A STUDY OF THERMAL STABILITY OF DIFFERENT ZNO/P-SI DIODE STRUCTURE TOWARD APPLICATION OF RADIATION DETECTORS

HARZAWARDI BIN HASIM

UNIVERSITI TEKNOLOGI MALAYSIA

A STUDY OF THERMAL STABILITY OF DIFFERENT ZNO/P-SI DIODE STRUCTURE TOWARD APPLICATION OF RADIATION DETECTORS

HARZAWARDI BIN HASIM

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Computer and Microelectronic System)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2018

Dedication to my beloved father, my wife, and kids

ACKNOWLEDGEMENT

I am gratefull to God Almighty with His grace giving me the opportunity to pursue my study. I would also like to express my gratitude to Dr. Suhana Mohammed Sultan for her time and guidance. My wife Azriyani Md. Yusoff for her support and commitment. My understanding son, daughter and family members. Lastly Public Service Department and Malaysia Nuclear Agency for their sponsorship and permission to further study.

ABSTRACT

Radiation hard detectors are difficult and costly to design. Moreover silicon based detectors are not superior in-term of high temperature environment compared to wide band semiconductor materials such as zinc oxide (ZnO). ZnO semiconductor are actively studied for the past decade due to its versatile properties such as high transparency, ability to be deposited at low temperatures, and high resistance towards radiation. Radiation hard materials must be able to withstand high temperature operation. A nuclear power plant demands high temperature up to 673 K operation especially near reactor pressure vessel. Not many work are done on the effect of temperature on radiation hard semiconductor material. The aims of this research is to remodel and simulating two different ZnO/p-Si heterojunction diode structure material and to study the temperature effect of diode parameters such as barrier height, apparent barrier height, ideality factor (η), series resistance, shunt resistance, simulation of Spice ZnO/p-Si heterojunction diode model and subsequently to optimize thermal stability for high temperature application such as radiation detector and electrical power plant. Modeling and simulation was analyzed and executed in Matlab and LTSpice. During characterization, the temperature were ramped-up from room temperature to 673 K. Furthermore, this analyzed result were compared to experimental result that have been published on high ranking journal. For each temperature, the parameters extracted were tabulated. Subsequently, all electrical characteristic obtained have been plotted on graph. On top of that, the effect of barrier inhomogeneity have been carried out and there were three prime prove of barrier inhomogeneity which is small barrier height value obtain from gradient of $ln(\frac{I_O}{T^2})$ versus V^{-1} , low Richardson constant value, and linearly lines on plotted barrier height against ideality factor. Result shows the structure 1 ideality factor of 2.07 were achieved at 673 K temperature with semi-empirical structure 2 hole concentration and calculated structure 1 electron concentration of 7.05x10$^6 cm^{-3}$ and 2.59x10$^{13} cm^{-3}$ respectively. Beside that, the activation energy was found at 0.35 eV. In conclusion, structure 1 ZnO/p-Si heterojunction diode shows good thermal stability compared to structure 2 but structure 2 show ability to fabricate high current and low turn on voltage of 0.8 V at room temperature. It has been observed that structure 1 ZnO/p-Si can withstand up to 673 K temperature thus proven that ZnO/p-Si as an substitute or alternative to high temperature environment operation.

ABSTRAK

Pengesan radiasi adalah sukar dan mahal untuk direka cipta. Tambahan pula pengesan radiasi berasaskan silikon memiliki ketahanan yang kurang baik untuk digunakan pada suhu yang tinggi berbanding semikonduktor yang bahannya daripada Zink Oksida (ZnO). Banyak kajian telah dijalankan terhadap semikonductor ZnO kerana sifatnya yang tinggi kadar lut sinar, kebolehupayaan untuk didepositkan ketika suhu rendah, dan kerintangan yang tinggi terhadap radiasi. Bahan yang tahan radiasi adalah tinggi daya tahan dan beroperasi pada suhu yang tinggi. Loji jana kuasa nuklear memerlukan bahan yang berupaya untuk manampung suhu yang tinggi dan beroperasi pada suhu 673 K terutamanya berhampiran dengan kerangka jana tekan. Namun begitu tidak banyak kajian yang dijalankan terhadap bahan semikonductor yang tinggi kadar ketahanan radiasinya kepada perubahan suhu yang tinggi. Matlamat kajian ini adalah untuk merangka model dan menjalankan simulasi dua jenis struktur bahan ZnO/p-Si persimpangan hetero diod bagi mengkaji kesan suhu terhadap parameternya iaitu penghadang, penghadang yang benar, faktor ideal, rintangan sesiri, rintangan selari, simulasi di dalam Spice, dan untuk mengenalpasti struktur yang optimal dan stabil terhadap suhu yang tinggi iaitu sesuai untuk digunapakai sebagai pengesan radiasi dan di dalam aplikasi jana kuasa elektrik. Semua model dan simulasi ini dianalisa dan dilaksanakan di dalam perisian Matlab dan LTSpice. Semasa pencirian parameter dijalananankan, suhunya diubah dari suhu bilik ke 673 K. Analisa kajian ini dibandingkan dengan hasil kajian yang diterbitkan di dalam jurnal yang terkenal. Bagi setiap suhu, semua parameter yang diperolehi direkodkan. Semua pencirian elektrikal juga di lukiskan grafnya. Tambahan pula, kesan penghadang yang diluar jangkaan juga telah dikaji. Berdasarkan kajian, terdapat tiga bukti yang menunjukkan kesan penghadang diluar jangkaan iaitu melalui hasil penemuan nilai penghadang yang dijumpai melalui kaedah kecerunan graf $ln(\frac{I_O}{T^2})$ berlawanan V^{-1} adalah kecil, nilai Richardson yang sekata adalah kecil, dan wujudnya graf garis lurus di antaran penghadang berlawan faktor ideal. Hasil penemuan struktur 1 menunjukkan faktor idealnya ialah 2.07 ketika suhu mencecah 673 K dan kepadatan lohong struktur 2 ialah 7.05x10$^{6}cm^{-3}$ manakala kepadatan elektron struktur 1 ialah 2.59x10$^{13}cm^{-3}$. Selain daripada itu, pengaktifan tenaga yang diperolehi ialah 0.35 eV. Secara kesimpulannya struktur 1 menunjukkan ketahanan terhadap suhu yang tinggi berbanding struktur 2. Walau bagaimanapun struktur 2 berupaya untuk menghasilkan arus elektrik yang tinggi pada nilai permulaan voltan yang rendah iaitu 0.8 V sewaktu suhu bilik. Oleh yang demikian, didapati struktur 1 memiliki kebolehupayaan untuk bertahan sehingga suhu mencecah 673 K dan sekali gus membuktikan bahawa ZnO/p-Si boleh digantikan atau menjadi alternatif kepada aplikasi yang memerlukan suhu pengoperasian yang tinggi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Si	-	Silicon
AZO	-	Aluminum Doped Zinc Oxide
ZnO	-	Zinc Oxide
Ti	-	Titanium
ZnO/p-Si	-	Zinc Oxide and p-type Silicon
$SrCu_2O_2$	-	Strontium Copper Preoxide
NiO	-	Nickel Oxide
$ZnRh_2O_4$	-	Zinc Rhodium Tetraoxygen
UV	-	Ultra Voilet
PMT	-	Photomultiplier Tube
HV-DC	-	High Voltage Direct Current
KeV	-	Kilo Electron Volt
MeV	-	Mega Electron Volt

LIST OF SYMBOLS

$e\phi$	-	Workfunction
χ	-	Electron Affinity
E_F	-	Fermi Level Energy
E_{Fi}	-	Intrinsic Fermi Level Energy
E_C	-	Conduction Band Energy
E_V	-	Valance Band Energy
ΔE_C	-	Conduction Band Offset
ΔE_V	-	Valance Band Offset
E_g	-	Energy Band Gap
m_e	-	Electron Effective Mass Density of State
m_{oe}	-	Electron Mass
n_c	-	Conduction Band Density of State
n_a	-	Acceptor Concentration
n_d	-	Donor Concentration
V_{bi}	-	Build in Potential
T	-	Temperature
n_i	-	Intrinsic Concentration
V_{do}	-	Diffusion Voltage
K	-	Boltzmann Constant
I_O	-	Reverse Saturation Current
A	-	Contact Area
$A^\star$	-	Richardson Constant
V_T	-	Thermal Voltage
R	-	Universal Gas Constant
e_{vc}	-	Electron Volt Constant
η	-	Ideality Factor
I	-	Current

V_{bias}	-	Bias Voltage
R_j	-	Junction Resistance
r_d	-	Piecewise Linear Model Resistance

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Zinc Oxide (ZnO) is one of the propitious material for semiconductor device applications. ZnO also have large free exciton binding energy [1],wide band gap, high electron mobility, good transparency, high thermal conductivity [2], large saturation velocity, exitonical emission process above room temperature, and strong radiation hardness [3]. It is also available in large bulk single crystal. Besides, it exhibit good design and fabrication process, it performs well in wet chemical etching with low growth cost. ZnO are almost n-type, that has been the reason an extensive debate and research.

ZnO proffer numerous synthesis technique such as metal organic chemical vapor deposition, chemical bath deposition, pulsed laser deposition, spray pyrolysis, thermal evaporation, vapor phase transport, arc discharge, template directed wet and dry, sol gel, microwave synthesis, carbothermal, sputtering, and so forth. Furthermore, ZnO electrical properties can be controlled by doping level, thus it can change from insulator through ZnO semiconductor to metal. Indeed, there are few ZnO heterojunction devices such as $SrCu_2O_2$/ZnO [4], NiO/ZnO [4], ZnO/SiC [5], $ZnRh_2O_4$/ZnO [4] and ZnO/Si. Consequently, ZnO/Si is the most established heterostructure in term of cost effectiveness and maturity of Si based material. ZnO has been actively researched for various electronic applications such as UV astronomy, sensors, light emitting diodes, piezoelectric, solar cell, actuator, space to space communication [3] and environmental monitoring [6].

However there are lack of study on ZnO as semiconductor radiation detector. It is known that a good commercial radiation detector in the current market is on scintillation detector(inorganic scintillator) but this detector require additional cooler to operate at high temperature and bulky in size. Apart of that, ZnO as a wide band gap semiconductor has good radiation absorption efficiency toward gamma and photon.

However, no research have been carried out to find thermally stable structure that can be operated at temperature up to 673 K.

1.1 Project Problem Statement

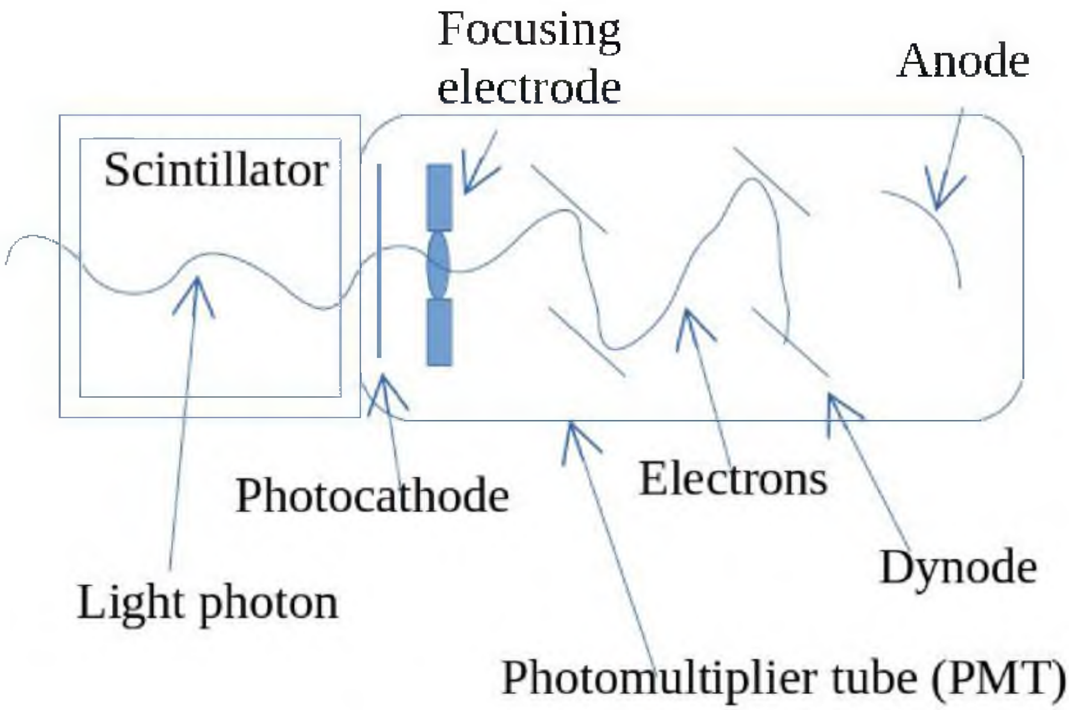

Figure 1.1: Basic Scintillation Detector.

The definition of scintillation is a luminescence of light with characteristic spectrum produces by passing a particle and absorb radiation energy. Beside that, scintillation also transpire from inorganic material such as liquid, gases, and salt. Based of Fig.1.1 above, a scintillation detector has been made up of scintillator and light detector also known as photomultiplier tube(PMT). Scintillator will absorb energy when it gets excited when strucked by incoming ionizing radiation particle such as electron, alpha, ion, or even high photon energy and produce light energy. Photoelectric effect occur in PMT that convert an absorbed light energy to electron form. Conventionally, ionizing radiation energy ranges from a few kilo electron volts to mega electron volts (KeV to MeV) in form of alpha, beta particle, x-ray and y-ray. However, in terms of implementation, scintillation detector commonly connected to direct current high voltage (HV-DC) power source from 450 V to 1000 V. Meanwhile, output signal will be preamplified before amplified and analyzed using either single channel analyzer or multichannel analyzer as show on Fig.1.2.

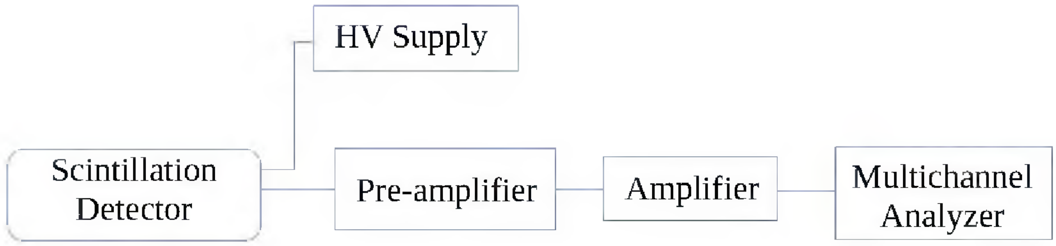

Figure 1.2: Basic Scintillation Detector Block Diagram.

The predicament when using scintillation detector require additional cooling when operating at high temperature(up to 673 K) and bulky in size. The prospect of using ZnO/p-Si device as a radiation detector is high due to its thermal stability [7] [1]. Thus ZnO/p-Si device is a suitable complimentary or cost effective to scintillation detector.

1.2 Project Objectives

There are three main objectives that need to achieve. These three main aims are listed as below :

- To remodel and simulate two different heterojunction diode structures based on ZnO/p-Si material in Matlab and LTSpice.
- To study the temperature effect of diode parameters such as ideality factor, barrier height, apparent barrier height, series resistance, shunt resistance, and simulation of Spice ZnO/p-Si Heterojunction Diode Model.
- To determine suitable structure for thermally stable high temperature application such as radiation detector.

1.3 Project Scope of Work

Basically ZnO/p-Si heterojunction diode research is governed either by

- Modeling
- Simulation

- Fabrication
- Electrical Characterization

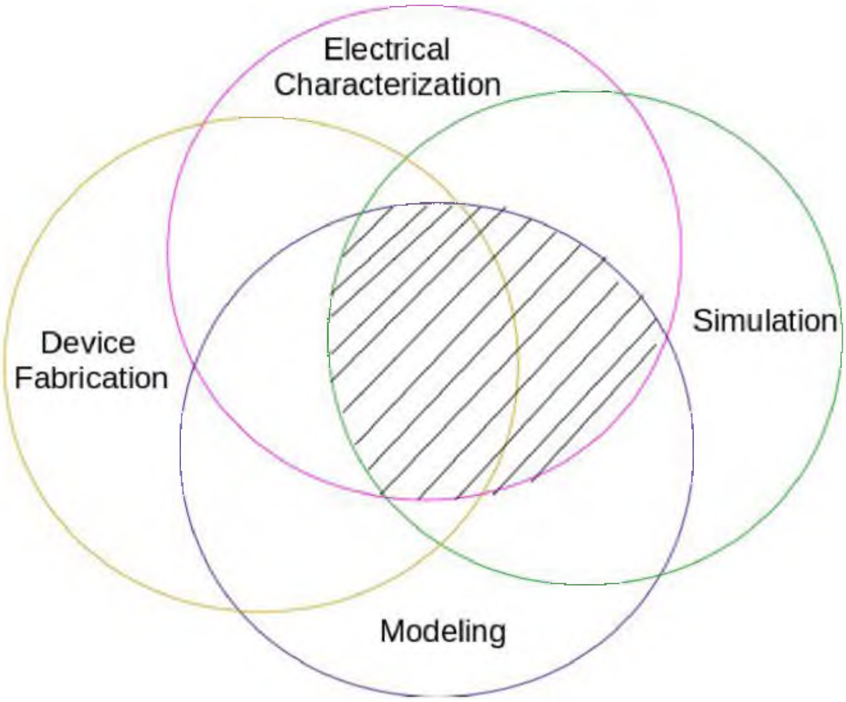

Figure 1.3: Basic ZnO/p-Si Heterojunction Diode Research Scope of Work.

However this project is limited to basic modeling, simulation, and electrical characterization using Matlab and LTSpice as show on Fig.1.3, the shaded area. Beside that, this project also limited to certain constraints as follow :

i. Limited to ZnO/p-Si material as heterojunction diode.
ii. Lattice matching, effect of series and shunt resistance in circuit modeling and analysis is not covered in this study.
iii. Basic modeling and simulation is run in Matlab and LTSpice.
iv. All chareacterization result are plotted and tabled.
v. The maximum temperature is being studied at 673 K.
vi. Spice ZnO/p-Si Heterojunction Diode Model is limited on positive forward bias voltage and DC voltage source only.
vii. Minimum ideality factor is assume to be 1.
viii. Some experimental data are taken from golden reference and some of experimental data are calculated based on given data from golden reference.

1.4 Summary of Contribution

In this project I strive to remodeled and simulated two ZnO/p-Si heterojunction diode structures taken from literature using Matlab and LTSpice. The effect of ideality factor, barrier height, apparent barrier height, series resistance, and shunt resistance towards temperature variation are studied and finding apparent ideality factor, activation energy, Richardson constant without barrier inhomogeneity, Richardson constant with barrier inhomogeneity, junction resistance, turn on voltage, and current-voltage. Hence the main accomplishment are as follow:

a. H. Hasim, S.M. Sultan,'Temperature Analysis of. ZnO/p-Si Heterojunction Using Thermionic Emission Model',AIP Conference Proceeding.(Submitted)

b. Successfully remodel and simulate ideality factor towards temperature variation in Matlab.

c. Successfully remodel and simulate barrier height towards temperature variation in Matlab.

d. Successful remodel and simulate apparent barrier height towards temperature variation in Matlab.

e. Successful remodel and simulate series resistance towards temperature variation in Matlab.

f. Successful remodel and simulate shunt resistance towards temperature variation in Matlab.

g. Successful remodel and simulate activation energy in Matlab.

h. Successful remodel and simulate Richardson Constant with and without barrier inhomogeneity in Matlab.

i. Successful remodel and simulate apparent ideality factor in Matlab.

j. Successful remodel and simulate junction resistance in Matlab.

k. Successful remodel and simulate turn on voltage in Matlab and LTSpice.

l. Successful remodel and simulate current-voltage in Matlab and LTSpice.

1.5 Thesis Organization

This thesis is divided into five further chapters. Chapter two covers literature review of ZnO/p-Si heterojunction diode at various temperature. This literature review with structure within have been published on recognized journals and conference from 2007 to 2017. Following on chapter 3, the theoretical background cover theory behind heterojunction diode such as ohmic contact, heterojunction contact, structure 1 and structure 2 overview. On chapter 4, this thesis will cover basic modeling and Spice simulation technique. It will start from basic modeling flow chart to electrical characterization and end at Spice simulation. In addition to that, Chapter 5 will be finding semi-empirical electrical characterization of ZnO/p-Si heterojunction diode on first structure and semi-empirical electrical characterization of ZnO/p-Si heterojunction diode on second structure . In this chapter, it also narrate the comparison of semi-empirical structure 1 and semi-empirical structure 2 for thermally stable structure to operated at 673 K. Lastly chapter 6 will be the conclusion, suggestion, and possible future work on ZnO/p-Si heterojunction diode.

REFERENCES

1. Badran, R. I., Umar, A., Al-heniti, S., Al-hajry, A. and Al-harbi, T. Synthesis and characterization of zinc oxide nanorods on silicon for the fabrication of p -Si / n -ZnO heterojunction diode. *Journal of Alloys and Compounds*, 2010. 508(2): 375–379.

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

3. Sharma, S., Bayer, B. C., Skakalova, V., Singh, G. and Periasamy, C. Structural, Electrical, and UV Detection Properties of ZnO/Si Heterojunction Diodes. *IEEE Transactions on Electron Devices*, 2016. 63(5): 1949–1956.

4. Sharma, S. and Periasamy, C. A study on the electrical characteristic of n-ZnO / p-Si heterojunction diode prepared by vacuum coating technique. *Superlattices and Microstructures*, 2014. 73: 12–21.

5. Li, X., Zhang, B., Dong, X., Zhang, Y., Xia, X., Zhao, W. and Du, G. Room temperature electroluminescence from ZnO / Si heterojunction devices grown by metal organic chemical vapor deposition. *Journal of Luminescence*, 2009. 129: 86–89.

6. Zahedi, F., Dariani, R. S. and Rozati, S. M. Ultraviolet photoresponse properties of ZnO : N / p-Si and ZnO / p-Si heterojunctions ZnO or ZnO : N. *Sensors & Actuators: A. Physical*, 2013. 199: 123–128.

7. Pietruszka, R., Luka, G., Witkowski, B. S., Kopalko, K., Zielony, E., Bieganski, P., Placzek-popko, E. and Godlewski, M. Electrical and photovoltaic properties of ZnO / Si heterostructures with ZnO fi lms grown by atomic layer deposition. *Thin Solid Films*, 2014. 563: 28–31.

8. Aksoy, S. and Caglar, Y. Effect of ambient temperature on electrical properties of nanostructure n-ZnO/p-Si heterojunction diode. *Superlattices and Microstructures*, 2012. 51(5): 613–625.

9. Al-hardan, N. H., Jalar, A., Hamid, M. A. A., Kar, L., Ahmed, N. M. and Shamsudin, R. A wide-band UV photodiode based on n-ZnO / p-Si heterojunctions. *Sensors & Actuators: A. Physical*, 2014. 207: 61–66.

10. Bedia, F. Z., Bedia, A., Benyoucef, B. and Hamzaoui, S. Electrical characterization of n-ZnO / p-Si heterojunction prepared by spray pyrolysis technique. *Physics Procedia*, 2014. 55: 61–67.

11. Chirakkara, S. and Krupanidhi, S. B. Study of n-ZnO / p-Si (100) thin fi lm heterojunctions by pulsed laser deposition without buffer layer. *Thin Solid Films*, 2012. 520(18): 5894–5899.

12. Cho, S. G., Lee, D. U. and Kim, E. K. Photoresponse of n-ZnO / p-Si photodiodes to violet-green bandwidth light caused by defect states. *Thin Solid Films*, 2013. 545: 517–520.

13. Cho, S. G., Nahm, T.-u. and Kim, E. K. Deep level states and negative photoconductivity in n-ZnO / p-Si hetero-junction diodes. *Current Applied Physics*, 2014. 14(3): 223–226.

14. He, G.-r., Lin, Y.-j., Chang, H.-c. and Chen, Y.-h. Effects of interface modification by H 2 O 2 treatment on the electrical properties of n-type ZnO / p-type Si diodes. *Thin Solid Films*, 2012. 525: 154–157.

15. Hwang, J. O., Lee, D. H., Kim, J. Y., Han, T. H., Kim, B. H., Park, M., No, K. and Kim, S. O. Vertical ZnO nanowires/graphene hybrids for transparent and flexible field emission. *J. Mater. Chem.*, 2011. 21(10): 3432–3437.

16. Hwang, J. D. and Chen, Y. H. Carrier transport mechanism on ZnO nanorods / p-Si heterojunction diodes with various atmospheres annealing hydrothermal seed-layer. *Thin Solid Films*, 2012. 520(16): 5409–5412.

17. Hwang, J. D. and Chen, Y. H. Effects of pre-annealing conditions on the characteristics of ZnO nanorods and ZnO / p-Si heterojunction diodes grown through hydrothermal method. *Thin Solid Films*, 2012. 520(16): 5294–5299.

18. Jin, C., Narayan, R., Tiwari, A., Zhou, H., Kvit, A. and Narayan, J. Epitaxial growth of zinc oxide thin films on silicon. *Materials Science and Engineering B*, 2005. 117: 348–354.

19. Kim, K., Moon, T., Lee, M., Kang, J., Jeon, Y. and Kim, S. Light-emitting diodes composed of n-ZnO and p-Si nanowires constructed on plastic substrates by dielectrophoresis. *Solid State Sciences*, 2011. 13(9): 1735–1739.

20. Kim, C., Lee, H., Lee, B., Lee, Y., Lee, S. and Kim, D. Y. Effects of oxygen plasma pre-treatments on the characteristics of n -ZnO / p -Si heterojunction diodes. *Current Applied Physics*, 2014. 14(10): 1380–1384.

21. Klason, P., Rahman, M. M., Hu, Q., Nur, O., Turan, R. and Willander, M. Fabrication and characterization of p-Si / n-ZnO heterostructured junctions.

Microelectronics Journal journal, 2009. 40: 706–710.

22. Luo, J. T., Zhu, X. Y., Chen, G., Zeng, F. and Pan, F. The electrical , optical and magnetic properties of Si-doped ZnO films. *Applied Surface Science*, 2012. 258(6): 2177–2181.

23. Ocak, Y. S. Electrical characterization of DC sputtered ZnO / p-Si heterojunction. *Journal of Alloys and Compounds*, 2012. 513: 130–134.

24. Physics, A. Epitaxial growth and luminescence properties of ZnO-based heterojunction light-emitting diode on Si (1 1 1) substrate. *J. Phys. D: Appl. Phys.*, 2014. 41(September 2008).

25. Pietruszka, R., Luka, G., Kopalko, K., Zielony, E. and Bieganski, P. Photovoltaic and photoelectrical response of n-ZnO / p-Si heterostructures with ZnO films grown by an Atomic Layer Deposition method. *Materials Science in Semiconductor Processing*, 2014. 25: 190–196.

26. Pietruszka, R., Schifano, R., Krajewski, T. A., Witkowski, B. S., Kopalko, K., Wachnicki, L., Zielony, E., Gwozdz, K., Bieganski, P., Placzek-popko, E. and Godlewski, M. Improved ef fi ciency of n-ZnO / p-Si based photovoltaic cells by band offset engineering. *Solar Energy Materials and Solar Cells*, 2016. 147: 164–170.

27. Rajabi, M., Dariani, R. S., Iraji, A. and Zahedi, F. Optoelectronic properties of cauliflower like ZnO ZnO nanorod / p-Si heterostructure. *Solid State Electronics*, 2013. 80: 33–37.

28. Rodríguez-moreno, J., Navarrete-astorga, E., Romero, R., Martín, F., Schrebler, R., Ramos-barrado, J. R. and Dalchiele, E. A. Electrochemically grown vertically aligned ZnO nanorod array / p + -Si (100) heterojunction contact diodes. *Thin Solid Films*, 2013. 548: 235–240.

29. Shen, L., Ma, Z. Q., Shen, C., Li, F., He, B. and Xu, F. Studies on fabrication and characterization of a ZnO / p-Si-based solar cell. *Superlattices and Microstructures*, 2010. 48(4): 426–433.

30. Shokeen, P., Jain, A. and Kapoor, A. Plasmonic ZnO / p-silicon heterojunction solar cell. *Optical Materials*, 2017. 67: 32–37.

31. Singh, A., Senapati, K., Datta, D. P., Singh, R., Som, T., Bhunia, S., Kanjilal, D. and Sahoo, P. K. Synthesis of p n junctions in ZnO nanorods by O + ion implantation. *Nuclear Inst. and Methods in Physics Research, B*, 2017: 2–5.

32. Somvanshi, D. and Jit, S. Analysis of temperature-dependent electrical characteristics of n-ZnO Nanowires (NWs)/p-Si heterojunction diodes. *IEEE*

Transactions on Nanotechnology, 2014. 13(1): 62–69.

33. Yakuphanoglu, F., Caglar, Y., Caglar, M. and Ilican, S. ZnO / p-Si heterojunction photodiode by sol gel deposition of nanostructure n-ZnO film on p-Si substrate. *Materials Science in Semiconductor Processing*, 2010. 13(3): 137–140.

34. Zebbar, N., Kheireddine, Y., Mokeddem, K., Hafdallah, A., Kechouane, M. and Aida, M. S. Structural , optical and electrical properties of n-ZnO / p-Si heterojunction prepared by ultrasonic spray. *Materials Science in Semiconductor Processing*, 2011. 14(3-4): 229–234.

35. Gao, Z., Jahed, N. M. S. and Sivoththaman, S. Biased Photoresponse Analysis of Al-ZnO Heterojunctions with n- and p-Type Silicon. *IEEE Trnsactions on Electron Devices*, 2017. 64(3): 1100–1107.

36. Schmitsdorf, R.F., Kampen, T.U., Mönch, W. Explanation of the linear correlation between barrier heights and ideality factors of real metal-semiconductor contacts by laterally nonuniform Schottky barriers. *Journal of Vacuum Science and Technology B: Microelectronics and Nanometer Structures*, 1997. 15,(4,): 1221–1226.