stanum oksida (ITO) menggunakan kaedah pelapisan putaran sol-gel dan hidroterma. Al-ZnO NWs dengan kepekatan Al sehingga 6% telah disepuhlindap pada 450-600 °C. Pencirian sifat struktur, elektrik dan optik sampel telah dibuat menggunakan pembelauan sinar-X (XRD), spektroskop sinar-X tenaga-serakan (EDX), mikroskop elektron pengimbasan medan pancaran (FE-SEM), mikroskop daya atom (AFM), spektrofotometer UV-cahaya nampak dan spektrometer kefotopendarcahayaan (PL). Sementara itu, tahap kekonduksian Al-ZnO NWs ditentukan menggunakan kaedah Van der Pauw. Analisis XRD mengesahkan sampel berstruktur spinel fasa tunggal dengan saiz hablur antara 20-50 nm dikira menggunakan formula Scherrer. Puncak pembelauan utama tertinggi sepadan dengan orientasi (002) adalah berpunca daripada fasa dominan Al-ZnO pada suhu penyepuhlindapan 550 °C. Mikrograf FE-SEM dan AFM memaparkan pembentukan butiran hablur yang sekata dan homogen. Saiz butiran terbesar 37 nm diperhatikan bagi Al-ZnO NWs yang disediakan dengan kepekatan 6% dan disepuhlindapkan pada 550 °C. Sampel menunjukkan kehantaran tinggi melebihi 85% dalam rantau cahaya nampak dengan jurang jalur tenaga antara 3.25 hingga 3.35 eV. Disamping itu, hasil pengukuran elecktrik Al-ZnO NWs menunjukkan nilai kekonduksian terendah 2.49×10^{-4} S/cm dengan tenaga pengaktifan E_a = 27 meV. Solar sel terpeka pewarna (DSSC) dengan reka bentuk ini menunjukkan kepadatan arus litar pintas yang tinggi 3.94 mA/cm^2 dan voltan litar terbuka 0.48 V. DSSC dengan kecekapan 0.72% telah terhasil dengan menggunakan foto-anod ini.

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LIST OF ABBREVIATIONS

AFM	-	Atomic Force Microscope
Al Cl_3-6H_2O	-	Aluminum Nitrate Hexahydrate
DC	-	Direct Current
DEA	-	Diethanolamine
DSSC	-	Dye-Sensitized Solar Cell
EDX	-	Energy dispersive X-ray
FESEM	-	Field emission scanning electron microscopy
FPP	-	Four point probe
FWHM	-	Full with at half maximum
HMTA	-	Hexamethylenetetramine
ITO	-	Indium Tin Oxide
IPCE	-	Incident-Photon-to-electron Conversion Efficiency
NaOH	-	Sodium Hydroxide
NW	-	Nanowire
PL	-	Photoluminescence
SC	-	Solar cell
UV-VIR	-	Fourier transform Infrared
XRD	-	X-ray Diffraction
Zn $(CH3COO)_2 \cdot 2H_2O$	-	Zinc Acetate Di-hydrate
Zn $(NO_3)_2 \cdot 6H_2O$	-	Zinc Nitrate Hexahydrate
ZnO	-	Zinc Oxide

LIST OF SYMBOL

μ_0	-	Permeability
Å	-	Angstrom
A	-	Area
a, c	-	lattice constant
a,	-	Lattice parameter
P_{in}	-	Input Power [mW/cm^2]
Cu Kα	-	Copper K-alpha line
d	-	Inter planar distance
D	-	Crystallite
FF	-	Fill Factor [dimensionless]
J_{sc}	-	Short Circuit Current Density [A/cm^2]
I	-	Current [A]
I_o	-	Incident Photon Flux [$cm^{-2}s^{-1}$]
IPCE	-	Incident Photon-To-Electron Conversion Efficiency [%]
J	-	Current Density [A/m2]
V	-	Voltage [V]
V_{oc}	-	Open Circuit Voltage [V]

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CHAPTER 1

INTRODUCTION

1.1 Background of study

In twenty first century a wide interest to fabricate nanostructure materials and devices. These materials and devices have structures with nano-scale dimensions. One of the main reasons for interesting to nano-materials is because of different properties from those bulk materials. These properties such as large surface area have applications for various uses. Specially, Zinc oxide (ZnO) nanostructures are attracting interest since the techniques used to fabricate them are largely correspondent with available semiconductor production processes. ZnO nanostructures properties are different from that bulk ZnO.

ZnO is a key technology material with numerous applications ranging from chemical sensors to optoelectronics because of unique optical, electronic, and chemical properties [1-5]. The lattice parameters of ZnO are a=0.3249 nm and c=0.5206 nm at temperature room (300K), with a c/a ratio of 1.602. Moreover, ZnO has a wide band-gap 3.37 eV II-VI compound semiconductor that is suitable for short wavelength optoelectronic applications [6-9]. ZnO has an effective electron mass of ~0.24 Me, and a large exciton binding energy of 60 meV at temperature room [10-13]. In addition, ZnO is a transparent material to visible light; also, it can to highly conductive by doping. The intrinsic defect levels that lead to *n*-type doping lay approximately 10– 50 meV below the conduction band [14, 15]. The reliable and reproducible *p*-type conductivity has not yet been achieved due to many issues. The compensation of dopants by energetically favorable native defects such as zinc interstitials or oxygen vacancies is one of the obstacles [16]. The low dopant solubility is another issue. One of the optical properties of ZnO is extensively studied because of their promising applications in optoelectronics. Furthermore, the lasing conditions can be further improved with low dimensional ZnO structures, which enhance the excition oscillator strength and quantum efficiency [17,18]. Therefore bulk ZnO has a small exciton Bohr radius (~2.34 nm). The Quantum Confinement effect in ZnO nanowires could be observable at the scale of an exciton Bohr radius. It has been reported by Gu*et al.* [19] that the excition binding energy is significantly enhanced due to size confinement in ZnO nano-rods with diameter of ~2 nm. Various types of solar cell, such as silicon-based, GaAs and organic have recently been developed [19, 20]. Semiconductor nano-wires (NWs) have been proposed as basic “building blocks” in a variety of devices, for example, photonics, electronics, and chemical sensing [20].

Nowadays, one-dimensional (1D) nano-wires and nano-rods have attracted a lot of attention. Compared to thin- film and bulk devices, 1DNW devices are expected to have a larger response to light due to the high length-to-diameter aspect ratio and high surface-to-volume ratio of 1D-NWs. Investigations into semiconductor nano-material systems have demonstrated that ZnO is a promising material for application in various devices because it is a chemically and thermal ways stable and n-type semiconductor with a large band-gap energy and a large exciton binding energy at room temperature. ZnO nano-structures can be synthesized using different techniques. Vapor phase deposition [21] and hydrothermal synthesis [22] are the most commonly used low-temperature synthesis techniques for zinc oxide nanostructures.

In particular, dye-sensitized solar cells (DSSCs) of the third generation of solar cells have become a very interesting and practical alternative for advances in solar cell technology. The working mechanism of the DSSC is unique in that it does not follow the principles of the traditional p-n junction solar cell. The dye sensitizer absorbs the photons, while the role of the semiconductor film is to facilitate charge transport to the collecting transparent conductive oxide glass substrate. Since its introduction into the science community in 1991, the nanocrystalline photoanode in DSSC have predominantly been comprised of nanoparticles. With efficiencies reaching a plateau of 11-12% for TiO_2 nanoparticle-based dye sensitized solar cells [6, 9], many researchers became very interested in studying the dye-sensitized solar cell performance of alternative semiconducting nanomaterials. Specifically, ZnO has been an ideal alternative to TiO_2 because ZnO has a similar conduction band edge that is appropriate for proper electron injection from the excited dyes; moreover, ZnO provides better electron transport due to its higher electronic mobility.

Over the past decade, there has been a heightened interest in using ZnO NWs as the semiconducting photoanode in dye-sensitized solar cells. Utilizing wide-band gap semiconductor nanowires (e.g., ZnO NWs) instead of TiO_2 nanoparticles has been thought to be very advantageous because i) the NW morphology allows for electrons to travel a more direct 3 conduction path from the point of injection to the point of collection, and ii) the NW possess a large enough surface area for adequate dye adsorption [9]. The NW photoanode has a very fast electron injection rate and the electron diffusivity in crystalline wires (ZnO NW) has been reported as several orders of magnitude larger than electron diffusivity within TiO_2 nanoparticles [17]. The superior electron transport within the NW photoanode can be attributed to its higher crystallinity and the presence of an internal electric field that facilitates electron transport to the collecting glass substrate by effectively separating the injected electrons from the oxidized species of the electrolyte; this, in turn, improves the charge collection efficiency [17]. Furthermore, NWs can be synthesized at low temperatures, which allow the use of various substrates including polymers, and the employment of low temperatures greatly reduces energy costs. However, researchers have yet to fabricate ZnO NW-based DSSC with efficiencies similar or higher than TiO_2 nanoparticle-based DSSCs. Although the vertical NW morphology has many advantages, there is also a critical disadvantage. Compared to the closely packed nanoparticle thin film, more uncovered substrate surface between the NWs is present in the vertical NW array. These open spaces lead to direct contact between the electrons at the conducting glass substrate and either the oxidized dye molecules or oxidized species in the electrolyte during the charge transport process. This phenomenon is known as either electron recombination or electron back transfer. Interestingly, many have referred to the occurrence of electron back transfer as the most crucial limitation of DSSC as it severely affects its performance by short-circuiting the cell. It is thought that by placing a barrier layer between the conducting glass substrate and the NWs, the contact at the conducting substrate-electrolyte interface can be significantly reduced or avoided completely. Another major challenge of ZnO NW-based dye sensitized solar cells stems from the lower surface area of the ZnO NW array to that of the network of TiO_2 nanoparticles on the substrate. By having a larger surface area, the nanocrystalline photoanode is able to absorb a greater amount of the incoming light. Thus, improvements in the surface area of the ZnO NWs array used for the DSSC will significantly enhance the light harvesting efficiency, which in turn results in an overall increase in the power conversion efficiency of the cell. In addition to providing better charge collection, the use of very long and dense ZnO NW arrays results in a greater surface area that is necessary for an increase of adsorbed dye molecules, which leads to improved light harvest efficiency [17]. As an alternative to synthesizing longer NWs, the concept of producing dense hierarchal NW structures should also yield larger surface areas needed to improve the conversion efficiency of ZnO NW-based DSSC.

1.2 Problem statement

This research shows that ZnO NWs have been studied almost two decades, to emphasize generally on their synthesis and properties [23]. Most of the techniques employed are based on chemical methods comprising of electrochemical and chemical bath deposition (CBD) [24-25]. The second methods appeared to be more reliable in terms of its ease of use, less expensive and the ability for commercial production [26-27].

Synthesis and Controlled growth using different techniques and using Al instead of Pt in ZnO NWs by easy and economic method is demanding for optoelectronic application. since many techniques, are for fabricate Solar Cell technique including advantages for large scale, and high density fabrication of Al-ZnO NWs. However, we achieved this method with various growth conditions to study the role of annealing, a variation of substrate temperature, annealing time, and another growth parameter on sample morphology.

However, there is No progress of works using the conventional bath techniques which revealed the formation of ZnO NWs with less defines the structures. Further examination showed that the NWs the same ZnO appeared as simple and short, ascribed by their non-random orientations via chemical bath deposition [29]. A CBD method is proposed which will result in quality of ZnO NWs. The novel corresponding structural and optical properties are expected to improve significantly. And the following method of preparation and optimum synthesis of Al-ZnO NWs by presented method can approach to optimum nanostructure for semiconductor application.

1.3 Research Objectives

This study presents the following objectives:

I. To fabrication photo anod of ZnO NWs

II. To determine the structure of Al-ZnO by chemical deposition method in different temperature and ratio and protract employing XRD and EDX.

III. To analyze of surface morphology such as ZnO roughness, number density, ratio of grain area, shape and size of the ZnO NWs by AFM and FE-SEM.

IV. To determine the optical properties of nanowire ZnO in different annealing temperature (value of 450-600 °C) and concentration by UV-visible and photo-luminance (PL).

V. To determinate effects of the current density of ZnO NWs arrays on the overall DSSC power conversion efficiency by designing a one-dimensional ZnO NWs that increases the NWs density and enhances surface area, and thus enhances light absorption.

1.4 Scope of research

This project aims to synthesize and investigation of structural, optical and electrical properties of ZnO NWs. The concentrations of Al- ZnO seeded catalyst expressed as were $(0-6\ \%)$.

This material is selected for this study in view of their technological importance. The crystallinity of the film is developed by calcinate at 450 - 600 °C. To growth ZnO NWs, several steps must be taken, which each step is depend on benefits and builds on the information found in the previous steps. These are reflected in the experimental approach. Sol-gel and Chemical Bath Deposition (CBD) methods are employed to prepare ZnO nanowire on Indium-tin-Oxide (ITO) glass substrate, ZnO bilayer, and glass/ITO/AZO/ ZnO heterostructure. Different deposition parameters such as; time deposition, substrate temperature and treatment that in different temperatures and times are applied to investigate the growth process and surface evolution of zinc oxide nano-wires. Energy dispersive X-ray diffraction (EDX) and field emission scanning electron microscopy (FE-SEM)are used to characterize the surface morphology of samples.

Optical properties of samples and the effect of growth parameter, ZnO space layer thickness and ITO substrate thickness on the optical behaviour are studied by photoluminescence (PL) and UV-Visible. This project involves the preparation and characterization of ZnO nanostructure.

1.5 Significant of study

Nano-structuring of semiconductors is a novel device of developing new electronic and optoelectronic devices. Particularly, it is one of the discoveries of room-temperature (RT) visible photoluminescence (PL) from ITO and ZnO. Furthermore, nanostructures have very much interest in these particular kinds of Nanoclusters and small semiconductor nanoparticles. Setting the optical response of ITO and zinc oxide nanomaterial by changing their size to become also a the most challenging aspects of recent research on semiconductors.

Easy and economical fabrication technique would be developed. The instrumentation for large-scale fabrication has socio-economic impact. The fundamental physics behind the growth would be understood. The data generated throw this research will be published in high impact factor journal, and research data would be presented in conferences, workshops, and seminars. Ph.D. and Masters Research Scholar can be trained using this methodology to pursue their future research.

The high quality of the sample needed for the optoelectronic industries can be supported by using rf magnetron sputtering method. The device would be cheaper and economic. A set of characterization, which we propose, would be able to measure the band gap, right sample structure, and right physics. An extension of this research is that these methodologies are not just limited to the Zinc, another semiconductor nanostructure like ZnO and other also can be grown by using this method. This method can be extended and become versatile for nanostructure growth.

1.6 Organization of research

This research is concluding of five chapters. Chapter 1 begins with the introduction, followed by the research background, the statement of the problem, research objective, research questions, and the scope of the study, research hypothesis, and the organization of the study.

Chapter 2 provided an extensive literature review that had been done serve as a guide for understanding the following chapters. This detailed review will be based primarily on, **i**) the properties, characteristics, and attractive uses of ZnO and its nanomaterials; and **ii**) the fundamental principles of photovoltaic and particularly advancements of dye-sensitized solar cells within the nanotechnology field.

Chapter 3 focused on, **i**) the fabrication of ZnO nanowires based on a hydrothermal process synthesis; **ii**) an investigative study of ZnO morphology based on varied synthesis conditions and **iii**) examined various methodologies to improve the overall power conversion efficiencies of ZnO nanowires based dye-sensitized solar cells via the fabrication of a one-dimensional solar cell design.

Chapter 4 described the basic recipe used to grow ZnO NWs. To grow these nanowires successfully, various growth parameters were studied. The growth mechanism was explained, and structural characterizations on grown ZnO NWs were performed.

Lastly, Chapter 5 concludes all major findings and rationalizations from this research project.

REFERENCES

[1] Lopatiuk, O., W. Burdett, et al. (2004). "Minority carrier transport in p-type Zn0. 9Mg0. 1O doped with phosphorus." Applied Physics Letters 86(1): 012105.

[2] Padmavathy, N., & Vijayaraghavan, R. (2016). Enhanced bioactivity of ZnO nanoparticles—an antimicrobial study. *Science and Technology of Advanced Materials*.

[3] Kumar, S. S., Venkateswarlu, P., Rao, V. R., & Rao, G. N. (2013). Synthesis, characterization and optical properties of zinc oxide nanoparticles. *International Nano Letters*, *3*(1), 1-6.

[4] Yang, Q., Liu, Y., Pan, C., Chen, J., Wen, X., & Wang, Z. L. (2013). Largely enhanced efficiency in ZnO nanowire/p-polymer hybridized inorganic/organic ultraviolet light-emitting diode by piezo-phototronic effect. *Nano letters*, *13*(2), 607-613.

[5] Wang, Z. L. (Ed.). (2013). *Nanowires and Nanobelts: Materials, Properties and Devices. Volume 1: Metal and Semiconductor Nanowires*. Springer Science & Business Media.

[6] Al-Hardan, N. H., Jalar, A., Hamid, M. A., Keng, L. K., Ahmed, N. M., & Shamsudin, R. (2014). A wide-band UV photodiode based on n-ZnO/p-Si heterojunctions. *Sensors and Actuators A: Physical*, *207*, 61-66.

[7] Khoshman, J. M., & Kordesch, M. E. (2007). Optical constants and band edge of amorphous zinc oxide thin films. *Thin Solid Films*, *515*(18), 7393-7399.

[8] Zhang, Y., & Hao, J. (2013). Metal-ion doped luminescent thin films for optoelectronic applications. *Journal of Materials Chemistry C*, *1*(36), 5607 5618.

[9] Kim, C., Kim, Y. J., 이규철, Kim, H. H., Yi, G. C., & Jang, E. S. (2006). Whispering-gallery-modelike-enhanced emission from ZnO nanodisk.

[10] Akasaki, I., & Amano, H. (1997). Crystal growth and conductivity control of group III nitride semiconductors and their application to short wavelength light emitters. *Japanese journal of applied physics, 36*(9R), 5393.

[11] Saw, K. G., Ibrahim, K., Lim, Y. T., & Chai, M. K. (2007). Self-compensation in ZnO thin films: An insight from X-ray photoelectron spectroscopy, Raman spectroscopy and time-of-flight secondary ion mass spectroscopy analyses. *Thin Solid Films, 515*(5), 2879-2884.

[12] Ilyas, U., Rawat, R. S., Tan, T. L., Lee, P., Chen, R., Sun, H. D., ... & Zhang, S. (2011). Oxygen rich p-type ZnO thin films using wet chemical route with enhanced carrier concentration by temperature-dependent tuning of acceptor defects. *Journal of Applied Physics, 110*(9), 093522.

[13] Przeździecka, E., Kamińska, E., Pasternak, I., Piotrowska, A., & Kossut, J. (2007). Photoluminescence study of p-type ZnO: Sb prepared by thermal oxidation of the Zn-Sb starting material. *Physical Review B, 76*(19), 193303.

[14] Park, C., Zhang, S., & Wei, S.-H. (2002). Origin of p-type doping difficulty in ZnO: The impurity perspective. *Physical Review B, 66*(7), 073202.

[15] Özgür, Ü., Y. I. Alivov, et al. (2005). "A comprehensive review of ZnO materials and devices." Journal of applied physics 98(4): 041301.

[16] Shariffudin, S. S., Ibrahim, M. H., Zulkifli, Z., Hamzah, A. S., & Rusop, M. (2010). *The optical properties of nanocomposite MEH-PPV: ZnO thin films.* Paper presented at the Enabling Science and Nanotechnology (ESciNano), 2010 International Conference on.

[17] Ximello-Quiebras, J. (2004). "Physical properties of chemical bath deposited CdS thin films." Solar energy materials and solar cells 82(1): 263-268.

[18] Yu, K., Lakhani, A., & Wu, M. C. (2010). Subwavelength metal-optic semiconductor nanopatch lasers. *Optics express, 18*(9), 8790-8799.

[19] Gu, Y., I. L. Kuskovsky, et al. (2004). "Quantum confinement in ZnO nanorods." Applied physics letters 85(17): 3833-3835.

[20] Wu, J., Shao, D., Li, Z., Manasreh, M., Kunets, V. P., Wang, Z. M., et al. (2009). Intermediate-band material based on GaAs quantum rings for solar cells. *Applied Physics Letters, 95*(7), 071908.

[21] Chen, X., J. Yang, et al. (2009). "Ionic liquid-functionalized carbon nanoparticles-modified cathode for efficiency enhancement in polymer solar cells." Applied Physics Letters 95(13): 133305.

[22] Weng, W., Chang, S., Hsu, C., & Hsueh, T. (2011). A ZnO-nanowire phototransistor prepared on glass substrates. *ACS applied materials & interfaces, 3*(2), 162-166.

[23] Liu, C., Yiu, W., Au, F., Ding, J., Lee, C., & Lee, S. (2003). Electrical properties of zinc oxide nanowires and intramolecular p–n junctions. *Applied physics letters, 83*(15), 3168-3170.

[24] Cao, B. and W. Cai (2008). "From ZnO nanorods to nanoplates: chemical bath deposition growth and surface-related emissions." The Journal of Physical Chemistry C 112(3): 680-685.

[25] Xia, X., Tu, J., Zhang, Y., Wang, X., Gu, C., Zhao, X.-b., et al. (2012). High-quality metal oxide core/shell nanowire arrays on conductive substrates for electrochemical energy storage. *ACS nano, 6*(6), 5531-5538.

[26] McPeak, K. M., & Baxter, J. B. (2009). Microreactor for high-yield chemical bath deposition of semiconductor nanowires: ZnO nanowire case study. *Industrial & Engineering Chemistry Research, 48*(13), 5954-5961.

[27] Yodyingyong, S., Zhang, Q., Park, K., Dandeneau, C. S., Zhou, X., Triampo, D., et al. (2010). ZnO nanoparticles and nanowire array hybrid photoanodes for dye-sensitized solar cells. *Applied Physics Letters, 96*(7), 073115.

[28] Soci, C., A. Zhang, et al. (2007). "ZnO nanowire UV photodetectors with high internal gain." Nano letters 7(4): 1003-1009.

[29] Xie, J., P. Li, et al. (2009). "Synthesis of needle-and flower-like ZnO microstructures by a simple aqueous solution route." Journal of Physics and Chemistry of Solids 70(1): 112-116.

[30] Ashrafi, A. A., Ueta, A., Avramescu, A., Kumano, H., Suemune, I., Ok, Y. W., & Seong, T. Y. (2000). Growth and characterization of hypothetical zinc-blende ZnO films on GaAs (001) substrates with ZnS buffer layers. *Applied Physics Letters*, *76*(5), 550-552.

[31] Kim, S. K., Jeong, S. Y., & Cho, C. R. (2003). Structural reconstruction of hexagonal to cubic ZnO films on Pt/Ti/SiO2/Si substrate by annealing.*Applied Physics Letters*, *82*, 562.

[32] Tanigaki, T., Kimura, S., Tamura, N., & Kaito, C. (2002). A new preparation method of ZnO cubic phase particle and its IR spectrum. *Japanese journal of applied physics, 41*(9R), 5529.

[33] Decremps, F., Zhang, J., & Liebermann, R. C. (2000). New phase boundary

and high-pressure thermoelasticity of ZnO. *EPL (Europhysics Letters)*, *51*(3), 268.

[34] Wang, Z. L. (2004). Zinc oxide nanostructures: growth, properties and applications. *Journal of Physics: Condensed Matter*, *16*(25), R829.

[35] Reynolds, D. C., Look, D. C., & Jogai, B. (1996). Optically pumped ultraviolet lasing from ZnO. *Solid State Communications*, *99*(12), 873-875.

[36] D.M. Bagnall, Y.F. Chen, Z. Zhu, T. Yao, S. Koyama, M.Y. Shen, and T. Goto,Optically pumped lasing of ZnO at room temperature, *Appl. Phys. Lett.*, 70,2230−2232, 1997.

[37] Klingshirn, C., Hauschild, R., Fallert, J., & Kalt, H. (2007). Room-temperature stimulated emission of ZnO: Alternatives to excitonic lasing.*Physical Review B*, *75*(11), 115203.

[38] Chen, Y., Tuan, N. T., Segawa, Y., Ko, H. J., Hong, S. K., & Yao, T. (2001). Stimulated emission and optical gain in ZnO epilayers grown by plasma-assisted molecular-beam epitaxy with buffers. *Applied Physics Letters*,*78*(11), 1469-1471.

[39] Makino, T., Segawa, Y., Kawasaki, M., Ohtomo, A., Shiroki, R., Tamura, K., ... & Koinuma, H. (2001). Band gap engineering based on Mg x Zn 1-x O and Cd y Zn 1-y O ternary alloy films. *Applied Physics Letters*, *78*(9), 1237-1239.

[40] Gruber, T., Kirchner, C., Kling, R., Reuss, F., & Waag, A. (2004). ZnMgO epilayers and ZnO-ZnMgO quantum wells for optoelectronic applications in the blue and UV spectral region. *Applied physics letters*, *84*, 5359.

[41] Gruber, T., Kirchner, C., Kling, R., Reuss, F., Waag, A., Bertram, F., ... & Schreck, M. (2003). Optical and structural analysis of ZnCdO layers grown by metalorganic vapor-phase epitaxy. *Applied physics letters*, *83*(16), 3290-3292.

[42] Ohtomo, A., Tamura, K., Kawasaki, M., Makino, T., Segawa, Y., Tang, Z. K., ... & Koinuma, H. (2000). Room-temperature stimulated emission of excitons in ZnO/(Mg, Zn) O superlattices. *Applied Physics Letters*, *77*(14), 2204-2206.

[43] Fujita, S., Tanaka, H., & Fujita, S. (2005). MBE growth of wide band gap wurtzite MgZnO quasi-alloys with MgO/ZnO superlattices for deep ultraviolet optical functions. *Journal of crystal growth*, *278*(1), 264-267.

[44] Thompson, A. V., Boutwell, C., Mares, J. W., Schoenfeld, W. V., Osinsky, A., Hertog, B., ... & Norton, D. P. (2007). Thermal stability of CdZnO/ZnO multi-quantum-wells. *Applied Physics Letters*, *91*(20), 1921.

[45] Vanheusden, K., Warren, W. L., Seager, C. H., Tallant, D. R., Voigt, J. A., & Gnade, B. E. (1996). Mechanisms behind green photoluminescence in ZnO phosphor powders. *Journal of Applied Physics*, *79*(10), 7983-7990.

[46] Shan, W., Walukiewicz, W., Ager III, J. W., Yu, K. M., Yuan, H. B., Xin, H. P., ... & Song, J. J. (2004). Nature of room-temperature photoluminescence in ZnO. *Lawrence Berkeley National Laboratory*.

[47] Djurišić, A. B., Leung, Y. H., Choy, W. C., Cheah, K. W., & Chan, W. K. (2004). Visible photoluminescence in ZnO tetrapod and multipod structures.*Applied physics letters*, *84*(14), 2635-2637.

[48] Zhang, D. H., Wang, Q. P., & Xue, Z. Y. (2003). Photoluminescence of ZnO films excited with light of different wavelength. *Applied Surface Science*,*207*(1), 20-25.

[49] Usui, H., Shimizu, Y., Sasaki, T., & Koshizaki, N. (2005). Photoluminescence of ZnO nanoparticles prepared by laser ablation in different surfactant solutions. *The Journal of Physical Chemistry B*, *109*(1), 120-124.

[50] Fujihara, S., Ogawa, Y., & Kasai, A. (2004). Tunable visible photoluminescence from ZnO thin films through Mg-doping and annealing. *Chemistry of materials*, *16*(15), 2965-2968.

[51] Chen, T., Xing, G. Z., Zhang, Z., Chen, H. Y., & Wu, T. (2008). Tailoring the photoluminescence of ZnO nanowires using Au nanoparticles. *Nanotechnology*, *19*(43), 435711.

[52] Zhang, Y., Zhang, Z., Lin, B., Fu, Z., & Xu, J. (2005). Effects of Ag doping on the photoluminescence of ZnO films grown on Si substrates. *The Journal of Physical Chemistry B*, *109*(41), 19200-19203.

[53] Özgür, Ü., Alivov, Y. I., Liu, C., Teke, A., Reshchikov, M., Doğan, S., ... & Morkoc, H. (2005). A comprehensive review of ZnO materials and devices.*Journal of applied physics*, *98*(4), 041301.

[54] Wang, Z. L. (2009). ZnO nanowire and nanobelt platform for nanotechnology.*Materials Science and Engineering: R: Reports*, *64*(3), 33-71.

[55] Choi, H. W. (2012). *1-Dimensional Zinc Oxide Nanomaterial Growth and Solar Cell Applications* (Doctoral dissertation, Arizona State University).

[56] Park, W. I., Kim, D. H., Jung, S. W., & Yi, G. C. (2002). Metalorganic vapor-phase epitaxial growth of vertically well-aligned ZnO nanorods. *Applied Physics Letters*, *80*(22), 4232-4234.

[57] Raoufi, D., & Raoufi, T. (2009). The effect of heat treatment on the physical properties of sol–gel derived ZnO thin films. *Applied Surface Science*, *255*(11), 5812-5817.

[58] Gong, Lv, J., W., Huang, K., Zhu, J., Meng, F., Song, X., & Sun, Z. (2011). Effect of annealing temperature on photocatalytic activity of ZnO thin films prepared by sol–gel method. *Superlattices and Microstructures*, *50*(2), 98-106.

[59] Ahmed, N. A., Fortas, G., Hammache, H., Sam, S., Keffous, A., Manseri, A., & Gabouze, N. (2010). Structural and morphological study of ZnO thin films electrodeposited on n-type silicon. *Applied Surface Science*, *256*(24), 7442-7445.

[60] Cai, R., Hashimoto, K., Kubota, Y., & Fujishima, A. (1992). Increment of Photocatalytic Killing of Cancer Cells Using TiO2 with the Aid of Superoxide Dismutase. *Chemistry Letters*, (3), 427-430.

[61] Sclafani, A., & Herrmann, J. M. (1996). Comparison of the photoelectronic and photocatalytic activities of various anatase and rutile forms of titania in pure liquid organic phases and in aqueous solutions. *The Journal of Physical Chemistry*, *100*(32), 13655-13661.

[62] Kawaguchi, H. (1984). Photocatalytic decomposition of phenol in the presence of titanium dioxide. *Environmental Technology*, *5*(1-11), 471-474.

[63] Kohan, A. F., Ceder, G., Morgan, D., & Van de Walle, C. G. (2000). First-principles study of native point defects in ZnO. *Physical Review B*, *61*(22), 15019.

[64] Janotti, A., & Van de Walle, C. G. (2009). Fundamentals of zinc oxide as a semiconductor. *Reports on Progress in Physics*, *72*(12), 126501.

[65] Mkawi, E. M., Ibrahim, K., Ali, M. K. M., Farrukh, M. A., & Mohamed, A. S. (2015). The effect of dopant concentration on properties of transparent conducting Al-doped ZnO thin films for efficient Cu2ZnSnS4 thin-film solar

cells prepared by electrodeposition method. Applied Nanoscience, 5(8), 993-1001.

[66] Shakti, N., & Gupta, P. S. (2010). Structural and optical properties of sol-gel prepared ZnO thin film. *Applied Physics Research*, *2*(1), 19.

[67] Meyer, B. K., Alves, H., Hofmann, D. M., Kriegseis, W., Forster, D., Bertram, F., ... & Haboeck, U. (2004). Bound exciton and donor–acceptor pair recombinations in ZnO. *physica status solidi (b)*, *241*(2), 231-260.

[68] Oosterhout, S. D., & Wienk, M. M. (2009). SS v. Bavel, R. Thiedmann, LJA Koster, J. Gilot, J. Loos, V. Schmidt and RAJ Janssen. *Nat. Mater*, *8*, 818-824.

[69] Choi, H. W. (2012). *1-Dimensional Zinc Oxide Nanomaterial Growth and Solar Cell Applications* (Doctoral dissertation, Arizona State University).

[70] Li, S. Y., Lee, C. Y., & Tseng, T. Y. (2003). Copper-catalyzed ZnO nanowires on silicon (100) grown by vapor–liquid–solid process. *Journal of Crystal Growth*, *247*(3), 357-362.

[71] Vanheusden, K., Warren, W. L., Seager, C. H., Tallant, D. R., Voigt, J. A., & Gnade, B. E. (1996). Mechanisms behind green photoluminescence in ZnO phosphor powders. *Journal of Applied Physics*, *79*(10), 7983-7990.

[72] Yamauchi, S., Goto, Y., & Hariu, T. (2004). Photoluminescence studies of undoped and nitrogen-doped ZnO layers grown by plasma-assisted epitaxy. *Journal of Crystal Growth*, *260*(1), 1-6.

[73] Q. X. Zhao, P. Klason, M. Willander, H. M. Zhong, W. Lu, and J. H. Yang, Deep-level emissions influenced by O and Zn implantations in ZnO, Appl. Phys. Lett. 87 (2005) 211912-1-3.

[74] Yang, X., Du, G., Wang, X., Wang, J., Liu, B., Zhang, Y., ... & Yang, S. (2003). Effect of post-thermal annealing on properties of ZnO thin film grown on c-Al 2 O 3 by metal-organic chemical vapor deposition. *Journal of crystal growth*, *252*(1), 275-278.

[75] Zhao, Q. X., Klason, P., Willander, M., Zhong, H. M., Lu, W., & Yang, J. H. (2005). Deep-level emissions influenced by O and Zn implantations in ZnO. *Applied Physics Letters*, *87*(21), 211912.

[76] T. Moe B̋rseth, B. G. Svensson, A. Yu. Kuznetsov, P. Klason, Q. X. Zhao, and M. Willander, Identification of oxygen and zinc vacancy optical signals in ZnO, Appl. Phys. Lett. 89 (2006) 262112-1-3.

[77] Meyer, B. K., Alves, H., Hofmann, D. M., Kriegseis, W., Forster, D., Bertram, F., & Haboeck, U. (2004). Bound exciton and donor–acceptor pair recombinations in ZnO. *physica status solidi (b)*, *241*(2), 231-260.

[78] Guo, L., Ji, Y. L., Xu, H., Simon, P., & Wu, Z. (2002). Regularly shaped, single-crystalline ZnO nanorods with wurtzite structure. *Journal of the American Chemical Society*, *124*(50), 14864-14865.

[79] Xu, S., Qin, Y., Xu, C., Wei, Y., Yang, R., & Wang, Z. L. (2010). Self-powered nanowire devices. *Nature nanotechnology*, *5*(5), 366-373.

[80] Lu, J. G., Chang, P., & Fan, Z. (2006). Quasi-one-dimensional metal oxide materials—Synthesis, properties and applications. *Materials Science and Engineering: R: Reports*, *52*(1), 49-91.

[81] Yan, M., Zhang, H. T., Widjaja, E. J., & Chang, R. P. H. (2003). Self-assembly of well-aligned gallium-doped zinc oxide nanorods. *Journal of applied physics*, *94*(8), 5240-5246.

[82] Nguyen, P., Ng, H. T., & Meyyappan, M. (2005). Catalyst metal selection for synthesis of inorganic nanowires. *Advanced Materials*, *17*(14), 1773-1777.

[83] Chik, H., Liang, J., Cloutier, S. G., Kouklin, N., & Xu, J. M. (2004). Periodic array of uniform ZnO nanorods by second-order self-assembly. *Applied physics letters*, *84*(17), 3376-3378.

[84] Wang, X., Summers, C. J., & Wang, Z. L. (2004). Large-scale hexagonal-patterned growth of aligned ZnO nanorods for nano-optoelectronics and nanosensor arrays. *Nano Letters*, *4*(3), 423-426.

[85] Zhang, B. P., Binh, N. T., Wakatsuki, K., Segawa, Y., Kashiwaba, Y., & Haga, K. (2004). Synthesis and optical properties of single crystal ZnO nanorods. *Nanotechnology*, *15*(6), S382.

[86] Zhang, B., Binh, N., Wakatsuki, K., Segawa, Y., Yamada, Y., Usami, N., et al. (2004). Formation of highly aligned ZnO tubes on sapphire (0001) substrates. *Applied physics letters*, *84*(20), 4098-4100.

[87] Zhang, B. P., Wakatsuki, K., Binh, N. T., Segawa, Y., & Usami, N. (2004). Low-temperature growth of ZnO nanostructure networks. *Journal of applied physics*, *96*(1), 340-343.

[88] Xie, R., Su, J., Li, M., & Guo, L. (2013). Structural and photoelectrochemical properties of Cu-doped CdS thin films prepared by ultrasonic spray pyrolysis.*International Journal of Photoenergy*, *2013*.

[89] Greene, L. E., Law, M., Tan, D. H., Montano, M., Goldberger, J., Somorjai, G., & Yang, P. (2005). General route to vertical ZnO nanowire arrays using textured ZnO seeds. *Nano Letters*, *5*(7), 1231-1236.

[90] Boercker, J. E., Schmidt, J. B., & Aydil, E. S. (2009). Transport limited growth of zinc oxide nanowires. *Crystal Growth and Design*, *9*(6), 2783-2789.

[91] Hsueh, T. J., Hsu, C. L., Chang, S. J., & Chen, I. C. (2007). Laterally grown ZnO nanowire ethanol gas sensors. *Sensors and Actuators B: Chemical*,*126*(2), 473-477.

[92] Saurakhiya, N., Sharma, S. K., Kumar, R., & Sharma, A. (2014). Templated Electrochemical Synthesis of Polyaniline/ZnO Coaxial Nanowires with Enhanced Photoluminescence. *Industrial & Engineering Chemistry Research*, *53*(49), 18884-18890.

[93] Wang, Z. L. (2004). Zinc oxide nanostructures: growth, properties and applications. *Journal of Physics: Condensed Matter*, *16*(25), R829.

[94] Baruah, S., & Dutta, J. (2009). pH-dependent growth of zinc oxide nanorods.*Journal of Crystal Growth*, *311*(8), 2549-2554.

[95] Gao, P. X., & Wang, Z. L. (2005). Nanoarchitectures of semiconducting and piezoelectric zinc oxide. *Journal of Applied physics*, *97*(4), 044304.

[96] Willander, M., Nur, O., Zhao, Q. X., Yang, L. L., Lorenz, M., Cao, B. Q., ... & Bakin, A. (2009). Zinc oxide nanorod based photonic devices: recent progress in growth, light emitting diodes and lasers. *Nanotechnology*, *20*(33), 332001.

[97] Weintraub, B., Zhou, Z., Li, Y., & Deng, Y. (2010). Solution synthesis of one-dimensional ZnO nanomaterials and their applications. *Nanoscale*, *2*(9), 1573-1587.

[98] Zhang, L., & Zhu, Y. J. (2009). ZnO micro-and nano-structures: microwave-assisted solvothermal synthesis, morphology control and photocatalytic properties. *Applied Physics A*, *97*(4), 847-852.

[99] Baruah, S., & Dutta, J. (2016). Hydrothermal growth of ZnO nanostructures.*Science and Technology of Advanced Materials*.

[100] Kitamura, K., Yatsui, T., Ohtsu, M., & Yi, G. C. (2008). Fabrication of vertically aligned ultrafine ZnO nanorods using metal–organic vapor phase epitaxy with a two-temperature growth method. *Nanotechnology*, *19*(17), 175305.

[101] Sudhagar, P., Kumar, R. S., Jung, J. H., Cho, W., Sathyamoorthy, R., Won, J., & Kang, Y. S. (2011). Facile synthesis of highly branched jacks-like ZnO nanorods and their applications in dye-sensitized solar cells. *Materials Research Bulletin*, *46*(9), 1473-1479.

[102] Hu, H., Huang, X., Deng, C., Chen, X., & Qian, Y. (2007). Hydrothermal synthesis of ZnO nanowires and nanobelts on a large scale. *Materials Chemistry and Physics*, *106*(1), 58-62.

[103] Hughes, W. L., & Wang, Z. L. (2005). Controlled synthesis and manipulation of ZnO nanorings and nanobows. *Applied Physics Letters*, *86*(4), 043106.

[104] Brewster, M. M., Lu, M. Y., Lim, S. K., Smith, M. J., Zhou, X., & Gradecak, S. (2011). The growth and optical properties of ZnO nanowalls. *The Journal of Physical Chemistry Letters*, *2*(15), 1940-1945.

[105] Yu, K., Zhang, Q., Wu, J., Li, L., Xu, Y. E., Huang, S., & Zhu, Z. (2008). Growth and optical applications of centimeter-long ZnO nanocombs. *Nano Research*, *1*(3), 221-228.

[106] Barka-Bouaifel, F., Sieber, B., Bezzi, N., Benner, J., Roussel, P., Boussekey, L., ... & Boukherroub, R. (2011). Synthesis and photocatalytic activity of iodine-doped ZnO nanoflowers. *Journal of Materials Chemistry*,*21*(29), 10982-10989.

[107] Gao, P. X., Mai, W., & Wang, Z. L. (2006). Superelasticity and nanofracture mechanics of ZnO nanohelices. *Nano letters*, *6*(11), 2536-2543.

[108] Zhang, T., Dong, W., Keeter-Brewer, M., Konar, S., Njabon, R. N., & Tian, Z. R. (2006). Site-specific nucleation and growth kinetics in hierarchical nanosyntheses of branched ZnO crystallites. *Journal of the American Chemical Society*, *128*(33), 10960-10968.

[109] Cheng, C., Liu, B., Yang, H., Zhou, W., Sun, L., Chen, R., ... & Fan, H. J. (2009). Hierarchical assembly of ZnO nanostructures on SnO2 backbone nanowires: Low-temperature hydrothermal preparation and optical properties.*ACS nano*, *3*(10), 3069-3076.

[110] Yao, B. D., Chan, Y. F., & Wang, N. (2002). Formation of ZnO nanostructures by a simple way of thermal evaporation. *Applied Physics Letters*, *81*(4), 757-759.

[111] Park, W. I., Yi, G. C., Kim, M., & Pennycook, S. J. (2002). ZnO Nanoneedles Grown Vertically on Si Substrates by Non-Catalytic Vapor-Phase Epitaxy. *Advanced Materials*, *14*(24), 1841-1843.

[112] Yuan, H., & Zhang, Y. (2004). Preparation of well-aligned ZnO whiskers on glass substrate by atmospheric MOCVD. *Journal of crystal growth*, *263*(1), 119-124.

[113] Sun, Y., Fuge, G. M., & Ashfold, M. N. (2004). Growth of aligned ZnO nanorod arrays by catalyst-free pulsed laser deposition methods. *Chemical Physics Letters*, *396*(1), 21-26.

[114] Hong, J. I., Bae, J., Wang, Z. L., & Snyder, R. L. (2009). Room-temperature, texture-controlled growth of ZnO thin films and their application for growing aligned ZnO nanowire arrays. *Nanotechnology*, *20*(8), 085609.

[115] Tang, W., Hou, Y., Wang, F., Liu, L., Wu, Y., & Zhu, K. (2013). LiMn2O4 nanotube as cathode material of second-level charge capability for aqueous rechargeable batteries. *Nano letters*, *13*(5), 2036-2040.

[116] Xu, J., Pan, Q., & Tian, Z. (2000). Grain size control and gas sensing properties of ZnO gas sensor. *Sensors and Actuators B: Chemical*, *66*(1), 277-279.

[117] Zhang, F., Wang, X., Ai, S., Sun, Z., Wan, Q., Zhu, Z., ... & Yamamoto, K. (2004). Immobilization of uricase on ZnO nanorods for a reagentless uric acid biosensor. *Analytica Chimica Acta*, *519*(2), 155-160.

[118] Song, Y. Y., Lynch, R., Kim, D., Roy, P., & Schmuki, P. (2009). TiO2 nanotubes: efficient suppression of top etching during anodic growth key to improved high aspect ratio geometries. *Electrochemical and Solid-State Letters*, *12*(7), C17-C20.

[119] Hu, L., Ma, L., Hu, H., Zhang, Y., & Guo, T. (2015). Improving the field emission characteristics of tetrapod-like zinc oxide nanostructures by coating with silver nanowires. *Materials Letters*, *150*, 93-96.

[120] Akbarzadeh, A., Samiei, M., & Davaran, S. (2012). Magnetic nanoparticles: preparation, physical properties, and applications in biomedicine. *Nanoscale research letters*, *7*(1), 1-13.

[121] Xu, A. W., Antonietti, M., Cölfen, H., & Fang, Y. P. (2006). Uniform hexagonal plates of vaterite CaCO3 mesocrystals formed by biomimetic mineralization. *Advanced Functional Materials*, *16*(7), 903-908.

[122] Gao, P. X., & Wang, Z. L. (2004). Substrate atomic-termination-induced anisotropic growth of ZnO nanowires/nanorods by the VLS process. *The Journal of Physical Chemistry B*, *108*(23), 7534-7537.

[123] Ramirez, D., Pauporte, T., Gomez, H., & Lincot, D. (2008). Electrochemical growth of ZnO nanowires inside nanoporous alumina templates. A comparison with metallic Zn nanowires growth. *physica status solidi (a)*,*205*(10), 2371-2375.

[124] Willander, M., Nur, O., Zhao, Q. X., Yang, L. L., Lorenz, M., Cao, B. Q., ... & Bakin, A. (2009). Zinc oxide nanorod based photonic devices: recent progress in growth, light emitting diodes and lasers. *Nanotechnology*, *20*(33), 332001.

[125] Shi, R., Yang, P., Dong, X., Ma, Q., & Zhang, A. (2013). Growth of flower-like ZnO on ZnO nanorod arrays created on zinc substrate through low-temperature hydrothermal synthesis. *Applied Surface Science*, *264*, 162-170.

[126] Hatch, S. M., Briscoe, J., & Dunn, S. (2013). A Self-Powered ZnO-Nanorod/CuSCN UV Photodetector Exhibiting Rapid Response. *Advanced Materials*, *25*(6), 867-871.

[127] Chen, Z., & Gao, L. (2006). A facile route to ZnO nanorod arrays using wet chemical method. *Journal of Crystal growth*, *293*(2), 522-527.

[128] Wahab, R., Ansari, S. G., Kim, Y. S., Seo, H. K., Kim, G. S., Khang, G., & Shin, H. S. (2007). Low temperature solution synthesis and characterization of ZnO nano-flowers. *Materials Research Bulletin*, *42*(9), 1640-1648.

[129] Li, B., & Wang, Y. (2009). Facile synthesis and enhanced photocatalytic performance of flower-like ZnO hierarchical microstructures. *The Journal of Physical Chemistry C*, *114*(2), 890-896.

[130] Wang, Z., Qian, X. F., Yin, J., & Zhu, Z. K. (2004). Large-scale fabrication of tower-like, flower-like, and tube-like ZnO arrays by a simple chemical solution route. *Langmuir*, *20*(8), 3441-3448.

[131] Xu, F., Yuan, Z. Y., Du, G. H., Ren, T. Z., Volcke, C., Thiry, P., & Su, B. L. (2006). A low-temperature aqueous solution route to large-scale growth of ZnO nanowire arrays. Journal of non-crystalline solids, 352(23), 2569-2574.

[132] Lu, C., Qi, L., Yang, J., Tang, L., Zhang, D., & Ma, J. (2006). Hydrothermal growth of large-scale micropatterned arrays of ultralong ZnO nanowires and nanobelts on zinc substrate. Chemical Communications, (33), 3551-3553.

[133] Vergés, M. A., Mifsud, A., & Serna, C. J. (1990). Formation of rod-like zinc oxide microcrystals in homogeneous solutions. Journal of the Chemical Society, Faraday Transactions, 86(6), 959-963.

[134] Govender, K., Boyle, D. S., Kenway, P. B., & O'Brien, P. (2004). Understanding the factors that govern the deposition and morphology of thin films of ZnO from aqueous solution. *Journal of Materials Chemistry*, *14*(16), 2575-2591.

[135] Liu, J., She, J., Deng, S., Chen, J., & Xu, N. (2008). Ultrathin seed-layer for tuning density of ZnO nanowire arrays and their field emission characteristics. *The Journal of Physical Chemistry C, 112*(31), 11685-11690.

[136] Song, J., & Lim, S. (2007). Effect of seed layer on the growth of ZnO nanorods. The Journal of Physical Chemistry C, 111(2), 596-600.

[137] Xu, C., Shin, P., Cao, L., & Gao, D. (2009). Preferential growth of long ZnO nanowire array and its application in dye-sensitized solar cells. The Journal of Physical Chemistry C, 114(1), 125-129.

[138] Greene, L. E., Yuhas, B. D., Law, M., Zitoun, D., & Yang, P. (2006). Solution-grown zinc oxide nanowires. Inorganic chemistry, 45(19), 7535-7543.

[139] Baxter, J. B., Walker, A. M., Van Ommering, K., & Aydil, E. S. (2006). Synthesis and characterization of ZnO nanowires and their integration into dye-sensitized solar cells. Nanotechnology, 17(11), S304.

[140] Vayssieres, L. (2003). Growth of arrayed nanorods and nanowires of ZnO from aqueous solutions. Advanced Materials, 15(5), 464-466.

[141] Sugunan, A., Warad, H. C., Boman, M., & Dutta, J. (2006). Zinc oxide nanowires in chemical bath on seeded substrates: role of hexamine. Journal of Sol-Gel Science and Technology, 39(1), 49-56.

[142] Bang, S., Lee, S., Ko, Y., Park, J., Shin, S., Seo, H., & Jeon, H. (2012). Photocurrent detection of chemically tuned hierarchical ZnO nanostructures grown on seed layers formed by atomic layer deposition. Nanoscale research letters, 7(1), 1.

[143] Lee, J. H., Ko, K. H., & Park, B. O. (2003). Electrical and optical properties of ZnO transparent conducting films by the sol–gel method. Journal of Crystal Growth, 247(1), 119-125.

[144] Srinivasan, G., Gopalakrishnan, N., Yu, Y. S., Kesavamoorthy, R., & Kumar, J. (2008). Influence of post-deposition annealing on the structural and optical properties of ZnO thin films prepared by sol–gel and spin-coating method. Superlattices and Microstructures, 43(2), 112-119.

[145] Xue, S. W., Zu, X. T., Shao, L. X., Yuan, Z. L., Zheng, W. G., Jiang, X. D., & Deng, H. (2008). Effects of annealing on optical properties of Zn-implanted ZnO thin films. Journal of Alloys and Compounds, 458(1), 569-573.

[146] Delgado, G. T., Romero, C. Z., Hernández, S. M., Pérez, R. C., & Angel, O. Z. (2009). Optical and structural properties of the sol–gel-prepared ZnO thin films and their effect on the photocatalytic activity. Solar Energy Materials and Solar Cells, 93(1), 55-59.

[147] Vayssieres, L., Keis, K., Lindquist, S. E., & Hagfeldt, A. (2001). Purpose-built anisotropic metal oxide material: 3D highly oriented microrod array of ZnO. *The Journal of Physical Chemistry B*, *105*(17), 3350-3352.

[148] Dreyfors, J. M., Jones, S. B., & SAYED, Y. (1989). Hexamethylenetetramine: a review. *The American Industrial Hygiene Association Journal*, *50*(11), 579-585.

[149] Govender, K., Boyle, D. S., Kenway, P. B., & O'Brien, P. (2004). Understanding the factors that govern the deposition and morphology of thin films of ZnO from aqueous solution. *Journal of Materials Chemistry*, *14*(16), 2575-2591.

[150] Ma, S., Fang, G., Li, C., Sheng, S., Fang, L., Fu, Q., & Zhao, X. Z. (2006). Controllable synthesis of vertically aligned ZnO nanorod arrays in aqueous solution. *Journal of nanoscience and nanotechnology*, *6*(7), 2062-2066.

[151] Ladanov, M., Ram, M. K., Matthews, G., & Kumar, A. (2011). Structure and opto-electrochemical properties of ZnO nanowires grown on n-Si substrate.*Langmuir*, *27*(14), 9012-9017.

[152] Gao, Y., Nagai, M., Chang, T. C., & Shyue, J. J. (2007). Solution-derived ZnO nanowire array film as photoelectrode in dye-sensitized solar cells. *Crystal Growth and Design*, *7*(12), 2467-2471.

[153] Zhou, Z., & Deng, Y. (2009). Kinetics study of ZnO nanorod growth in solution. *The Journal of Physical Chemistry C*, *113*(46), 19853-19858.

[154] Ghayour, H., Rezaie, H. R., Mirdamadi, S., & Nourbakhsh, A. A. (2011). The effect of seed layer thickness on alignment and morphology of ZnO nanorods.*Vacuum*, *86*(1), 101-105.

[155] Shi, L., Bao, K., Cao, J., & Qian, Y. (2009). Sunlight-assisted fabrication of a hierarchical ZnO nanorod array structure. CrystEngComm, 11(9).

[156] Govender, K., Boyle, D. S., Kenway, P. B., & O'Brien, P. (2004). Understanding the factors that govern the deposition and morphology of thin films of ZnO from aqueous solution. Journal of Materials Chemistry, 14(16), 2575-2591.

[157] Trindade, T., de Jesus, J. D. P., & O'Brien, P. (1994). Preparation of zinc oxide and zinc sulfide powders by controlled precipitation from aqueous solution. Journal of Materials Chemistry, 4(10), 1611-1617.

[158] Chittofrati, A., & Matijević, E. (1990). Uniform particles of zinc oxide of different morphologies. Colloids and Surfaces, 48, 65-78.

[159] Becquerel, A. E. (1839). Photoelctrochemical effect. CR Acad. Sci. Paris, 9, 14.

[160] Zhang, Z. (2008). Enhancing the open-circuit voltage of dye-sensitized solar cells: coadsorbents and alternative redox couples (Doctoral dissertation, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE).

[161] Einstein, A. (1905). Un the movement of small particles suspended in statiunary liquids required by the molecular-kinetic theory 0f heat. Ann. Phys, 17, 549-560.

[162] Katzir, S. (2010). War and Peacetime Research on the Road to Crystal Frequency Control. Technology and Culture, 51(1), 99-125.

[163] Perlin, J. (1999). From space to earth: the story of solar electricity. Earthscan.

[164] Gonçalves, L. M., de Zea Bermudez, V., Ribeiro, H. A., & Mendes, A. M. (2008). Dye-sensitized solar cells: A safe bet for the future. Energy & Environmental Science, 1(6), 655-667.

[165] Perlin, J. (1999). From space to earth: the story of solar electricity. Earthscan.

[166] Garnett, E. C., & Yang, P. (2008). Silicon nanowire radial p− n junction solar cells. Journal of the American Chemical Society, 130(29), 9224-9225.

[167] Hoppe, H., & Sariciftci, N. S. (2007). Polymer solar cells. In Photoresponsive Polymers II (pp. 1-86). Springer Berlin Heidelberg.

[168] Kazmerski, L. L. (2011). National Renewable Energy Laboratory (NREL). Golden, Co.

[169] Bookbinder, D. C., Bruce, J. A., Dominey, R. N., Lewis, N. S., & Wrighton, M. S. (1980). Synthesis and characterization of a photosensitive interface for hydrogen generation: Chemically modified p-type semiconducting silicon photocathodes. Proceedings of the National Academy of Sciences, 77(11), 6280-6284.

[170] O'regan, B., & Grfitzeli, M. (1991). A low-cost, high-efficiency solar cell based on dye-sensitized. nature, 353(6346), 737-740.

[171] Snaith, H. J., Moule, A. J., Klein, C., Meerholz, K., Friend, R. H., & Grätzel, M. (2007). Efficiency enhancements in solid-state hybrid solar cells via reduced charge recombination and increased light capture. Nano Letters, 7(11), 3372-3376.

[172] O'regan, B., & Grfitzeli, M. (1991). A low-cost, high-efficiency solar cell based on dye-sensitized. nature, 353(6346), 737-740.

[173] Jose, R., Thavasi, V., & Ramakrishna, S. (2009). Metal oxides for dye-sensitized solar cells. Journal of the American Ceramic Society, 92(2), 289-301.

[174] Jose, R., Thavasi, V., & Ramakrishna, S. (2009). Metal Oxides for Dye-Sensitized Solar Cells. Journal of the American Ceramic Society, 92(2), 289-301.

[175] Bisquert, J., Cahen, D., Hodes, G., Rühle, S., & Zaban, A. (2004). Physical chemical principles of photovoltaic conversion with nanoparticulate, mesoporous dye-sensitized solar cells. The Journal of Physical Chemistry B, 108(24), 8106-8118.

[176] Snaith, H. J., & Schmidt-Mende, L. (2007). Advances in liquid-electrolyte and solid-state dye-sensitized solar cells. Advanced Materials, 19(20), 3187-3200.

[177] Xu, C., Wu, J., Desai, U. V., & Gao, D. (2011). Multilayer assembly of nanowire arrays for dye-sensitized solar cells. Journal of the American Chemical Society, 133(21), 8122-8125.

[178] Xu, F., Dai, M., Lu, Y., & Sun, L. (2010). Hierarchical ZnO nanowire−nanosheet architectures for high power conversion efficiency in dye-sensitized solar cells. The Journal of Physical Chemistry C, 114(6), 2776-2782.

[179] Baxter, J. B., & Aydil, E. S. (2006). Dye-sensitized solar cells based on semiconductor morphologies with ZnO nanowires. Solar Energy Materials and Solar Cells, 90(5), 607-622.

[180] Wu, M. K., Ling, T., Xie, Y., Huang, X. G., & Du, X. W. (2011). Performance comparison of dye-sensitized solar cells with different ZnO photoanodes. Semiconductor Science and Technology, 26(10), 105001.

[181] Rogers, J. A., Efimov, I., Gutbrod, S., Xu, L., Bonifas, A., Webb, R. C., & Ahyeon, K. O. H. (2014). U.S. Patent Application No. 14/504,736.

[182] Martinson, A. B., Góes, M. S., Fabregat-Santiago, F., Bisquert, J., Pellin, M. J., & Hupp, J. T. (2009). Electron transport in dye-sensitized solar cells based on ZnO nanotubes: evidence for highly efficient charge collection and exceptionally rapid dynamics†. The Journal of Physical Chemistry A, 113(16), 4015-4021.

[183] Kroon, J. M., Bakker, N. J., Smit, H. J. P., Liska, P., Thampi, K. R., Wang, P., ... & Würfel, U. (2007). Nanocrystalline dye-sensitized solar cells having maximum performance. Progress in Photovoltaics: Research and Applications, 15(1), 1-18.

[184] Wang, Z. S., Kawauchi, H., Kashima, T., & Arakawa, H. (2004). Significant influence of TiO 2 photoelectrode morphology on the energy conversion efficiency of N719 dye-sensitized solar cell. Coordination chemistry reviews, 248(13), 1381-1389.

[185] Wang, P., Klein, C., Humphry-Baker, R., Zakeeruddin, S. M., & Graetzel, M. (2005). A high molar extinction coefficient sensitizer for stable dye-sensitized solar cells. Journal of the American Chemical Society, 127(3), 808-809.

[186] Nazeeruddin, M. K., Klein, C., Liska, P., & Grätzel, M. (2005). Synthesis of novel ruthenium sensitizers and their application in dye-sensitized solar cells. Coordination chemistry reviews, 249(13), 1460-1467.

[187] Giannouli, M., & Spiliopoulou, F. (2012). Effects of the morphology of nanostructured ZnO films on the efficiency of dye-sensitized solar cells. Renewable Energy, 41, 115-122.

[188] Lu, L., Li, R., Fan, K., & Peng, T. (2010). Effects of annealing conditions on the photoelectron chemical properties of dye-sensitized solar cells made with ZnO nanoparticles. Solar Energy, 84(5), 844-853.

[189] Kim, J. Y., Kim, S. H., Lee, H. H., Lee, K., Ma, W., Gong, X., & Heeger, A. J. (2006). New Architecture for high, efficiency polymer photovoltaic cells using solution, based titanium oxide as an optical spacer. *Advanced materials*, *18*(5), 572-576.

[190] Bae, S., Kim, H., Lee, Y., Xu, X., Park, J. S., Zheng, Y., ... & Kim, Y. J. (2010). Roll-to-roll production of 30-inch graphene films for transparent electrodes. *Nature nanotechnology*, *5*(8), 574-578.

[191] Hautier, G., Miglio, A., Ceder, G., Rignanese, G. M., & Gonze, X. (2013). Identification and design principles of low hole effective mass p-type transparent conducting oxides. *Nature communications*, *4*.

[192] Wang, F. H., & Chang, C. L. (2016). Effect of substrate temperature on transparent conducting Al and F co-doped ZnO thin films prepared by rf magnetron sputtering. *Applied Surface Science*, *370*, 83-91.

[193] Stehr, J. E., Chen, W. M., Reddy, N. K., Tu, C. W., & Buyanova, I. A. (2015). Efficient nitrogen incorporation in ZnO nanowires. *Scientific reports*, *5*.

[194] Nomoto, J., Inaba, K., Osada, M., Kobayashi, S., Makino, H., & Yamamoto, T. (2016). Highly (0001)-oriented Al-doped ZnO polycrystalline films on amorphous glass substrates. *Journal of Applied Physics*, *120*(12), 125302.

[195] Mehra, S., Bergerud, A., Milliron, D. J., Chan, E., & Salleo, A. (2016). A Core/Shell Approach to Dopant Incorporation and Shape Control in Colloidal Zinc Oxide Nanorods. *Chemistry of Materials*.

[196] Li, H., Wang, J., Liu, H., Yang, C., Xu, H., Li, X., & Cui, H. (2004). Sol–gel preparation of transparent zinc oxide films with highly preferential crystal orientation. *Vacuum*, *77*(1), 57-62.

[197] Qu, B. T., Lai, J. C., Liu, S., Liu, F., Gao, Y. D., & You, X. Z. (2015). Cu- and Ag-Based Metal–Organic Frameworks with 4-Pyranone-2, 6-

dicarboxylic Acid: Syntheses, Crystal Structures, and Dielectric Properties. *Crystal Growth & Design*, *15*(4), 1707-1713.

[198] Qiu, Z., Gong, H., Yang, X., Zhang, Z., Han, J., Cao, B., ... & Okada, T. (2015). Phosphorus concentration dependent microstructure and optical property of ZnO nanowires grown by high-pressure pulsed laser deposition. *The Journal of Physical Chemistry C*, *119*(8), 4371-4378.

[199] Ellmer, K. (2012). Past achievements and future challenges in the development of optically transparent electrodes. *Nature Photonics*, *6*(12), 809-817.

[200] Erhart, P., & Albe, K. (2006). Diffusion of zinc vacancies and interstitials in zinc oxide. *Applied physics letters*, *88*(20), 201918.

[201] Goldstein, J., Newbury, D. E., Echlin, P., Joy, D. C., Romig Jr, A. D., Lyman, C. E., ... & Lifshin, E. (2012). *Scanning electron microscopy and X-ray microanalysis: a text for biologists, materials scientists, and geologists*. Springer Science & Business Media.

[202] Ounsi, H. F., Al-Shalan, T., Salameh, Z., Grandini, S., & Ferrari, M. (2008). Quantitative and qualitative elemental analysis of different nickel–titanium rotary instruments by using scanning electron microscopy and energy dispersive spectroscopy. *Journal of Endodontics*, *34*(1), 53-55.

[203] Li, C. C., Yin, X. M., Li, Q. H., & Wang, T. H. (2011). Enhanced gas sensing properties of ZnO/SnO 2 hierarchical architectures by glucose-induced attachment. *CrystEngComm*, *13*(5), 1557-1563.

[204] Malek, M. F., Mamat, M. H., Sahdan, M. Z., Zahidi, M. M., Khusaimi, Z., & Mahmood, M. R. (2013). Influence of various sol concentrations on stress/strain and properties of ZnO thin films synthesised by sol–gel technique. *Thin Solid Films*, *527*, 102-109.

[205] Sagalowicz, L., & Fox, G. R. (1999). Planar defects in ZnO thin films deposited on optical fibers and flat substrates. *Journal of materials research*, *14*(05), 1876-1885.

[206] Kumar, V., Singh, N., Mehra, R. M., Kapoor, A., Purohit, L. P., & Swart, H. C. (2013). Role of film thickness on the properties of ZnO thin films grown by sol-gel method. *Thin Solid Films*, *539*, 161-165.

[207] Oh, H., Krantz, J., Litzov, I., Stubhan, T., Pinna, L., & Brabec, C. J. (2011). Comparison of various sol–gel derived metal oxide layers for inverted

organic solar cells. *Solar Energy Materials and Solar Cells*, *95*(8), 2194-2199.

[208] Hsieh, C. T., Lin, C. Y., Chen, Y. F., & Lin, J. S. (2013). Synthesis of ZnO@ graphene composites as anode materials for lithium ion batteries. *Electrochimica Acta*, *111*, 359-365.

[209] Hsieh, C. T., Lin, J. S., Chen, Y. F., Lin, C. Y., & Li, W. Y. (2014). Graphene sheets anchored with ZnO nanocrystals as electrode materials for electrochemical capacitors. *Materials Chemistry and Physics*, *143*(2), 853-859.

[210] Ajili, M., Jebbari, N., Turki, N. K., & Castagné, M. (2010, November). Study of physical properties of aluminum doped ZnO sprayed thin layers. In *International Renewable Energy Congress* (pp. 5-7). Tunisia: Sousse.

[211] Badadhe, S. S., & Mulla, I. S. (2011). Effect of aluminium doping on structural and gas sensing properties of zinc oxide thin films deposited by spray pyrolysis. *Sensors and Actuators B: Chemical*, *156*(2), 943-948.

[212] Sahay, P. P., & Nath, R. K. (2008). Al-doped ZnO thin films as methanol sensors. *Sensors and Actuators B: Chemical*, *134*(2), 654-659.

[213] Kao, M. C., Chen, H. Z., Young, S. L., Lin, C. C., & Kung, C. Y. (2012). Structure and photovoltaic properties of ZnO nanowire for dye-sensitized solar cells. *Nanoscale research letters*, *7*(1), 1-6.

[214] Liu, X., Zhang, Q., Yip, J. N., Xiong, Q., & Sum, T. C. (2013). Wavelength tunable single nanowire lasers based on surface plasmon polariton enhanced Burstein–Moss effect. *Nano letters*, *13*(11), 5336-5343.

[215] Shahid, M. U., Deen, K. M., Ahmad, A., Akram, M. A., Aslam, M., & Akhtar, W. (2016). Formation of Al-doped ZnO thin films on glass by sol–gel process and characterization. *Applied Nanoscience*, *6*(2), 235-241.

[216] Vilkotskii, V. A., Domanevskii, D. S., Kakanakov, R. D., Krasovskii, V. V., & Tkachev, V. D. (1979). Burstein-Moss effect and near-band-edge luminescence spectrum of highly doped indium arsenide. *physica status solidi (b)*, *91*(1), 71-81.

[217] Lokhande, B. J., Patil, P. S., & Uplane, M. D. (2001). Studies on structural, optical and electrical properties of boron doped zinc oxide films prepared by spray pyrolysis technique. *Physica B: Condensed Matter*, *302*, 59-63.

[218] Mkawi, E. M., Ibrahim, K., Ali, M. K. M., Farrukh, M. A., & Mohamed, A. S. (2015). The effect of dopant concentration on properties of transparent conducting Al-doped ZnO thin films for efficient Cu2ZnSnS4 thin-film solar cells prepared by electrodeposition method. *Applied Nanoscience*, *5*(8), 993-1001

[219] Bagnall, D. M., Chen, Y. F., Shen, M. Y., Zhu, Z., Goto, T., & Yao, T. (1998). Room temperature excitonic stimulated emission from zinc oxide epilayers grown by plasma-assisted MBE. *Journal of crystal growth*, *184*, 605-609.

[220] Sun, Y., Mayers, B., Herricks, T., & Xia, Y. (2003). Polyol synthesis of uniform silver nanowires: a plausible growth mechanism and the supporting evidence. *Nano letters*, *3*(7), 955-960.

[221] Deenathayalan, J., Saroja, M., Venkatachalam, M., Gowthaman, P., & Shankar, S. (2012). A novel growth mechanism of ZnO nanorods using sol-gel dip coating method.

[222] Zak, A. K., Majid, W. A., Abrishami, M. E., & Yousefi, R. (2011). X-ray analysis of ZnO nanoparticles by Williamson–Hall and size–strain plot methods. *Solid State Sciences*, *13*(1), 251-256.

[223] Perera, V. Á. S. (1999). An efficient dye-sensitized photoelectrochemical solar cell made from oxides of tin and zinc. Chemical Communications, (1), 15-16.

[224] Keis, K., Magnusson, E., Lindström, H., Lindquist, S. E., & Hagfeldt, A. (2002). A 5% efficient photoelectrochemical solar cell based on nanostructured ZnO electrodes. Solar energy materials and solar cells, 73(1), 51-58.

[225] Yang, Y., Wang, X., Sun, C., & Li, L. (2009). Photoluminescence of ZnO nanorod-TiO2 nanotube hybrid arrays produced by electrodeposition. Journal of Applied physics, 105(9), 4304.

[226] Park, N. G., Kang, M. G., Kim, K. M., Ryu, K. S., Chang, S. H., Kim, D. K., ... & Frank, A. J. (2004). Morphological and photoelectrochemical characterization of core-shell nanoparticle films for dye-sensitized solar cells: Zn-O type shell on SnO2 and TiO2 cores. Langmuir, 20(10), 4246-4253.

[227] Mahendra, R., Wahyuono, R. A., Sawitri, D., & Risanti, D. D. Dye-Sensitized Solar Cells (DSSC) Based on ZnO Non-and Vertically Aligned Nanorod Structures.

[228] Gurrappa, I., & Binder, L. (2016). Electrodeposition of nanostructured coatings and their characterization—a review. Science and Technology of Advanced Materials.

[229] Karuppuchamy, S., Nonomura, K., Yoshida, T., Sugiura, T., & Minoura, H. (2002). Cathodic electrodeposition of oxide semiconductor thin films and their application to dye-sensitized solar cells. Solid State Ionics, 151(1), 19-27.

[230] Jiang, C. Y., Sun, X. W., Lo, G. Q., Kwong, D. L., & Wang, J. X. (2007). Improved dye-sensitized solar cells with a ZnO-nanoflower photoanode. Applied Physics Letters, 90(26), 263501.

[231] Akhtar, M. S., Khan, M. A., Jeon, M. S., & Yang, O. B. (2008). Controlled synthesis of various ZnO nanostructured materials by capping agents-assisted hydrothermal method for dye-sensitized solar cells. Electrochimica Acta, 53(27), 7869-7874.

[232] Cao, B., Cai, W., Zeng, H., & Duan, G. (2006). Morphology evolution and photoluminescence properties of ZnO films electrochemically deposited on conductive glass substrates. Journal of applied physics, 99(7), 073516.