UNIVERSITI PUTRA MALAYSIA

ELECTROCHEMICAL PREPARATION AND CHARACTERISATION OF ZINC OXIDE AND POLY(3,4-ETHYLENEDIOXYTHIOPHENE)/ZINC OXIDE THIN FILMS

ABDUL HADI BIN ISMAIL

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By

ABDUL HADI BIN ISMAIL

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in fulfilment of the Requirement for the Degree of Master of Science

March 2016

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DEDICATION

Dedicated to my parents, family, supervisory committees and friends for love, support, motivation, inspiration and encouragements

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science

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By

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March 2016

Chairman : Yusran Sulaiman, PhD
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The physical, chemical and electrochemical properties of zinc oxide (ZnO) and poly(3,4-ethylenedioxythiophene)/zinc oxide (PEDOT/ZnO) film electrode that were prepared electrochemically were studied. ZnO was electrodeposited on ITO glass substrate by applying five different electrodeposition potentials (-1.0 V, -1.3 V, -1.5 V, -1.7 V and -2.0 V), three different concentrations of the precursor solution (70 mM, 80 mM and 90 mM) and bath temperature (70 °C, 80 °C and 90 °C). The specific capacitance of the ZnO samples were observed to increase when the applied electrodeposition potential is increased from -1.3 V to -1.5 V. However, the specific capacitance is found to decrease when the applied electrodeposition potential is further increased to -1.7 V. PEDOT was potentiostatically deposited on the optimised hexagonal flake-like ZnO-covered ITO glass substrate by applying three different potentials (1.0 V, 1.25 V and 1.5 V) where under these circumstances, the effect of varying electropolymerisation potentials were studied. The optical band gap of each of the PEDOT/ZnO composites prepared were noticed to be within the range of 3.40 eV to 3.45 eV which were in between the optical band gap values of sole PEDOT and ZnO. The presence of both materials was asserted from XRD, FTIR and Raman spectroscopy analysis where all of the corresponding peaks for each of the materials in the spectra were assigned. SEM revealed the flake-like hexagonal morphology of ZnO which is in agreement with the XRD analysis. While the PEDOT morphology was discerned with round-shaped granular morphology where the average grain size decreased with the electropolymerisation potentials. The resistance of charge transfer of PEDOT/ZnO thin film is directly proportional to the electropolymerisation potential while on the specific capacitance was inversely proportional. The composite exhibit both PEDOT and ZnO unique properties that can be used as a multi-functional material in various potential applications.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Sarjana Sains

PENYEDIAAN SECARA ELEKTROKIMIA DAN PENCIRIAN FILEM ZINK OKSIDA DAN POLI(3,4-ETILENADIOKSITIOFINA)/ZINK OKSIDA

Oleh

ABDUL HADI ISMAIL

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Pengerusi : Yusran Sulaiman, PhD
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Sifat-sifat fizikal, kimia dan elektrokimia zink oksida (ZnO) dan poli(3,4-etilenadioksitiofina)/zink oksida (PEDOT/ZnO) filem elektrod yang disediakan secara elektrokimia telah dikaji. ZnO dielektroenap ke atas substrat kaca ITO dengan menggunakan lima keupayaan elektroenapan (-1.0 V, -1.3 V, -1.5V, -1.7 V dan -2.0 V), perubahan kepekatan bahan pemula (70 mM, 80 mM and 90 mM) dan suhu elektrolit yang berbeza (70 °C, 80 °C and 90 °C). Kapasiti spesifik sampel-sampel ZnO didapati meningkat dengan peningkatan keupayaan electroenapan dari -1.3 V sehingga -1.5 V. Namun demikian, nilai kapasiti spesifik didapati menurun dengan peningkatan keupayaan eletroenapan kepada -1.7 V. PEDOT telah disediakan secara potentiostatik ke atas ZnO optimum yang menutupi permukaan substrat kaca ITO dengan menggunakan tiga keupayaan yang berbeza (1.0 V, 1.25 V dan 1.5 V) di mana dengan keadaan ini, kesan perubahan nilai keupayaan elektropempolimeran telah dikaji. Nilai jurang optik untuk setiap komposit PEDOT/ZnO didapati mempunyai nilai jurang optik dalam lingkungan 3.40 eV hingga 3.45 eV. Nilai-nilai ini berada di dalam lingkungan nilai jurang optik PEDOT dan ZnO tunggal. Kehadiran PEDOT dan ZnO telah disahkan daripada analisis pembelauan tenaga sinaran-X (XRD), spektroskopi Fourier infra merah (FTIR) dan spektroskopi Raman di mana setiap puncak yang bersesuaian dengan setiap bahan-bahan tersebut telah ditentukan. Daripada analisis mikroskopi imbasan elektron (SEM), morfologi kepingan heksagon ZnO telah diketahui dan ia adalah bersamaan dengan analisis XRD yang telah dilakukan. Morfologi PEDOT menunjukkan bentuk butiran bulat dengan purata saiz butiran didapati berkurang dengan pengurangan keupayaan elektropempolimeran. Rintangan pemindahan cas PEDOT/ZnO adalah berkadar terus dengan keupayaan elektropempolimeran. Didapati ia berkadar songsang dengan nilai kapasiti spesifik. Komposit yang telah disediakan mempunyai ciri unik kedua-dua bahan PEDOT dan ZnO yang boleh digunakan sebagai bahan pelbagai fungsi di dalam pelbagai aplikasi yang berpotensi.

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Thank you.

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I certify that a Thesis Examinations Committee has met on March 29, 2016 to conduct the final examination of Abdul Hadi Bin Ismail on his thesis entitled "Electrochemical Preparation and Characterisation Of Zinc Oxide And Poly(3,4-Ethylenedioxythiophene)/Zinc Oxide Thin Films" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1988. The committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of University Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

Ag/AgCl	Silver/Silver chloride
C_f	Final current
C_i	Initial current
C_{int}	Intermediate current
CNT	Carbon nanotube
CNT/PANI	Carbon nanotube/Polyaniline
CPs	Conducting polymers
Cu K_α	Copper K-alpha emission line
CV	Cyclic voltammetry
ECD	Electrochemical deposition technique
EDOT	3,4-ethylenedioxythiophene
EIS	Electrochemical impedance spectroscopy
FTIR	Fourier transform infrared
FWHM	Full width half maximum
GaN/Sapphire	Gallium nitride on sapphire
ICPs	Intrinsically conducting polymers
IO	Inorganic-organic
ITO	Indium tin oxide
JCPDS	Joint Committee on Powder Diffraction Standards
MBE	Molecular beam epitaxy
MOCVD	Metal–Organic chemical vapor deposition
n-ZnO/*p*-PEDOT	*n*-doped Zinc oxide on *p*-doped Poly(3,4-ethylenedioxythiophene)

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OCP	Open circuit potential
OI	Organic-inorganic
P(TTPP)	Poly(2,5-di(thiophen-2-yl)-1-(4-(thiophen-3-yl) phenyl)-1-H-pyrrole)
PANI	Polyaniline
PEDOT	Poly(3,4-ethylenedioxythiophene)
PEDOT/ZnO	Poly(3,4-ethylenedioxythiophene) on Zinc oxide
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene) doped Poly(styrene sulfonate)
p-Si/*n*-ZnO	*p*-doped Silicon on *n*-doped Zinc oxide
RF-sputtering	Radio frequency-sputtering
SCE	Saturated calomel electrode
SEM	Scanning electron microscopy
TC(*hkl*)	Texture coefficient
UATR	Attenuated total reflectance
UV light	Ultraviolet light
UV-vis	Ultraviolet-visible
XRD	X-ray diffraction
ZnO/PEDOT:PSS	Zinc oxide/ Poly(3,4-ethylenedioxythiophene) doped Poly(styrene sulfonate)
λ_{max}	Maximum wavelength
CPE	Constant phase element
PZ 1V	PEDOT/ZnO electropolymerised at 1 V
PZ 1.25V	PEDOT/ZnO electropolymerised at 1.25 V
PZ 1.5V	PEDOT/ZnO electropolymerised at 1.5 V
ZnO [*x* mM, *y* °C, *z* V]	ZnO sample prepared from *x* mM of precursor solution, *y* °C of bath temperature, *z* V of electrodeposition potential

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LIST OF SYMBOLS

θ	Theta	°
R_s	Resistance of solution	Ω
C_{dl}	Double layer capacitance	F
R_{ct}	Resistance of charge transfer	Ω

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Extensive effort has been made recently to develop new electrode materials for various types of applications. Efforts on study of hybrid organic-inorganic materials have been continuously made recently resulting from its capability to provide positive and highly beneficial outcomes (Gómez-Romero, 2001). New inventions have been explored from time to time commenced from the stage of maturity of this research discipline. In particular, this field has focused on the formulation of functionality in the hybrid/composite materials while on the contrary, ameliorated control and comprehension of the processing, chemistry and the microstructure of the materials system has divulged advanced prospects in dealing with a more complex materials (Gómez-Romero and Sanchez, 2005). Integration of organic and inorganic materials is broadening the scope in seeking for new materials where the combinations were ranged from non–complex mixtures of bulk materials to merge the properties of individual organic and inorganic constituents (Yoshida *et al.*, 2009).

The pioneered work on the discovery of conducting polymer in 1977 by Shirakawa, MacDiarmid and Heeger has initiated a new era of technologically important conducting polymers which has led to a lot of works on its applications (Shirakawa *et al.*, 1977). Poly(3,4-ethylenedioxythiophene) (PEDOT) is among the one of intriguing conducting polymers which consist of organic elements that has unique electrochemical, electrical and optical characteristics. Currently, PEDOT plays a dominant role in electric, electronic and antistatic applications (Kateb *et al.*, 2013, Kirchmeyer and Reuter, 2005).

On the other hand, in the past decades, semiconductor nanostructures have engaged substantial attentions due to its captivating electronic and optical properties (Tong *et al.*, 2015, Wang and Herron, 1991). Amidst the semiconductor materials, zinc oxide (ZnO) is a direct wide band gap semiconductor with a large exciton binding energy of 60 meV is a material of exceptional electrical properties that possess a wide range of applications (Tong *et al.*, 2015, Wadowska *et al.*, 2013). The synergistic effects between different materials in a hybrid or composite system are hypothetically complex, but will offer massive potential for energy applications. Opportunities in scrutinising novel combinations of these materials, control and fundamental electrochemical properties of these complex systems are wide open for further inventions and improvements (Gómez-Romero *et al.*, 2010, Rodriguez-Moreno *et al.*, 2014).

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1.2 Problem statement

A combination of organic-inorganic materials constitutes different interface which consequently resulting in prominent advantages and restrictions. The ultimate obstacle in combining these two distinct materials is to keep or elevate the foremost characteristics of individual species while annihilating their notable limitations (Gómez-Romero, 2001). The growing interest on the importance of fabrication of conducting polymer-inorganic composite materials is currently overwhelming. The properties of the conducting polymer (organic component) or the inorganic component can be adjusted from the synergism between the properties of the individual components in the composite (Chen *et al.*, 2013). ZnO as a type of semiconductor oxides with a wide band gap ranging from less than 3.1 eV to 3.55 eV (Marotti *et al.*, 2004, Pauporté and Lincot, 2000) with and a large exciton binding energy of 60 meV (Singh *et al.*, 2013, Skompska and Zarębska, 2014, Wadowska *et al.*, 2013, Wei *et al.*, 2013) at room temperature (Chettah and Abdi, 2013, Çoban *et al.*, 2013) has been subjected to a renewed interest for numerous applications related to its excellent electrical and optical characteristics (Chettah and Abdi, 2013). Pertaining to the organic materials, poly(3,4-ethylenedioxythiophene) (PEDOT) is currently the most eminent type of conducting polymer due to its high stability, moderate band gap (Wang and Wong, 2006) and low redox potential (Selvaganesh *et al.*, 2007) has great potential in organic electronics field (Döbbelin *et al.*, 2009). The combination of PEDOT and ZnO is therefore offers an interesting option to fabricate p-n junctions composite (Döbbelin *et al.*, 2009). The performance of the composite material is closely imparted to its properties, which is exceedingly affected by corresponding fabrication parameters (Chen *et al.*, 2013). Thus, the optimisation of a set of various electrochemical deposition parameters upon the fabrication of PEDOT/ZnO thin film composite is principally important upon the detailed study on its morphological, physical, chemical and electrochemical properties with regard to its potential applications for supercapacitors and solar cells.

1.3 Objectives of Research

The following are the objectives of this study:

1. To prepare ZnO thin film via potentiostatic technique.
2. To evaluate and optimise the effect growth parameters (electrodeposition potentials, precursor concentrations and bath temperature) on the physical, chemical and electrochemical properties of ZnO and PEDOT/ZnO thin films.
3. To characterise the prepared ZnO and PEDOT/ZnO composite using scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transform infrared (FTIR), Raman spectrocopy, ultraviolet-visible (UV-Vis), cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS).

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1.4 Significance of study

This study was performed to synthesise PEDOT/ZnO thin film composite as a multifunctional material with great potentials for a number of potential applications. By retaining the advantages of both organic and inorganic materials, the composite which where synthesised via a low cost and low temperature electrochemical route certainly will offer impressive options in energy, electrical and optical applications.

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REFERENCES

Ait Ahmed, N., Eyraud, M., Hammache, H., Vacandio, F., Sam, S., Gabouze, N., Knauth, P., Pelzer, K. and Djenizian, T. (2013) New insight into the mechanism of cathodic electrodeposition of zinc oxide thin films onto vitreous carbon. *Electrochimica Acta.* 94**.** 238-244.

Ait Ahmed, N., Hammache, H., Makhloufi, L., Eyraud, M., Sam, S., Keffous, A. and Gabouze, N. (2015) Effect of electrodeposition duration on the morphological and structural modification of the flower-like nanostructured ZnO. *Vacuum.* 120, Part B**.** 100 - 106.

Alam, M., Alandis, N. M., Ansari, A. A. and Shaik, M. R. (2013) Optical and electrical studies of Polyaniline/ZnO nanocomposite. *Journal of Nanomaterials.* 2013**.** 5.

Anderson, J. and Chris, G. V. D. W. (2009) Fundamentals of zinc oxide as a semiconductor. *Reports on Progress in Physics.* 72**.** 126501.

Arslan, A., Hür, E., Ilican, S., Caglar, Y. and Caglar, M. (2014) Controlled growth of *c*-axis oriented ZnO nanorod array films by electrodeposition method and characterization. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy.* 128**.** 716-723.

Arthur, J. R. (1968) Interaction of Ga and As2 molecular beams with GaAs surfaces. *Journal of Applied Physics.* 39**.** 4032-4034.

Babakhani, B. and Ivey, D. G. (2010) Improved capacitive behavior of electrochemically synthesized Mn oxide/PEDOT electrodes utilized as electrochemical capacitors. *Electrochimica Acta.* 55**.** 4014-4024.

Back, J.-W., Lee, S., Hwang, C.-R., Chi, C.-S. and Kim, J.-Y. (2010) Fabrication of conducting PEDOT nanotubes using vapor deposition polymerization. *Macromolecular Research.* 19**.** 33-37.

Bai, X., Hu, X., Zhou, S., Yan, J., Sun, C., Chen, P. and Li, L. (2011) Controlled fabrication of highly conductive three-dimensional flowerlike poly (3,4-ethylenedioxythiophene) nanostructures. *Journal of Materials Chemistry.* 21**.** 7123-7129.

Baneto, M., Enesca, A., Lare, Y. L., Jondo, K., Napo, K. and Duta, A. (2014) Effect of precursor concentration on structural, morphological and opto-electric properties of ZnO thin films prepared by spray pyrolysis. *Ceramics International.* 40**.** 8397-8404.

Banfield, J. F., Welch, S. A., Zhang, H., Ebert, T. T. and Penn, R. L. (2000) Aggregation-Based crystal growth and microstructure development in natural Iron Oxyhydroxide biomineralization products. *Science.* 289**.** 751-754.

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Behpour, M., Ghoreishi, S. M., Mohammadi, N., Soltani, N. and Salavati-Niasari, M. (2010) Investigation of some Schiff base compounds containing disulfide bond as HCl corrosion inhibitors for mild steel. *Corrosion Science.* 52**.** 4046-4057.

Belghiti, H. E., Pauporté, T. and Lincot, D. (2008) Mechanistic study of ZnO nanorod array electrodeposition. *physica status solidi (a).* 205**.** 2360-2364.

Benramache, S., Belahssen, O., Guettaf, A. and Arif, A. (2014) Correlation between crystallite size–optical gap energy and precursor molarities of ZnO thin films. *Journal of Semiconductors.* 35**.** 042001.

Bobacka, J., Lewenstam, A. and Ivaska, A. (2000) Electrochemical impedance spectroscopy of oxidized poly(3,4-ethylenedioxythiophene) film electrodes in aqueous solutions. *Journal of Electroanalytical Chemistry.* 489**.** 17-27.

Botelho, A. L., Shin, Y., Liu, J. and Lin, X. (2014) Structure and optical bandgap relationship of π-Conjugated Systems. *PLoS ONE.* 9**.** e86370.

Brug, G. J., Van Den Eeden, A. L. G., Sluyters-Rehbach, M. and Sluyters, J. H. (1984) The analysis of electrode impedances complicated by the presence of a constant phase element. *Journal of Electroanalytical Chemistry and Interfacial Electrochemistry.* 176**.** 275-295.

Cembrero, J. and Busquets-Mataix, D. (2009) ZnO crystals obtained by electrodeposition: Statistical analysis of most important process variables. *Thin Solid Films.* 517**.** 2859-2864.

Chang, L. L., Esaki, L., Howard, W. E., Ludeke, R. and Schul, G. (1973) Structures grown by Molecular Beam Epitaxy. *Journal of Vacuum Science & Technology.* 10**.** 655-662.

Chen, Y., Zhao, Z. and Zhang, C. (2013) Structural and electrochemical study of polypyrrole/ZnO nanocomposites coating on nickel sheet synthesized by electrochemical method. *Synthetic Metals.* 163**.** 51-56.

Chettah, H. and Abdi, D. (2013) Effect of the electrochemical technique on nanocrystalline ZnO electrodeposition, its structural, morphological and photoelectrochemical properties. *Thin Solid Films.* 537**.** 119-123.

Çoban, Ö., Tekmen, S. and Tüzemen, S. (2013) Detection of oxygen with electrochemically deposited ZnO thin films. *Sensors and Actuators B: Chemical.* 186**.** 781-788.

Cruickshank, A. C., Tay, S. E. R., Illy, B. N., Da Campo, R., Schumann, S., Jones, T. S., Heutz, S., Mclachlan, M. A., Mccomb, D. W., Riley, D. J. and Ryan, M. P. (2011) Electrodeposition of ZnO nanostructures on molecular thin films. *Chemistry of Materials.* 23**.** 3863-3870.

Cullity, B. D. (1956) *Elements of X-Ray Diffraction.* Reading, Massachusetts, Addison-Wesley Publishing Company, Inc.

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Dalchiele, E. A., Giorgi, P., Marotti, R. E., Martín, F., Ramos-Barrado, J. R., Ayouci, R. and Leinen, D. (2001) Electrodeposition of ZnO thin films on n-Si(100). *Solar Energy Materials and Solar Cells.* 70**.** 245-254.

De Lima-Neto, P., Correia, A. N., Colares, R. P. and Araujo, W. S. (2007) Corrosion study of electrodeposited Zn and Zn-Co coatings in chloride medium. *Journal of the Brazilian Chemical Society.* 18**.** 1164-1175.

Döbbelin, M., Azaceta, E., Tena-Zaera, R., Marcilla, R., Pozo-Gonzalo, C., Pomposo, J. A. and Mecerreyes, D. (2009) Electrodeposition of ZnO/PEDOT hybrid nanostructures. *Meeting Abstracts.* MA2009-02**.** 2428.

Du, X. and Wang, Z. (2003) Effects of polymerization potential on the properties of electrosynthesized PEDOT films. *Electrochimica Acta.* 48**.** 1713-1717.

Eda, K. (1989) Zinc oxide varistors. *Electrical Insulation Magazine, IEEE.* 5**.** 28-30.

Ezema, F. I. (2004) Fabrication, optical properties and applications of undoped chemical bath deposited ZnO thin films. *Journal of Research (Science).* 15**.** 343-350.

Fabretto, M., Zuber, K., Hall, C., Murphy, P. and Griesser, H. J. (2009) The role of water in the synthesis and performance of vapour phase polymerised PEDOT electrochromic devices. *Journal of Materials Chemistry.* 19**.** 7871-7878.

Fahoume, M., Maghfoul, O., Aggour, M., Hartiti, B., Chraïbi, F. and Ennaoui, A. (2006) Growth and characterization of ZnO thin films prepared by electrodeposition technique. *Solar Energy Materials and Solar Cells.* 90**.** 1437-1444.

Feng, Z.-Q., Wu, J., Cho, W., Leach, M. K., Franz, E. W., Naim, Y. I., Gu, Z.-Z., Corey, J. M. and Martin, D. C. (2013) Highly aligned poly(3,4-ethylene dioxythiophene) (PEDOT) nano- and microscale fibers and tubes. *Polymer.* 54**.** 702-708.

Gao, Y. F., Nagai, M., Masuda, Y., Sato, F. and Koumoto, K. (2006) Electrochemical deposition of ZnO film and its photoluminescence properties. *Journal of Crystal Growth.* 286**.** 445-450.

Gleiter, H. (2000) Nanostructured materials: basic concepts and microstructure. *Acta Materialia.* 48**.** 1-29.

Gómez-Romero, P. (2001) Hybrid Organic—Inorganic Materials — In Search of Synergic Activity*. *Adv. Mater.* 13**.** 5.

Gómez-Romero, P., Ayyad, O., Suárez-Guevara, J. and Muñoz-Rojas, D. (2010) Hybrid organic—inorganic materials: from child's play to energy applications. *Journal of Solid State Electrochemistry.* 14**.** 1939-1945.

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Gómez-Romero, P. and Sanchez, C. (2005) Hybrid materials. Functional properties. From Maya Blue to 21st century materials. *New Journal of Chemistry.* 29**.** 57-58.

Goto, S., Fujimura, N., Nishihara, T. and Ito, T. (1991) Heteroepitaxy of zinc oxide thin films, considering non-epitaxial preferential orientation. *Journal of Crystal Growth.* 115**.** 816-820.

Goux, A., Pauporté, T., Chivot, J. and Lincot, D. (2005) Temperature effects on ZnO electrodeposition. *Electrochimica Acta.* 50**.** 2239-2248.

Govender, K., Boyle, D. S., Kenway, P. B. and 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**.** 2575-2591.

Groenendaal, L., Jonas, F., Freitag, D., Pielartzik, H. and Reynolds, J. R. (2000) Poly(3,4-ethylenedioxythiophene) and its derivatives: past, present, and future. *Advanced Materials.* 12**.** 481-494.

Habibi, M. H. and Rahmati, M. H. (2014) Fabrication and characterization of ZnO@CdS core—shell nanostructure using acetate precursors: XRD, FESEM, DRS, FTIR studies and effects of cadmium ion concentration on band gap. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy.* 133**.** 13-18.

Heeger, A. J. (2001) Semiconducting and Metallic Polymers: The Fourth Generation of Polymeric Materials† *The Journal of Physical Chemistry B.* 105**.** 8475-8491.

Heinze, S., Krtschil, A., Bläsing, J., Hempel, T., Veit, P., Dadgar, A., Christen, J. and Krost, A. (2007) Homoepitaxial growth of ZnO by metalorganic vapor phase epitaxy in two-dimensional growth mode. *Journal of Crystal Growth.* 308**.** 170-175.

Heller, R. B., Mcgannon, J. and Weber, A. H. (1950) Precision determination of the lattice constants of Zinc Oxide. *Journal of Applied Physics.* 21**.** 1283-1284.

Henni, A., Merrouche, A., Telli, L., Azizi, A. and Nechache, R. (2014) Effect of potential on the early stages of nucleation and properties of the electrochemically synthesized ZnO nanorods. *Materials Science in Semiconductor Processing.* 31**.** 380-385.

Hirano, S., Masuya, K. and Kuwabara, M. (2004) Multi-Nucleation-Based formation of oriented Zinc Oxide microcrystals and films in aqueous solutions. *The Journal of Physical Chemistry B.* 108**.** 4576-4578.

Holmes, P. J. (1962) *The Electrochemistry of Semiconductors.* London, Academic Press.

Hussain, I., Bano, N., Hussain, S., Nur, O. and Willander, M. (2011) Study of intrinsic white light emission and its components from ZnO-nanorods/p-polymer

© COPYRIGHT UPM

hybrid junctions grown on glass substrates. *Journal of Materials Science.* 46**.** 7437-7442.

Hyde, F. J. (1965) *Semiconductors.* London, Macdonald and Co.

Illy, B. N., Cruickshank, A. C., Schumann, S., Da Campo, R., Jones, T. S., Heutz, S., Mclachlan, M. A., Mccomb, D. W., Riley, D. J. and Ryan, M. P. (2011) Electrodeposition of ZnO layers for photovoltaic applications: controlling film thickness and orientation. *Journal of Materials Chemistry.* 21**.** 12949-12957.

Illy, B. N., Ingham, B. and Ryan, M. P. (2010) Effect of supersaturation on the growth of Zinc Oxide nanostructured films by electrochemical deposition. *Crystal Growth & Design.* 10**.** 1189-1193.

Im, S. G. and Gleason, K. K. (2007) Systematic control of the electrical conductivity of Poly(3,4-ethylenedioxythiophene) via oxidative chemical vapor deposition. *Macromolecules.* 40**.** 6552-6556.

Inamdar, A. I., Mujawar, S. H., Barman, S. R., Bhosale, P. N. and Patil, P. S. (2008) The effect of bath temperature on the electrodeposition of Zinc Oxide thin films via an acetate medium. *Semiconductor Science and Technology.* 23**.** 085013.

Inamdar, A. I., Mujawar, S. H., Sadale, S. B., Sonavane, A. C., Shelar, M. B., Shinde, P. S. and Patil, P. S. (2007) Electrodeposited Zinc Oxide thin films: Nucleation and growth mechanism. *Solar Energy Materials and Solar Cells.* 91**.** 864-870.

Injeti, G. and Leo, B. (2008) Electrodeposition of nanostructured coatings and their characterization—a review. *Science and Technology of Advanced Materials.* 9**.** 043001.

Ive, T., Ben-Yaacov, T., Van De Walle, C. G., Mishra, U. K., Denbaars, S. P. and Speck, J. S. (2008) Step-flow growth of ZnO(0 0 0 1) on GaN(0 0 0 1) by metalorganic chemical vapor epitaxy. *Journal of Crystal Growth.* 310**.** 3407-3412.

Izaki, M. and Omi, T. (1996a) Electrolyte optimization for cathodic growth of Zinc Oxide films. *Journal of The Electrochemical Society.* 143**.** L53-L55.

Izaki, M. and Omi, T. (1996b) Transparent Zinc Oxide films prepared by electrochemical reaction. *Applied Physics Letters.* 68**.** 2439-2440.

Izyumskaya, N., Avrutin, V., Schoch, W., El-Shaer, A., Reuß , F., Gruber, T. and Waag, A. (2004) Molecular beam epitaxy of high-quality ZnO using hydrogen peroxide as an oxidant. *Journal of Crystal Growth.* 269**.** 356-361.

Jan, T., Iqbal, J., Ismail, M., Mansoor, Q., Mahmood, A. and Ahmad, A. (2014) Eradication of multi-drug sesistant bacteria by Ni doped ZnO nanorods: structural, raman and optical characteristics. *Applied Surface Science.* 308**.** 75-81.

© COPYRIGHT UPM

Jiang, S., Wu, M., Zhou, Y., Wen, Y., Yang, C. and Zhang, S. (2007) Effects of electrodeposition conditions on the mivrostructures of ZnO thin films. *Integrated Ferroelectrics.* 88**.** 33-43.

Jones, A. C. (1998) MOCVD of Electroceramic Oxides: A precursor manufacturer′s perspective. *Chemical Vapor Deposition.* 4**.** 169-179.

Judeinstein, P. and Sanchez, C. (1996) Hybrid organic-inorganic materials: a land of multidisciplinarity. *Journal of Materials Chemistry.* 6**.** 511-525.

Kateb, M., Ahmadi, V. and Mohseni, M. (2013) Fast switching and high contrast electrochromic device based on PEDOT nanotube grown on ZnO nanowires. *Solar Energy Materials and Solar Cells.* 112**.** 57-64.

Khamlich, S., Bello, A., Fabiane, M., Ngom, B. D. and Manyala, N. (2013) Hydrothermal synthesis of simonkolleite microplatelets on nickel foam-graphene for electrochemical supercapacitors. *Journal of Solid State Electrochemistry.* 17**.** 2879-2886.

Khelladi, M. R., Mentar, L., Boubatra, M. and Azizi, A. (2012) Study of nucleation and growth process of electrochemically synthesized ZnO nanostructures. *Materials Letters.* 67**.** 331-333.

Kirchmeyer, S. and Reuter, K. (2005) Scientific importance, properties and growing applications of poly(3,4-ethylenedioxythiophene). *Journal of Materials Chemistry.* 15**.** 2077-2088.

Kissinger, P. T. and Heineman, W. R. (1983) Cyclic voltammetry. *Journal of Chemical Education.* 60**.** 702.

Knodle, W. S., Chow, R. and Seshan, K. (2001) 10 - Molecular Beam Epitaxy: equipment and practice. *Handbook of Thin Film Deposition Processes and Techniques (Second Edition).* Norwich, NY. William Andrew Publishing.

Ko, Y., Ramana, D. K. and Yu, J. (2013) Electrochemical synthesis of ZnO branched submicrorods on carbon fibers and their feasibility for environmental applications. *Nanoscale Research Letters.* 8**.** 262.

Lee, J., Nam, S. and Tak, Y. (2005) On the origin of electrodeposition mechanism of ZnO on ITO substrate. *Korean Journal of Chemical Engineering.* 22**.** 161-164.

Lee, W., Jeong, M.-C. and Myoung, J.-M. (2004) Catalyst-free growth of ZnO nanowires by metal-organic chemical vapour deposition (MOCVD) and thermal evaporation. *Acta Materialia.* 52**.** 3949-3957.

Li, H., Gao, Y., Pan, L., Zhang, Y., Chen, Y. and Sun, Z. (2008) Electrosorptive desalination by carbon nanotubes and nanofibres electrodes and ion-exchange membranes. *Water research.* 42**.** 4923-4928.

© COPYRIGHT UPM

Li, J., Liu, Z., Lei, E. and Zhu, Z. (2011) Effects of potential and temperature on the electrodeposited porous zinc oxide films. *Journal of Wuhan University of Technology-Mater. Sci. Ed.* 26**.** 47-51.

Lide, D. R. (1998) *Handbook of Chemistry and Physics, 79th edition.* Boca Raton, Florida, CRC Press.

Lin, Y., Yang, J. and Zhou, X. (2011) Controlled synthesis of oriented ZnO nanorod arrays by seed-layer-free electrochemical deposition. *Applied Surface Science.* 258**.** 1491-1494.

Lincot, D. (2005) Electrodeposition of semiconductors. *Thin Solid Films.* 487**.** 40-48.

Liu, R. and Lee, S. B. (2008) MnO2/Poly(3,4-ethylenedioxythiophene) coaxial nanowires by one-step coelectrodeposition for electrochemical energy storage. *Journal of the American Chemical Society.* 130**.** 2942-2943.

Long, Y., Chen, Z., Zhang, X., Zhang, J. and Liu, Z. (2004) Synthesis and electrical properties of carbon nanotube polyaniline composites. *Applied Physics Letters.* 85**.** 1796-1798.

Look, D. C. (2001) Recent advances in ZnO materials and devices. *Materials Science and Engineering: B.* 80**.** 383-387.

Look, D. C. (2007) Quantitative analysis of surface donors in ZnO. *Surface Science.* 601**.** 5315-5319.

Ludwig, W., Ohm, W., Correa-Hoyos, J.-M., Zhao, Y., Lux-Steiner, M. C. and Gledhill, S. (2013) Electrodeposition parameters for ZnO nanorod arrays for photovoltaic applications. *physica status solidi (a).* 210**.** 1557-1563.

Lv, X. J., Sun, J. W., Hu, B., Ouyang, M., Fu, Z. Y., Wang, P. J., Bian, G. F. and Zhang, C. (2013) Effective process to achieve enhanced electrochromic performances based on poly(4,4',4''-tris[4-(2-bithienyl)pheny]amine)/ZnO nanorod composites. *Nanotechnology.* 24**.** 265705.

Macdiarmid, A. G. (2001) Synthetic metals: a novel role for organic polymers. *Synthetic Metals.* 125**.** 11-22.

Macdonald, J. R. and Kenan, W. R. (1987) *Impedance Spectroscopy: Emphasizing Solid Materials and Systems.* Wiley.

Mahalingam, T., John, V. S., Raja, M., Su, Y. K. and Sebastian, P. J. (2005) Electrodeposition and characterization of transparent ZnO thin films. *Solar Energy Materials and Solar Cells.* 88**.** 227-235.

Mahalingam, T., John, V. S. and Sebastian, P. J. (2003) Growth and characterization of electrosynthesised zinc oxide thin films. *Materials Research Bulletin.* 38**.** 269-277.

Manasevit, H. M. (1968) Single–Crystal Gallium Arsenide on insulating substrates. *Applied Physics Letters.* 12**.** 156-159.

© COPYRIGHT UPM

Mang, A., Reimann, K. and Rübenacke, S. (1995) Band gaps, crystal-field splitting, spin-orbit coupling, and exciton binding energies in ZnO under hydrostatic pressure. *Solid State Communications.* 94**.** 251-254.

Marotti, R. E., Giorgi, P., Machado, G. and Dalchiele, E. A. (2006) Crystallite size dependence of band gap energy for electrodeposited ZnO grown at different temperatures. *Solar Energy Materials and Solar Cells.* 90**.** 2356-2361.

Marotti, R. E., Guerra, D. N., Bello, C., Machado, G. and Dalchiele, E. A. (2004) Bandgap energy tuning of electrochemically grown ZnO thin films by thickness and electrodeposition potential. *Solar Energy Materials and Solar Cells.* 82**.** 85-103.

Matei, E., Enculescu, M., Preda, N. and Enculescu, I. (2012) ZnO morphological, structural and optical properties control by electrodeposition potential sweep rate. *Materials Chemistry and Physics.* 134**.** 988-993.

Mcbride, R. A., Kelly, J. M. and Mccormack, D. E. (2003) Growth of well-defined ZnO microparticles by hydroxide ion hydrolysis of zinc salts. *Journal of Materials Chemistry.* 13**.** 1196-1201.

Mitzi, D. B. (2001) Thin-film deposition of organic-inorganic hybrid materials. *Chemistry of Materials.* 13**.** 3283-3298.

Montibon, E., Järnström, L. and Lestelius, M. (2009) Characterization of poly(3,4-ethylenedioxythiophene)/poly(styrene sulfonate) (PEDOT:PSS) adsorption on cellulosic materials. *Cellulose.* 16**.** 807-815.

Nasybulin, E., Wei, S., Cox, M., Kymissis, I. and Levon, K. (2011) Morphological and spectroscopic studies of electrochemically deposited Poly(3,4-ethylenedioxythiophene) (PEDOT) hole extraction layer for organic photovoltaic device (OPVd) fabrication. *The Journal of Physical Chemistry C.* 115**.** 4307-4314.

Özgür, Ü., Alivov, Y. I., Liu, C., Teke, A., Reshchikov, M. A., Doäÿan, S., Avrutin, V., Cho, S. J. and Morkoç, H. (2005) A comprehensive review of ZnO materials and devices. *Journal of Applied Physics.* 98**.** 041301.

Pacholski, C., Kornowski, A. and Weller, H. (2002) Self-assembly of ZnO: From nanodots to nanorods. *Angewandte Chemie International Edition.* 41**.** 1188-1191.

Palma-Cando, A. U., Frontana-Uribe, B. A., Maldonado, J. L. and Hernández, M. R. (2014) Control of thickness of PEDOT electrodeposits on Glass/ITO electrodes from organic solutions and its use as anode in organic solar cells. *Procedia Chemistry.* 12**.** 92-99.

Panda, N. R., Acharya, B. S., Nayak, P. and Bag, B. P. (2014) Studies on growth morphology, UV absorbance and luminescence properties of sulphur doped

© COPYRIGHT UPM

ZnO nanopowders synthesized by the application of ultrasound with varying input power. *Ultrasonics Sonochemistry.* 21**.** 582-589.

Patil, A. O., Heeger, A. J. and Wudl, F. (1988) Optical properties of conducting polymers. *Chemical Reviews.* 88**.** 183-200.

Patten, H., Ventosa, E., Colina, A., Ruiz, V., López-Palacios, J., Wain, A., Lai, S. S., Macpherson, J. and Unwin, P. (2011) Influence of ultrathin poly-(3,4-ethylenedioxythiophene) (PEDOT) film supports on the electrodeposition and electrocatalytic activity of discrete platinum nanoparticles. *Journal of Solid State Electrochemistry.* 15**.** 2331-2339.

Pauporté, T. and Lincot, D. (2000) Electrodeposition of semiconductors for optoelectronic devices: results on zinc oxide. *Electrochimica Acta.* 45**.** 3345-3353.

Peulon, S. and Lincot, D. (1996) Cathodic electrodeposition from aqueous solution of dense or open-structured zinc oxide films. *Advanced Materials.* 8**.** 166-170.

Pigani, L., Heras, A., Colina, Á., Seeber, R. and López-Palacios, J. (2004) Electropolymerisation of 3,4-ethylenedioxythiophene in aqueous solutions. *Electrochemistry Communications.* 6**.** 1192-1198.

Prasad, B., Kamath, P. V. and Ranganath, S. (2012) Electrodeposition of ZnO coatings from aqueous $Zn(NO_3)_2$ baths: effect of Zn concentration, deposition temperature, and time on orientation. *Journal of Solid State Electrochemistry.* 16**.** 3715-3722.

Qiu, J., Guo, M. and Wang, X. (2011) Electrodeposition of hierarchical ZnO nanorod-nanosheet structures and their applications in dye-sensitized solar cells. *ACS Applied Materials & Interfaces.* 3**.** 2358-2367.

Quiñones-Galván, J. G., Sandoval-Jiménez, I. M., Tototzintle-Huitle, H., Hernández-Hernández, L. A., De Moure-Flores, F., Hernández-Hernández, A., Campos-González, E., Guillén-Cervantes, A., Zelaya-Angel, O. and Araiza-Ibarra, J. J. (2013) Effect of precursor solution and annealing temperature on the physical properties of Sol–Gel-deposited ZnO thin films. *Results in Physics.* 3**.** 248-253.

Ramírez, D., Gómez, H., Riveros, G., Schrebler, R., Henríquez, R. and Lincot, D. (2010) Effect of Zn(II) Concentration on the Morphology of Zinc Oxide Nanorods During Electrodeposition on Very Thin Alumina Membrane Templates. *The Journal of Physical Chemistry C.* 114**.** 14854-14859.

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

Rayerfrancis, A., Balaji Bhargav, P., Ahmed, N., Chandra, B. and Dhara, S. (2015) Effect of pH on the morphology of ZnO nanostructures and its influence on structural and optical properties. *Physica B: Condensed Matter.* 457**.** 96-102.

© COPYRIGHT UPM

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

Rodriguez-Moreno, J., Navarrete-Astorga, E., Dalchiele, E. A., Schrebler, R., Ramos-Barrado, J. R. and Martin, F. (2014) Vertically aligned ZnO@CuS@PEDOT core@shell nanorod arrays decorated with MnO2 nanoparticles for a high-performance and semi-transparent supercapacitor electrode. *Chemical Communications.* 50**.** 5652-5655.

Rodríguez-Moreno, J., Navarrete-Astorga, E., Martín, F., Schrebler, R., Ramos-Barrado, J. R. and Dalchiele, E. A. (2012) Semitransparent ZnO/poly(3,4-ethylenedioxythiophene) based hybrid inorganic/organic heterojunction thin film diodes prepared by combined radio-frequency magnetron-sputtering and electrodeposition techniques. *Thin Solid Films.* 525**.** 88-92.

Ruffo, R., Hong, S. S., Chan, C. K., Huggins, R. A. and Cui, Y. (2009) Impedance analysis of Silicon nanowire Lithium ion battery anodes. *The Journal of Physical Chemistry C.* 113**.** 11390-11398.

S. Shionoya, Y. W. M., H. Yamamoto (1997) *Phosphor Handbook.* Florida, CRC Press.

Salazar, R., Lévy-Clément, C. and Ivanova, V. (2012) Galvanostatic deposition of ZnO thin films. *Electrochimica Acta.* 78**.** 547-556.

Schirmer, O. F. and Zwingel, D. (1970) The yellow luminescence of zinc oxide. *Solid State Communications.* 8**.** 1559-1563.

Schlapak, R., Armitage, D., Saucedo-Zeni, N., Latini, G., Gruber, H. J., Mesquida, P., Samotskaya, Y., Hohage, M., Cacialli, F. and Howorka, S. (2007) Preparation and characterization of dense films of Poly(amidoamine) dendrimers on Indium Tin Oxide. *Langmuir.* 23**.** 8916-8924.

Schmidt, O., Geis, A., Kiesel, P., Van De Walle, C. G., Johnson, N. M., Bakin, A., Waag, A. and Döhler, G. H. (2006) Analysis of a conducting channel at the native zinc oxide surface. *Superlattices and Microstructures.* 39**.** 8-16.

Selvaganesh, S. V., Mathiyarasu, J., Phani, K. L. N. and Yegnaraman, V. (2007) Chemical synthesis of PEDOT–Au nanocomposite. *Nanoscale Research Letters.* 2**.** 546-549.

Shiloh, M. and Gutman, J. (1971) Growth of ZnO single crystals by chemical vapour transport. *Journal of Crystal Growth.* 11**.** 105-109.

Shirakawa, H., Louis, E. J., Macdiarmid, A. G., Chiang, C. K. and Heeger, A. J. (1977) Synthesis of electrically conducting organic polymers: halogen derivatives of polyacetylene, (CH). *Journal of the Chemical Society, Chemical Communications.* 578-580.

© COPYRIGHT UPM

Singh, P., Kumar, A., Deepak and Kaur, D. (2007) Growth and characterization of ZnO nanocrystalline thin films and nanopowder via low-cost ultrasonic spray pyrolysis. *Journal of Crystal Growth.* 306**.** 303-310.

Singh, S. and Chakrabarti, P. (2013) Comparison of the structural and optical properties of ZnO thin films deposited by three different methods for optoelectronic applications. *Superlattices and Microstructures.* 64**.** 283-293.

Singh, T., Pandya, D. K. and Singh, R. (2013) Effect of supporting electrolytes on the growth and optical properties of electrochemically deposited ZnO nanorods. *Optical Materials.* 35**.** 1493-1497.

Sithole, J., Ngom, B. D., Khamlich, S., Manikanadan, E., Manyala, N., Saboungi, M. L., Knoessen, D., Nemutudi, R. and Maaza, M. (2012) Simonkolleite nano-platelets: Synthesis and temperature effect on hydrogen gas sensing properties. *Applied Surface Science.* 258**.** 7839-7843.

Skompska, M. and Zarębska, K. (2014) Electrodeposition of ZnO nanorod arrays on transparent conducting substrates-a review. *Electrochimica Acta.* 127**.** 467-488.

Soo Kim, Y., Bin Oh, S., Hyeok Park, J., Suk Cho, M. and Lee, Y. (2010) Highly conductive PEDOT/silicate hybrid anode for ITO-free polymer solar cells. *Solar Energy Materials and Solar Cells.* 94**.** 471-477.

Su, C., Wang, G. and Huang, F. (2007) Preparation and characterization of composites of polyaniline nanorods and multiwalled carbon nanotubes coated with polyaniline. *Journal of Applied Polymer Science.* 106**.** 4241-4247.

Taleatu, B. A., Makinde, W. O., Eleruja, M. A. and Fasasi, A. Y. (2013) Band alignment and charge transport characteristics of TPP/ZnO hybrid for photovoltaic cell potential. *Current Applied Physics.* 13**.** 97-102.

Tamburri, E., Orlanducci, S., Toschi, F., Terranova, M. L. and Passeri, D. (2009) Growth mechanisms, morphology, and electroactivity of PEDOT layers produced by electrochemical routes in aqueous medium. *Synthetic Metals.* 159**.** 406-414.

Therese, G. H. A. and Kamath, P. V. (2000) Electrochemical synthesis of metal oxides and hydroxides. *Chemistry of Materials.* 12**.** 1195-1204.

Thomas, D. G. (1960) The exciton spectrum of zinc oxide. *Journal of Physics and Chemistry of Solids.* 15**.** 86-96.

Tong, X., Zhang, S., Xue, X. and Lu, G. (2015) Unique approach to change ZnO appearance and its properties during its growth: Current. *Materials Letters.* 139**.** 311-313.

Trenque, I., Mornet, S., Duguet, E. and Gaudon, M. (2013) New insights into crystallite size and cell parameters correlation for ZnO nanoparticles obtained from Polyol-mediated synthesis. *Inorganic Chemistry.* 52**.** 12811-12817.

© COPYRIGHT UPM

Turac, E., Sahmetlioglu, E., Toppare, L. and Yuruk, H. (2012) Synthesis, characterization and optoelectrochemical properties of Poly(2,5-di(thiophen-2-yl-)1-(4-(thiophen-3-yl)phenyl)-1H-pyrrole-co-EDOT). *Designed Monomers and Polymers.* 13**.** 261-275.

V. Manzano, C., Caballero-Calero, O., Hormeño, S., Penedo, M., Luna, M. and Martín-González, M. S. (2012) ZnO morphology control by pulsed electrodeposition. *The Journal of Physical Chemistry C.* 117**.** 1502-1508.

Verges, M. A., Mifsud, A. and Serna, C. J. (1990) Formation of rod-like zinc oxide microcrystals in homogeneous solutions. *Journal of the Chemical Society, Faraday Transactions.* 86**.** 959-963.

Vettumperumal, R., Kalyanaraman, S. and Thangavel, R. (2014) A comparative study of structural, surface morphology and optical properties of Na and Mg codoped ZnO nanocrystalline thin films prepared using sol-gel spin coating technique. *Journal of Molecular Structure.* 1059**.** 61-67.

Wadowska, M., Frade, T., Siopa, D., Lobato, K. and Gomes, A. (2013) ZnO nanostructured films electrodeposited at room temperature. *ECS Electrochemistry Letters.* 2**.** D40-D42.

Walatka, V. V., Labes, M. M. and Perlstein, J. H. (1973) Polysulfur Nitride—a one-dimensional chain with a metallic ground state. *Physical Review Letters.* 31**.** 1139-1142.

Wang, F., Liu, R., Pan, A., Cao, L., Cheng, K., Xue, B., Wang, G., Meng, Q., Li, J., Li, Q., Wang, Y., Wang, T. and Zou, B. (2007) The optical properties of ZnO sheets electrodeposited on ITO glass. *Materials Letters.* 61**.** 2000-2003.

Wang, X. J. and Wong, K. Y. (2006) Effects of a base coating used for electropolymerization of poly(3,4-ethylenedioxythiophene) on indium tin oxide electrode. *Thin Solid Films.* 515**.** 1573-1578.

Wang, X. Z., Li, M. G., Chen, Y. W., Cheng, R. M., Huang, S. M., Pan, L. K. and Sun, Z. (2006) Electrosorption of ions from aqueous solutions with carbon nanotubes and nanofibers composite film electrodes. *Applied Physics Letters.* 89**.** 053127.

Wang, Y. and Herron, N. (1991) Nanometer-sized semiconductor clusters: materials synthesis, quantum size effects, and photophysical properties. *The Journal of Physical Chemistry.* 95**.** 525-532.

Warren, B. E. (1990) *X-Ray Diffraction.* New York, Dover Publications Inc.

Wasan, R. S., Nada, M. S., Wesam, A. T. and Mohammed, A. (2011) Synthesis sol-gel derived highly transparent ZnO thin films for optoelectronic applications. *Advances in Materials Physics and Chemistry.* Vol.02No.01**.** 6.

© COPYRIGHT UPM

Wei, A., Xiong, L., Sun, L., Liu, Y., Li, W., Lai, W., Liu, X., Wang, L., Huang, W. and Dong, X. (2013a) One-step electrochemical synthesis of a graphene–ZnO hybrid for improved photocatalytic activity. *Materials Research Bulletin.* 48**.** 2855-2860.

Wei, A., Xiong, L., Sun, L., Liu, Y., Li, W., Lai, W., Liu, X., Wang, L., Huang, W. and Dong, X. (2013b) One-step electrochemical synthesis of a graphene—ZnO hybrid for improved photocatalytic activity. *Materials Research Bulletin.* 48**.** 2855-2860.

West, A. R. (1988) *Basic Solid State Chemistry.* New York, John Wiley & Sons.

Wynne, K. J. and Street, G. B. (1982) Conducting polymers. A short review. *Industrial & Engineering Chemistry Product Research and Development.* 21**.** 23-28.

Xia, F. and Jiang, L. (2008) Bio-Inspired, Smart, Multiscale Interfacial Materials. *Advanced Materials.* 20**.** 2842-2858.

Xie, J., Li, P., Li, Y., Wang, Y. and Wei, Y. (2009) Morphology control of ZnO particles via aqueous solution route at low temperature. *Materials Chemistry and Physics.* 114**.** 943-947.

Xu, F., Lu, Y., Xie, Y. and Liu, Y. (2009) Controllable morphology evolution of electrodeposited ZnO nano/micro-scale structures in aqueous solution. *Materials & Design.* 30**.** 1704-1711.

Xu, L., Chen, Z., Chen, W., Mulchandani, A. and Yan, Y. (2008) Electrochemical synthesis of perfluorinated ion doped conducting polyaniline films consisting of helical fibers and their reversible switching between superhydrophobicity and superhydrophilicity. *Macromolecular Rapid Communications.* 29**.** 832-838.

Xu, L., Guo, Y., Liao, Q., Zhang, J. and Xu, D. (2005) Morphological control of ZnO nanostructures by electrodeposition. *The Journal of Physical Chemistry B.* 109**.** 13519-13522.

Yao, G., Zhang, M., Lv, J., Xu, K., Shi, S., Gong, Z., Tao, J., Jiang, X., Yang, L., Cheng, Y., He, G., Chen, X. and Sun, Z. (2015) Effects of electrodeposition electrolyte concentration on microstructure, optical properties and wettability of ZnO nanorods. *Journal of The Electrochemical Society.* 162**.** D300-D304.

Yoshida, T., Komatsu, D., Shimokawa, N. and Minoura, H. (2004) Mechanism of cathodic electrodeposition of zinc oxide thin films from aqueous zinc nitrate baths. *Thin Solid Films.* 451-452**.** 166-169.

Yoshida, T., Zhang, J., Komatsu, D., Sawatani, S., Minoura, H., Pauporté, T., Lincot, D., Oekermann, T., Schlettwein, D., Tada, H., Wöhrle, D., Funabiki, K., Matsui, M., Miura, H. and Yanagi, H. (2009) Electrodeposition of inorganic/organic hybrid thin films. *Advanced Functional Materials.* 19**.** 17-43.

© COPYRIGHT UPM

Yu, Z., Duong, B., Abbitt, D. and Thomas, J. (2013) Highly ordered MnO2 nanopillars for enhanced supercapacitor performance. *Advanced Materials.* 25**.** 3302-3306.

Zakirov, A. S., Yuldashev, S. U., Cho, H. D., Lee, J. C. and Kang, T. W. (2011) Electrical and photoelectrical characteristics of the ZnO/organic hybrid heterostructure. *Journal of the Korean Physical Society.* 59**.** 482-484.

Zhai, Y., Zhai, S., Chen, G., Zhang, K., Yue, Q., Wang, L., Liu, J. and Jia, J. (2011) Effects of morphology of nanostructured ZnO on direct electrochemistry and biosensing properties of glucose oxidase. *Journal of Electroanalytical Chemistry.* 656**.** 198-205.

Zhang, X., Shi, F., Niu, J., Jiang, Y. and Wang, Z. (2008) Superhydrophobic surfaces: from structural control to functional application. *Journal of Materials Chemistry.* 18**.** 621-633.

Zhang, Y., Li, H., Pan, L., Lu, T. and Sun, Z. (2009) Capacitive behavior of graphene-ZnO composite film for supercapacitors. *Journal of Electroanalytical Chemistry.* 634**.** 68-71.

Zheng, H., Jiang, Y., Xu, J. and Yang, Y. (2010) The characteristic properties of PEDOT nano-particle based on reversed micelle method. *Science China Technological Sciences.* 53**.** 2355-2362.

Zhong, W., Liu, S., Chen, X., Wang, Y. and Yang, W. (2006) High-Yield synthesis of superhydrophilic Polypyrrole nanowire networks. *Macromolecules.* 39**.** 3224-3230.

Zhou, C., Liu, Z., Yan, Y., Du, X., Mai, Y.-W. and Ringer, S. (2011) Electro-synthesis of novel nanostructured PEDOT films and their application as catalyst support. *Nanoscale Research Letters.* 6**.** 364.

Zhu, Y., Li, J., Wan, M. and Jiang, L. (2008) Superhydrophobic 3D microstructures assembled from 1D nanofibers of Polyaniline. *Macromolecular Rapid Communications.* 29**.** 239-243.

Zilko, J. L. and Seshan, K. (2001) 4 - Metal Organic Chemical Vapor Deposition: technology and equipment. *Handbook of Thin Film Deposition Processes and Techniques (Second Edition).* Norwich, NY. William Andrew Publishing.

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