A Highly Sensitive Heterojunction Photodetector for UV Application

Jitty Jose
PG Scholar
Saintgits college of Engineering.
Kottayam, Kerala

Ajith Ravindran
Assistant professor
Saintgits college of Engineering
Kottayam,Kerala

Keerthi K Nair
PG Scholar
Saintgits college of Engineering
Kottayam, Kerala

***Abstract*— ZnO is considered as the most eminent semiconductors in the metal-oxide family because of its supreme properties which tempt many researcher groups to use this material for UV detection applications. In the earlier days, ZnSe and GaN based technologies create remarkable advance in the blue and UV LEDs and injection laser. Undoubtedly, GaN is considered to be the suitable candidate for optoelectronic devices fabrication.The effectiveness of photodetector is measured in terms of responsivity. The responsivity of n-ZnO/p-GaN is 0.678 mA/W at zero bias condition was reported, which can be improved by adding an intrinsic layer in between ZnO and GaN. At zero bias voltage, the peak responsivity of n-ZnO/i-ZnO/p-GaN heterojunction photodetector was 138.9 mA/W at 362 nm under the front illumination condition. This responsivity is still lower for various sensing and military applications. The responsivity of n-ZnO/i-ZnO/p-GaN heterojunction photodetector can be further improved by adding a SiO_2 layer in between p-GaN and i-ZnO. The insertion of SiO_2 layer reduces the visible response and boost the UV response. It is very important in many application such as whenever it is desirable to detect UV in visible and IR background. The n-Zno/i-ZnO/SiO_2/p-GaN is a perfect structure for solar blind detector. By adding SiO_2 layer the responsivity can be improved to 172.7 mA/W at 362 nm. This analysis is done by using TCAD tool.**

Keywords*— Photodetector, Heterojunction, Responsivity, ZnO, GaN.

I. INTRODUCTION

Over a last five decades, the opto-sensing industry has also seen in rapid growth. The researcher develop a multilayer substrate with high density interconnect that is the reason for rapid acceleration in this field. Now a days, opto-sensing field not only need to improvement of existing system but also required to perspicacious next generation system. The components which are used to optoelectronics sensing field are photodetector, phototransistor, photo resistor etc. The benefits of photodetectors (PD) are fast response and produce measurable output electrical parameter for a small amount of light, which can be easily regenerated, and are economical for various application like sensing, high speed optical communication, Bio sensing, gas detection, smoke detection etc. The major performance requirement of photodetectors are high sensitivity, low noise, wide bandgap, high reliability and low cost.

The working principle of photodetectors are varies according to different types and operate in slightly different ways, the basic operation of all photodiodes remains the same. The photodetectors are operated under a moderate reverse bias condition. Light energy consists of packet of lights known as photons. Under the reverse bias condition, the depletion regions are free from charge carriers and there is current flow occur. Whenever the photons with sufficient energy enters in to depletion region, it may hits an atoms in the crystal lattice and release an electrons. In this way electron hole pair is generated. The generated electron hole pair moves the opposite direction under the effect of electric field. The generated output current is proportional to the amount of light entering to the depletion region. The intensity of light is increase, the number of generated electron hole pair is increased and which leads to greater current flow. An increase in reverse bias voltage causes the depletion region become wider and wider, which increases sensitive area or active area of photodetector. The basic requirement of electron hole pair generations in the photodetector are the bandgap energy of a material should be smaller than incident photon energy. When photons of energy greater than bandgap energy of silicon i.e. 1.1eV fall on the device, the electron hole pair is generated. The depth of absorption of photon depends on their energy. The depth of absorption is increases with decrease in energy of photon. Due to the reverse bias the carriers are drift apart, resulting the minority carriers reach the junction, this carriers are swept across by the electric field in the depletion junction. If both sides are electrically connected, an external current flow occur through the connection. The carriers generated outside the active area do not have an effect on generation of illumination current. So the active area of photodetector should be maximized for better responsivity and higher switching speed. PIN structure contributes better responsivity [1]

Nowadays, Homo junction and heterojunction photodetector application goes through a wide variety of shorter and longer wavelength range. Researchers developed, some of the photodetectors are highly sensitive to particular wavelength region and blind in other regions, and also others detect one or more wavelength simultaneously over a single structure. Homo junction PD have higher noise and large leakage current. This problem can be reduced by using heterojunction photodetectors that have different bandgap energies but firmly matching lattice parameters. Various compound semiconductor materials like group III-V, II-VI and IV-VI are commonly used for photo detection applications. Technological development in fabrication of materials and their built in favorable properties make II-VI oxide as most promising material for UV applications. ZnO is one of the properties semiconductors in this oxide family with large bandgap (3.37 eV) and large extinction energy

(~60meV) and is very sensitive to UV region because of its higher photoconductivity and ultra violet absorbance. ZnO/GaN the best choice because of its adaptability with integrated circuit technology and also small in plane lattice mismatch, less than 1.8% [2- 3].

This paper is structured into various sections. Section II includes the literature review which cover the responsivity of photodetector, material for heterojunction photodetector and ZnO photodetectors. Section III analysis ZnO UV detector with GaN structure and responsivity curve of n-ZnO/p-GaN structure, n-ZnO/i-ZnO/p-GaN & n-ZnO/i-ZnO/SiO_2/p-GaN structure. Section VI deals with the results and discussion. Section VII concludes the paper, along with scope for future work in this topic.

II. LITERATURE REVIEW

A. *Responsivity of photo detectors*

Responsivity is the one of the crucial parameters that describe the behavior of photodetector. Responsivity of a photodetector may be defined as the ratio of photocurrent to the incident light power at given wavelength. It is the measure of the sensitivity to light. Responsivity indicates the effectiveness of the conversion of light power in to electrical current. The responsivity of photodiode changes with incident wavelength, applied voltage and also temperature. Responsivity increases with reverse bias voltage this is due to improved charge collection efficiency in the photodiode. Temperature affects responsivity, because of decreases or increase of the bandgap, due to increase or decreases in temperature respectively. The responsivity is given by the equation 1

$$R=\frac{q\eta\lambda}{hc} \tag{1}$$

Where, R denotes the responsivity, λ is the wavelength of light, η is the external quantum efficiency, c is the velocity of light and h is the Plancks constant. External quantum efficiency is obtained from the ratio of cathode current to source photocurrent. Source photo current may be defined as the current available in light beam or the amount of current generated by the light source. Cathode current is the output current

The various parameters that depend on the responsivity of photodetectors are oxide thickness, acceptor concentration and donor concentration. Responsivity increases with oxide thickness because decrease in resistivity of ZnO layer with increase in thickness. The acceptor and donor concentration increases with decrease in responsivity [4].

B. *Material for heterojunction photodetector*

Heterojunction devices are playing a crucial role in optoelectronics field. The material used within a photodiode determine many of its important properties. The level of noise and range of wavelength to which the photodetectors respond are most crucial parameters that are dependent up on the material used in the photodiode. Different material have different wavelength sensitivity because only light with sufficient energy to excite an electron across the bandgap of the material will produce sufficient energy to create the current from the photodiode. The recent optoelectronics devices are produced by combining semiconductor material that have different bandgap energies but firmly matching lattice parameters. The group III-V compound heterojunction photodetector have been extensively developed in the past decades and other II-V and IV-VI compound materials are also used for optoelectronics industry.

The group II-VI compound semiconductor based on zinc chalcogenides and cadmium chalcogenides are ZnO, ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe etc. The properties of this chalcogenides are direct bandgap, large exciton binding energy, and high fluorescent yield which results flexibility to fabricate the device such as photodetectors and LED. II-VI compound semiconductors are not commonly used in practical optoelectronic devices despite of their excellent attributes. The current II-VI wafer fabrication technology offers a poor material quality which acts as obstacle for making of II-VI based devices.

The researcher team effectively utilised the nanotechnology to overcome the material difficulties. In practical aspects, the effect made in the area of II-VI nanostructures is appreciable. The researcher in this area have been successfully conduct control synthesis and assembly of these nanostructures. And also explore and investigate the fascinating optical properties in synthesized II-VI nanostructure of nanoscale. The results shows that huge material advantages of II-VI semiconductor nanostructure over their bulk counterparts. The advantages of II-VI compound semiconductor are easier to grow Nano sized crystals with surpassing optical qualities and low detect density, II-VI compound semiconductors with different chemical compositions could be integrated into one hierarchical nanostructure conveniently and also, nanostructures of II-VI compound semiconductors could be gently doped to modify their optical properties with ease.
Based on the advantage of II-V compound material as said above this compound material has replaced existing materials used in the optoelectronics industry. The II-VI elements enhance the photocurrent and reduce the dark current in the photodetectors. The proper selections of II-V compound materials improve the responsivity, detectivity and enhance the noise equivalent power.The findings have great application for II-VI compound semiconductors nanostructure devices in high-sensitivity and high-speed nanoscale device [5-6].

C. *ZnO photodetector*

ZnO is the one of the promising wide bandgap semiconductor material for UV and blue optoelectronics devices such as photodiodes, laser diodes, solar cells, light emitting diodes etc. ZnO exhibits many advantages like large exciton binding energy (~60meV), high radiation hardness, relatively low material cost for large area substrate, ZnO offers a simplified processing, and it can be fabricated by conventional wet-chemical etching process. Large excition binding energy leads to UV source with higher brightness and lower power threshold at lower temperature and also higher radiation hardness of ZnO leads to suitable choice for space applications. One of the major drawback of ZnO is the p type doping. Usually ZnO have n type conductivity, it is very difficult to make p type ZnO films due to extensive accepter level, low dopants solubility, and self-compensation process. Due to this reason the researchers choose the p type material

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 09, September-2016

such as GaN, Si, NiO, $Sr_2Cu_2O_2$ for realize p-n heterojunction. The researchers develop ZnO based p-n homo junction photodiode in the beginning of 20th century but this is not popular as much [7].

Different semiconductor material have been used to fabricate photodetector with high efficiency in the UV region. Wide bandgap semiconductor material like ZnO and GaN and their various alloys shows extremely interesting properties in terms of bandgap engineering. Now the researcher are interested in n-ZnO/p-GaN heterojunction photodetector over a homo junction photodetector which shows improved current confinement which leads to higher recombination rates at interface as a result the efficiency of the device become higher The lattice mismatch between ZnO and GaN are less than 1.8 % . ZnO/GaN structure provides the freedom to design unique optoelectronics device overcoming the problem of p-type ZnO.

III. ZNO UV PHOTODETECTOR

The important applications of UV photodetectors are smoke sensing, gas sensing, space to space communications and various military applications. All of these applications required to quick response to input parameters and fast and effective conversion to this input parameter in to electrical impulse. This effectives of conversion is measured in terms of responsivity. The important properties required to the UV photodetector are very sensitive devices with high signal-to-noise ratio and high response speed. Among the various p-type material GaN is the best substrate for UV applications. GaN is act as a filter layer and provide sharp cut off between UV and visible region. The n-ZnO/p-GaN structure is best suited for solar blind detector [8-9].

A. Responsivity of n-ZnO/p-GaN Heterojunction photodetector

The researcher focused the responsivity of ZnO with GaN substrate structure at the beginning of 20th century. Various fabrication technique like MOCVD and MBE are used to improve the responsivity. Some of the researcher are focused on the structural modification and also angle of incident beam.

In 2013 L. Su et al realized n-ZnO/p-Si UV photo response based on MOCVD and MBE. At zero bias voltage peak responsivity of 0.68 mA/W at 358 nm peak was reported [10]. This is very low for higher ended applications. n-ZnO/p-GaN exhibits fast response and low dark current but the lower responsivity poses the major challenging problem [11]

The Fig 2.1 shows responsivity curve of n-ZnO/p-GaN heterojunction photodetector at zero biasing condition. At zero bias voltage the peak responsivity of n-ZnO/p-GaN heterojunction photodetector 0.678mA/W is obtained. The advantage of this structure is fast response speeds and low dark current, but the responsivity is very low for various applications. Responsivity of n-ZnO/p-GaN can further be improved by structural modification. Adding an intrinsic layer in-between ZnO and GaN provides better response over the PN structure

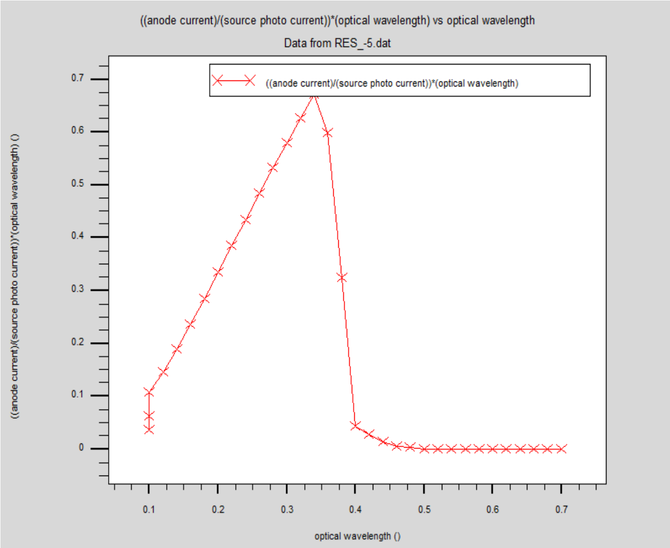

Fig.2.1 Responsivity curve of n-ZnO/p-GaN Heterojunction photodetector

B. Responsivity of n-ZnO/i-ZnO/p-GaN heterojunction photodetector

The responsivity of n-ZnO/p-GaN can be improved by adding an intrinsic layer in between n type and p type material. At 2015, Lichun et al conducted a study on optoelectronics characteristics of UV photodetectors based on n-ZnO/i-ZnO/p-GaN structure [12]. The carriers generated outside the depletion region or active area does not contributes any photocurrent. Due to the thick intrinsic layer most carriers are generated in the intrinsic region, which leads to improve the photocurrent as well as responsivity. Another effect of the thick intrinsic region is reduced capacitance, which allows for the higher perception bandwidth. [13-14]

The responsivity curve of n-ZnO/i-ZnO/p-GaN heterojunction photodetector is shown in the Fig 2.2. The responsivity of n-ZnO/p-GaN was 0.678mA/W has been improved to138.9mA/W at zero bias condition by inserting an intrinsic layer in between n-ZnO/p-GaN which is very suited for highly sensitive solar blind applications.

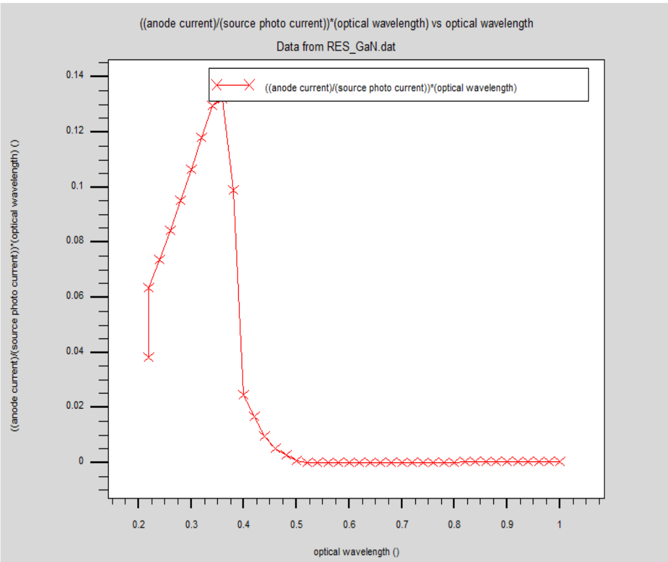

Fig.2.2 Responsivity curve of n-ZnO/i-ZnO/p-GaN

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 09, September-2016

C. Responsivity of n-ZnO/i-ZnO/SiO_2/p-GaN heterojunction photodetector

The responsivity of n-ZnO/i-ZnO/p-GaN can be further improved by adding a SiO_2 buffer layer in between i-ZnO and p-GaN. Observations found that the p-i-n heterojunction photodetector with SiO_2 insertion can decrease the leakage current and hence increase the rectification ratio. The insertion of SiO_2 also decreases visible response and enhance ultraviolet (UV) response, resulting in a higher ratio of UV to visible. that the ultrathin SiO_2 layer with positive fixed charges not only acts as a hole blocking layer but also helps the photo generated electrons to tunnel through the barrier. In addition, the SiO_2 layer can effectively passivate the defects generated by wet etching process. Under both of forward and reverse bias cases, the SiO_2 interlayer preferentially promotes electrons tunnelling through the barrier and hinders holes to stay in the initial generated layer [15-17]

The variation of responsivity with optical wavelength of n-ZnO/i-ZnO/SiO_2/p-GaN is shown in the Fig 2.3. The responsivity of n-ZnO/i-ZnO/p-GaN is low for very sensitive detection applications which can further improved by adding a tunneling layer of SiO_2 in between p type GaN and intrinsic ZnO. n-ZnO/i-ZnO/SiO_2/p-GaN heterojunction structure, the peak responsivity was 172 .7 mA/W at 365 nm under the front-illumination condition at zero bias voltage which is very much higher than n-ZnO/i-ZnO/p-GaN structure. The Fig 2.4 shows the responsivity curve of n-ZnO/i-ZnO/p-GaN with and without buffer layer. The peak responsivity of n-ZnO/i-ZnO/p-GaN is 138.9mA/W at zero bias condition

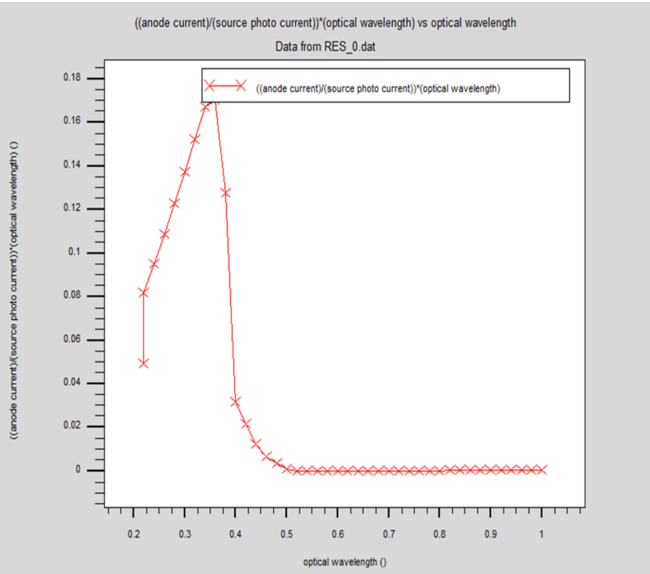

Fig.2.3 Responsivity curve of n-ZnO/i-ZnO/SiO_2/p-GaN

Adding a few nm buffer layer improves the responsivity to 172 .7 mA/W at 365 nm under the front-illumination condition at zero bias voltage. The thickness of this tunneling layer plays a major role in performance of photodetector. The oxide thickness should not be smaller or higher than a specific value which may affect the responsivity and switching ratio of detector.

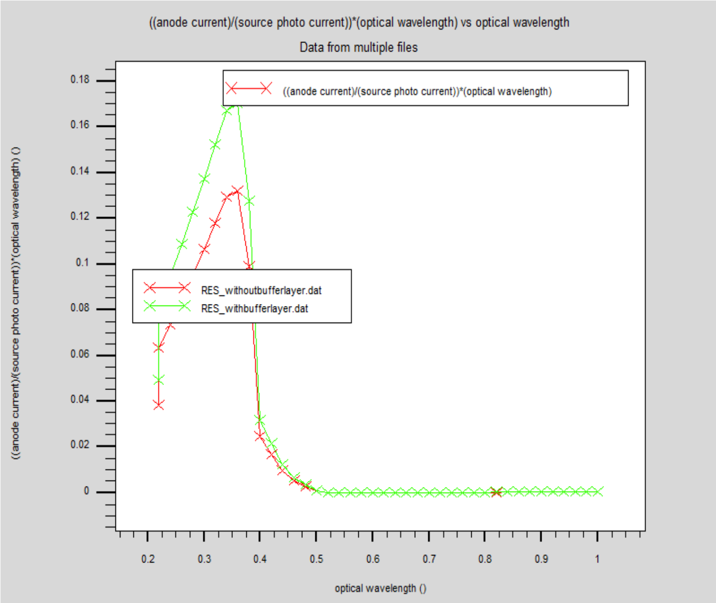

Fig.2.4 Responsivity curve of n-ZnO/i-ZnO/p-GaN

The Fig 2.5 shows the variations of responsivity curve different reverse bias voltage. Responsivity is increases with increase in reverse bias voltage until the breakdown occur. This breakdown voltage is known as maximum reverse bias voltage.

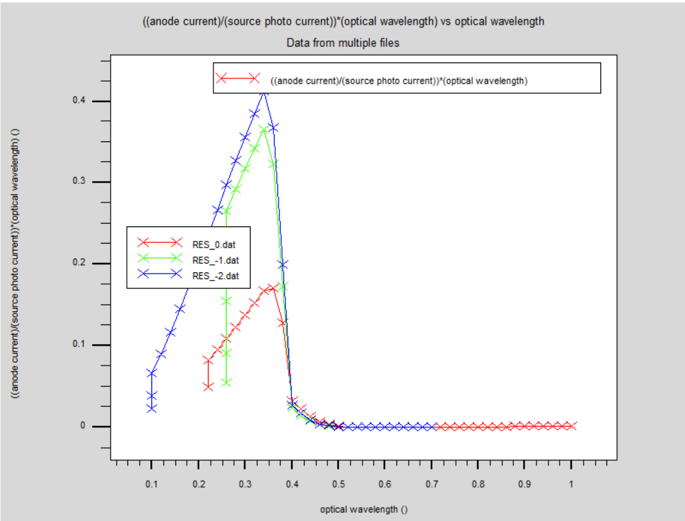

Fig.2.5 Responsivity curve of n-ZnO/i-ZnO/SiO_2/p-GaN

IV. RESULT AND DISCUSSION

The ZnO with GaN substrate photodetector can be a best choice for solar blind detector. GaN with large bandgap leads to sharp cut of between UV to Visible wavelength. GaN is a good substitute for Si in order to achieve higher responsivity in UV region. The n-ZnO/i-ZnO/p-GaN possess good responsivity. Responsivity can be further improved by adding few nm thickness SiO_2 layer in between GaN and intrinsic ZnO. n-ZnO/i-ZnO/SiO_2/p-GaN provides higher responsivity and also higher UV to visible rejection ratio. The responsivity of n-ZnO/p-GaN is only 0.678mA/W at zero bias condition which is further improved to 172.7mA/W in the proposed n-ZnO/i-ZnO/SiO_2/GaN photodetector.

Table 1: Comparison table of UV photodetector

Heterojunction Photodetector	Responsivity(mA/W)
n-ZnO/p-GaN	0.678
n-ZnO/i-ZnO/p-GaN	138.9
n-ZnO/i-ZnO/SiO_2/p-GaN	172.7

V. CONCLUSION

This analysis is mainly focused on ZnO based heterojunction UV photodetector. The ZnO/GaN heterojunction photodetector can detect UV light from visible and infrared background. The GaN can be act as the perfect filter layer and have higher UV to visible rejection ratio. The responsivity n-ZnO/p-GaN is improved by adding an intrinsic layer in between n-ZnO/p-GaN. Further improvement can be done by adding a buffer layer in between intrinsic layer and substrate material. This work can be extend to Analyze the responsivity of various buffer layer like AIN, Al_2O_3, and $LaAl_2O_3$ instead of SiO_2 buffer layer and also analyze the performance variations of responsivity in terms of buffer layer thickness variations.

ACKNOWLEDGMENT

I extend my sincere gratitude to Prof. Susan Abe, Head of the Department of Electronics and Communication; Saintgits College of Engineering, Prof. Riboy cherian, PG coordinator, Asst. Prof. Ajith Ravindran, my project guide and my colleague Keerthi K Nair for all their kind support and valuable suggestions.

REFERENCES

[1] Lakhotia, G., Umarji, G., Jagtap, S., Rane, S., Mulik, U., Amalnerkar, D., & Gosavi, S. (2010).An investigation on TiO2-ZnO based thick film 'solar blind', photo-conductor for'green' electronics. *Mater. Sci. Eng. B*, Vol.168, pp. 66-70

[2] Koch, U., Fojtik, A., Weller, H., & Henglein, A. (1985). Photochemistry of semiconductor colloids, preparation of extremely small ZnO particles, fluorescence phenomena and size quantization effects, *Chem.Phys.Lett.*, Vol.122, pp. 507-510

[3] Paul, G., Bhaumik, A., Patra, A., & Bera, S. (2007). Enhanced photo-electric response of ZnO/polyaniline layer-by-layer self-assembled films, Mater. Chem. Phys., Vol.106,pp. 360-363

[4] Sharma, Shashikant, and C. Periasamy. "Simulation study and performance analysis of n-ZnO/p-Si heterojunction photodetector." *J. Electron Devices* 19 (2014): 1633-6

[5] Moon, Tae-Hyoung, et al. "The fabrication and characterization of ZnO UV detector." *Applied Surface Science* 240.1 (2005): 280-285

[6] Mollow E. In: Proceedings of the Photoconductivity Conference. Breckenridge RG, editor. Wiley; New York, NY, USA: 1954. p. 509

[7] Fabricius H, Skettrup T, Bisgaard P. Ultraviolet Detectors in Thin Sputtered ZnO Films. Appl. Opt.1986;25:2764–2767

[8] Ümit, Özgür, Daniel Hofstetter, and Hadis Morkoc. "ZnO devices and applications: a review of current status and future prospects." *Proceedings of the IEEE* 98.7 (2010): 1255-1268.

[9] Janotti, Anderson, and Chris G. Van de Walle. "Fundamentals of zinc oxide as a semiconductor." *Reports on Progress in Physics* 72.12 (2009): 126501

[10] L. Su, Q. Zhang, T. Wu, M. Chen, Y. Su, Y. Zhu, R. Xiang,X. Gui, and Z. Tang, Appl. Phys. Lett. 105, 072106 (2014).

[11] Ding, Meng, et al. "Ultraviolet photodetector based on heterojunction of n-ZnO microwire/p-GaN film." *RSC Advances* 5.2 (2015): 908-912

[12] Zhang, Lichun, et al. "Optoelectronic characteristics of UV photodetector based on GaN/ZnO nanorods pin heterostructures." *Electronic Materials Letters* (2015)

[13] H. Zhu, C. X. Shan, B. Yao, B. H. Li, J. Y. Zhang, D. X. Zhao, D. Z. Shen, and X. W. Fan, J. Phys. Chem. C 112, 20546 (2008).

[14] C. H. Chen, S. J. Chang, S. P. Chang, M. J. Li, I. C. Chen,T. J. Hsueh, and C. L. Hsu, Chem. Phys. Lett. 476, 69(2009).

[15] Huang, Chun-Ying, et al. "p-Si nanowires/SiO2/n-ZnO heterojunction photodiodes." *Applied Physics Letters* 97.1 (2010): 3503.

[16] Wu, William-Ting Han, and Jun-Dar Hwang. "Enhancing the responsivity of UV to visible by inserting a SiO2 layer between p-Si and i-ZnO for the heterojunction photodiode with p-Si/SiO2/i-ZnO/n-ZnO structure." *Next-Generation Electronics (ISNE), 2013 IEEE International Symposium on*. IEEE, 2013.

[17] Çalışkan, Deniz, et al. "Low dark current and high speed ZnO metal–semiconductor–metal photodetector on SiO2/Si substrate." *Applied Physics Letters* 105.16 (2014): 161108.