ISSN: 2395-1680 (ONLINE)
DOI: 10.21917/ijme.2017.0053

A REVIEW ON ZnO HETEROJUNCTION PHOTODETECTOR FOR UV APPLICATION

Jitty Jose, Ajith Ravindran and Keerthi K Nair
Department of Electronics and Communication Engineering, Saintgits College of Engineering, India

Abstract

Hetero-structured photodetector is a rapidly growing field of optoelectronic sensing for designing ultraviolet photodetectors of high efficiency and high responsivity. In recent years, one of the next generation semiconductor material ZnO, has attracted much attention in shorter wavelength optoelectronics devices and sensors. ZnO is considered as an ideal candidate in UV region because of its large exciton binding energy (60 meV), and wide bandgap energy (3.37eV). Naturally ZnO has n type conductivity and is very difficult to produce p type ZnO. Various p type materials such as Si, GaN, NiO, and $Sr_2Cu_2O_2$ have been used to realize p-n hetero junction photodetector. ZnO/Si based heterojunction devices have good electrical and optical properties, are easy to fabricate and has low deposition temperature. GaN is one of the propitious material in terms of considerably small lattice mismatch, less than 1.8% with ZnO and also exhibits similar lattice structure (wurtzite). ZnO/GaN structure exhibits high UV to visible rejection ratio and is very useful for high sensitive UV applications. The responsivity of n type ZnO with Si and GaN as substrate material is analyzed in this work. Also analyzed the various parameters that affects the responsivity of photo detector.

Keywords:

Photodetector, Heterojunction, Responsivity, ZnO, GaN

1. INTRODUCTION

Optoelectronics or photonics is an emerging field of technology for generating and harnessing light. The most fascinating and quickly growing field of optoelectronics industry is sensing. These optoelectronics sensors contribute to a multimillion dollar market in the developed nations and are also known as photodetectors. Over the last five decades, researchers are focused on developing a multilayer substrate with highly packed interconnect which is the reason for rapid acceleration in this field. The opto-sensing field should have the capability to improve existing system along with perspicacious next generation system.

Nowadays, photodetector application goes through a wide variety of wavelength range, including infrared, UV and X-ray’s. Researchers developed the photodetector based on the application, some photodetectors are designed to detect only a particular wavelength region and blind in other regions, and some others detect one or more wavelength simultaneously over a single structure. The major application of photodetector includes aerospace, hydrospace, oil and flame detection, smoke detection, biomedical applications and also high speed optical communication. The homo junction photodetectors used in the earlier days 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. Compound semiconductors materials like group III-V, group II-VI and group IV-VI are commonly used for photo detection applications. 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. The energy of incident light must be greater than the bandgap energy of material. The electron-hole pair generated in the sensitive area or active area contributes to photocurrent. 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. An intrinsic layer is inserted in between p and n region that increases the width of active area, which reduces dark current and improve the illumination current which in turn increases the responsivity. Thus compound heterojunction PIN structure is suited for highly efficient photodetector application.

The recently developed heterojunction UV photodetector are much preferred due to its applicability in a wide range of military, civil, furnace control, and UV astronomy applications [1]. Technological advancement in fabrication of materials based on the II-VI oxides together with their built in favorable properties, make II-VI oxides the most promising material for applications in UV wavelength range. ZnO is one of the compound semiconductors in this family with large bandgap and large extinction energy and is very sensitive to UV region because of its higher photoconductivity and ultra violet absorbance. ZnO/Si the most mature choice because of its compatibility with integrated circuit technology and also has homogeneous properties to the nitride-based semiconductors such as GaN and possesses relatively small in plane lattice mismatch, less than 1.8% [2,3].

This paper is structured into various sections. Section 2 includes the literature review which cover the material used for photodetector, ZnO photodetector and ZnO based homo junction detector. Section 3 analysis ZnO UV detector, n-ZnO/p-Si structure, working principle and band diagram, responsivity curve, and various parameters affect the responsivity. Section 4 deals with the concept of n-ZnO/p-GaN structure, band diagram and responsivity curve and section 5 deals with n-ZnO/i-ZnO/p-GaN structure, band diagram, working principle and responsivity curve. Section 6 deals with the results and discussions. Section 7 concludes the paper, along with scope for future work in this topic.

2. LITERATURE REVIEW

Different semiconductor material has been used to fabricate photodetector with high efficiency in the UV region. Historically, the development of a high responsivity semiconductor detectors in the whole UV range has been hindered by extremely strong absorption and radiation causes aging effects in majority of the semiconductor materials.It is particularly visible in the case of silicon which is the most popular semiconductor material used for fabrication of UV detectors due to mature technology. The modern photodetectors are mainly fabricated using Si. The ruggedness of the Si material is very important for the UV detection involves hostile environments such as in situ combustion monitoring and satellite based missile plume detection. The other application of photodetector is air quality monitoring, gas sensing and personal UV exposure dosimetry. In the field of optical devices, several trends are pushing research into new materials. The most high temperature, high power device will be fabricated from SiC material. The wide bandgap energy of material also allows the fabrication of SiC UV detectors. A technological advancement in fabrication of materials based on the II–VI oxide together with their built in favourable properties, make II–VI oxides the most apt semiconductor materials for application in the UV wavelength range. III–V nitride devices will be capable of enhancing high power and temperature operation due to their large band gap.

2.1 ZnO PHOTODETECTOR

The UV photo response in ZnO films was first observed by Mollow in the 1940s. However, the research of ZnO based photodetectors thrives gradually since the 1980s [4]. At the beginning, the detector usually has simple structure and the properties are not favorable for real time applications. Different techniques are used to improvement of the fabrication of the ZnO-based films; many complex ZnO-based photodetectors (such as p-n junction photodetector, p-i-n junction structure and Schottky junction photodetector, etc.) with high performance were reported.

The lattice constants of ZnO are mostly range from 3.2475 to 3.2501Å for the a-parameter and from 5.2042 to 5.2075Å for the c-parameter. 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 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

2.2 ZnO HOMOJUNCTION PHOTODIODE

As it is generally known that, the involuntarily doped ZnO is n-type semiconductor for its intrinsic defects, such as oxygen vacancies [5]. A reproducible method is necessary for grow p-type ZnO film, essential for fabrication of p-n junction, is still attractive due to several reasons such as low solubility of the dopants, deep acceptor levels, and the self-compensation process. Therefore, very small information can be found about ZnO p-n homo junction photodiodes. In the year of 2005, Moon et al have fabricated a ZnO p-n homo junction photodiode by RF magnetron sputtering [6]. P-type ZnO film was fabricated by selecting GaAs as a substrate material which supplied the dopant element. The p-n homo junction shows the noticeable rectifying current-voltage characteristics. The turn-on voltage was measured to be ~3.0V under the forward bias condition. When UV light (λ = 325nm) was brighten on the p–n homo junction, photocurrent of ~2mA was detected. The same year, Hybrid Beam Deposition (HBD) method is used to fabricate ZnO p-n junction photodiodes based on As-doped p-type ZnO layers. The ohmic contacts for ZnO photodiode were formed on each of the p-type and n-type ZnO surfaces using Ni and Ti. The ratio of photo-to-dark current or Ion/Ioff ratio at zero bias is about 20. The dark leakage currents for the ZnO photodiodes are very small (lower than 10^{-6}A/cm^{-2}) in the reversed bias configuration. This behavior reveals that ZnO photodiodes might sensitively identify UV light with low noise. After that, ZnO p-n homo junction photodiodes were developed on the ZnO:Ga/ZnO:Sb materials using MBE. In order to form ohmic contacts Al/Ti metal was used on both the p-ZnO and n-ZnO layers. The rectifying I-V characteristics show the existence of the ZnO p-n homo junction and the turn-on voltage is around 2V. Very good sensitivity to ultraviolet light illumination was observed from photocurrent measurements. Furthermore, electron injection in the forward bias to the p side of a p-n homo junction could result in an increase of the peak illumination response and a proportionally rise in decay constant of the ZnO photodiodes [7]

3. ZnO UV PHOTODETECTOR

ZnO is the most promising candidate for UV application. ZnO based UV photodetector has drawn a great attention in recent years, because of its wide bandgap (3.37eV), low cost, strong radiation hardness and high chemical stability. These devices are highly sensitive in UV region with quick response and very low noise. ZnO have unique conductive, piezo electronics and optoelectronics properties which are very advantages for various commercial and military applications, such as early missile plume detection, safe space-to-space communications, pollution supervise, water sterilization, flame sensing, etc. Due to large saturation energy and high thermal and mechanical stability make it a very better choice for photodetectors, solar cells, light emitting diodes, piezo electronics device and sensors. All these applications needs very sensitive devices with high signal-to-noise ratio and high response speed

3.1 n-ZnO/p-Si HETEROJUNCTION PHOTO-DETECTOR

ZnO is considered as the one of the first semiconductors prepared in pure form after Si and Ge. Naturally ZnO has n type conductivity. It is very difficult to make p type ZnO because of low dopant solubility and self-compensation effect of intrinsic defects. ZnO/Si is the mature technology because of its compatibility with silicon integrated circuit technology, low deposition temperature, and low fabrication cost. In 2004 R. Romeo et al proposed electrical properties of n-ZnO/c-Si heterojunction prepared by chemical spray pyrolysis [8]. In 2007 Y.F Gu et.al proposed visible band UV detector based on n-ZnO/p-Si heterojunction [10]. In 2014 Shashikant Sharma et al did a study on performance estimation of ZnO/Si heterojunction photodetector with temperature, oxide thickness, doping profile variations and analyze the effects of parameter variation on performance of photodetector [9]. All the simulation results have been obtained using ATLAS simulator from SILVACO international. The fundamental structure of n-ZnO/p-Si is Shown Fig.1.

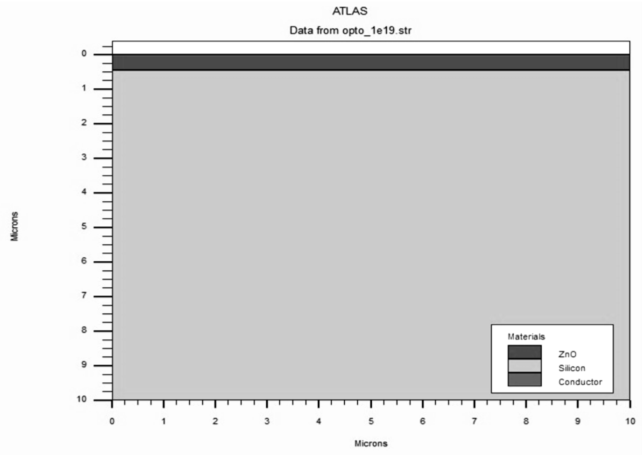

Fig.1. n-ZnO/p-Si heterojunction structure

3.1.1 *Working Principle of n-ZnO/p-Si Heterojunction Photodetector:*

The n-ZnO/p-Si heterojunction photodetector can act as a dual detector, which can detect visible light and UV light simultaneously.

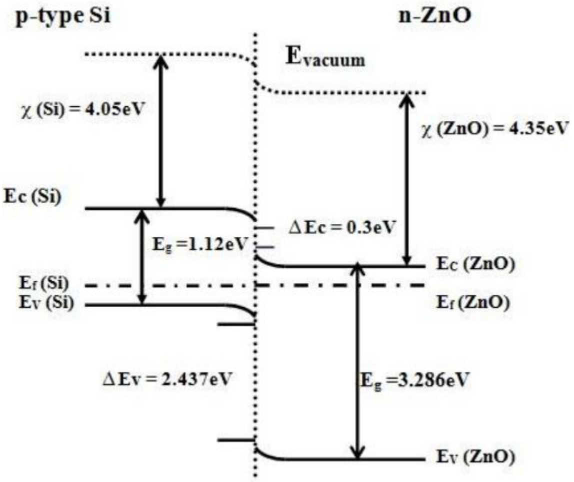

Fig.2. Band diagram of n-ZnO/p-Si heterojunction structure [9]

When light of shorter wavelength fall on the photodetector, photons are absorbed in ZnO layer and create electron-hole pair. Under the reverse bias condition the photo generated electron hole pair drift towards the positive electrodes in the depletion region of ZnO, which produce photocurrent. When visible light falls on the detector, the top ZnO layer acts as a transparent material and light get absorbed in the Si layer. This creates electron hole pair, which results in photocurrent. The reason of transparency of ZnO in the visible region is the larger bandgap of ZnO than the energy value of visible photons. The Fig.2 shows the band diagram of n-ZnO/p-Si heterojunction photodetector

3.2 RESPONSIVITY OF n-ZnO/p-Si HETERO JUNCTION PHOTODETECTOR

The responsivity of photodetector may be defined as the ratio of photocurrent generated to the optical power in linear region of response. It is the rate of electrical output per optical input and is also defined as the measure of effectiveness of the conversion of the light power into electrical current. Responsivity is the measure of sensitivity to the light. The responsivity is given by the Eq.(1) [9]

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

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.

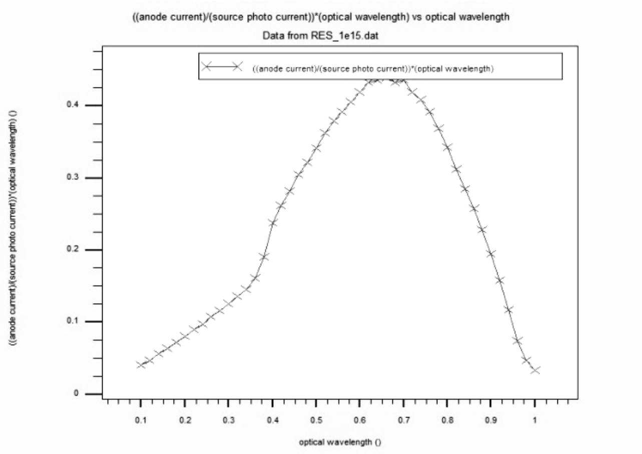

Fig.3. Variation of responsivity with optical wavelength

Generally responsivity increases for the wavelength region in which light energy is somewhat higher than the bandgap energy. The responsivity of n-ZnO/p-Si heterojunction photodetector is shown in Fig.3. 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

3.2.1 *Responsivity Variation with Dopping Concentration:*

The acceptor doping concentration affects the responsivity of the detector. The donor concentration varies from 10^{15} cm-^{3} to 10^{21} cm^{-3} and acceptor concentration varies from 10^{15} to 10^{19}. A convincing reduction in responsivity of photodetector has been observed with increases in doping concretion. The Fig.4 shows the wavelength versus responsivity at different donor concentration and Fig.5 shows the responsivity versus optical wavelength at different acceptor concentration

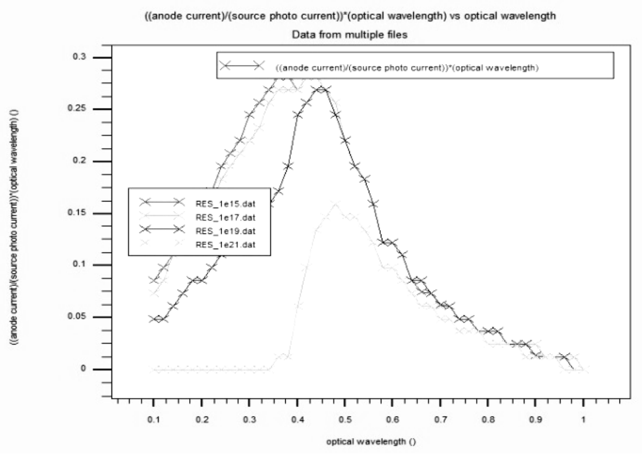

Fig.4. Variation of responsivity with donor concentration

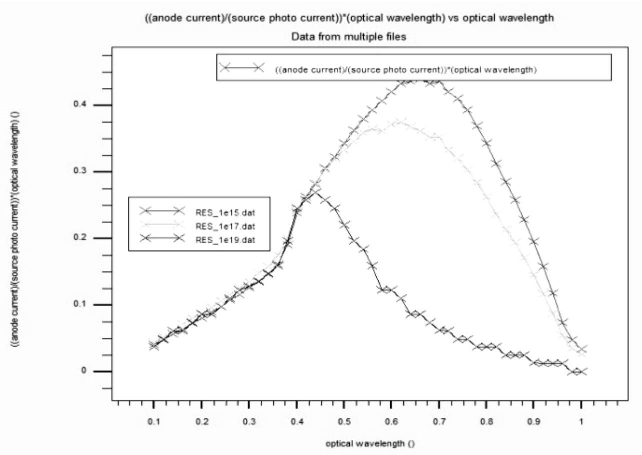

Fig.5.Variation of responsivity with accepter concentration

3.2.2 Responsivity Variation with Oxide Thickness:

The variations of responsivity with oxide thickness are shown in the Fig.6. Oxide thickness are increases from 200 to 2000nm. The responsivity of photodiode increases with increase in oxide thickness this is because of resistivity of oxide layer decreases with increase in thickness of oxide layer. The higher thickness of ZnO layer leads to higher electron hole pair generation which leads to enhanced photocurrent. Responsivity is the strong function of photocurrent. Higher responsivity can be achieved by increasing oxide thickness

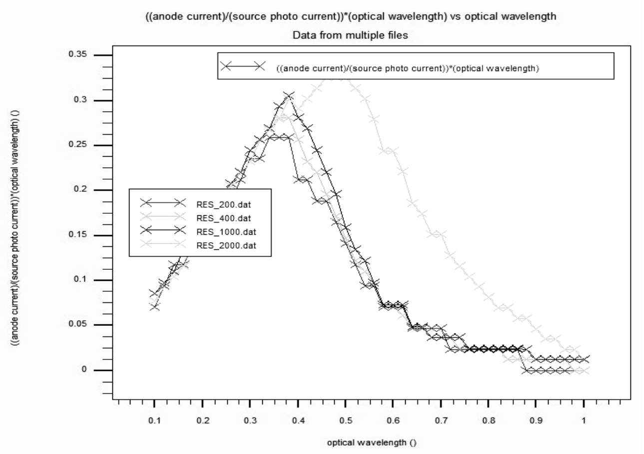

Fig.6. Variation of responsivity with ZnO thickness

4. n-ZnO/p-GaN HETEROJUNCTION PHOTO DETECTOR

The ZnO with GaN structure is a perfect structure for UV application. GaN has wide bandgap (3.40eV), so there is no responsivity in long wavelength region. This photodetector is very desirable to detect specifically UV light in infrared and visible background. GaN and ZnO have similar wurtzite structure very less lattice mismatch, approximately 1.8%. At 2015, Lichun et al conducted a study on optoelectronics characteristics of UV photodetectors based on n-ZnO/i-ZnO/p-GaN structure. This PIN structure provides lots of advantages over a PN structure [12].

4.1 STRUCTURE AND WORKING PRINCIPLE OF n-ZnO/p-GaN HETEROJUNCTION PHOTO DETECTOR

The structure of n-ZnO/p-GaN is shown in the Fig.7. The GaN material provides large rejection in visible light. It acts as a filter to visible rays and only detects the UV rays due to its large bandgap. When photons of shorter wavelength strike the depletion region of n-ZnO and p-GaN, the electron hole pairs are created in the n-ZnO. Under the reverse bias condition the photo generated electron hole pair drift towards the positive electrodes in the depletion region of ZnO, which produce photocurrent. When higher wavelength (visible or infrared) hits the detector, the GaN acts as the blocking layer due to its higher bandgap energy.

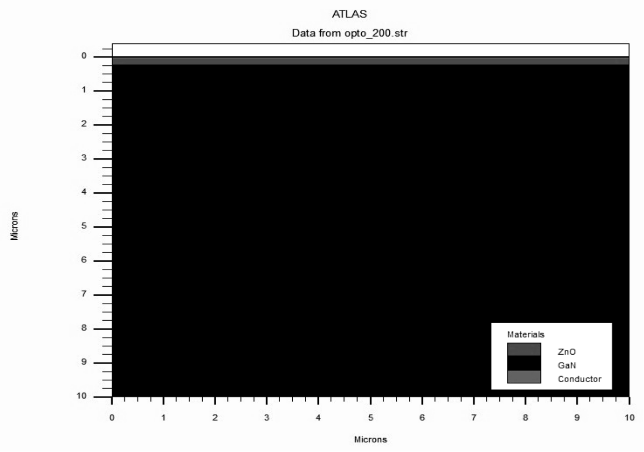

Fig.7. n-ZnO/p-GaN heterojunction structure

The n-ZnO/p-GaN structure is best suited for solar blind detector. The band diagram of n-ZnO/p-GaN is shown in the Fig.8 [15]

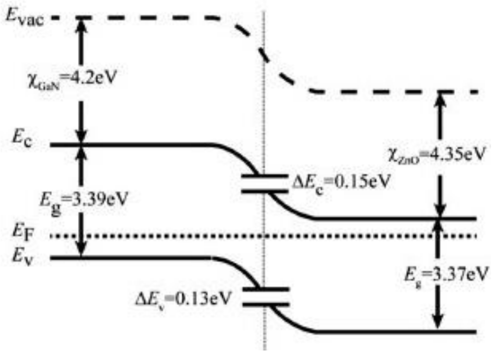

Fig.8. Band structure of n-ZnO/p-GaN heterojunction structure

4.2 RESPONSIVITY OF n-ZnO/p-GaN HETEROJUNCTION PHOTODETECTOR

The Fig.9 shows responsivity curve of n-ZnO/p-GaN heterojunction photodetector at no 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 adding an intrinsic layer in-between ZnO and GaN. This PIN structure provides better response over the PN structure

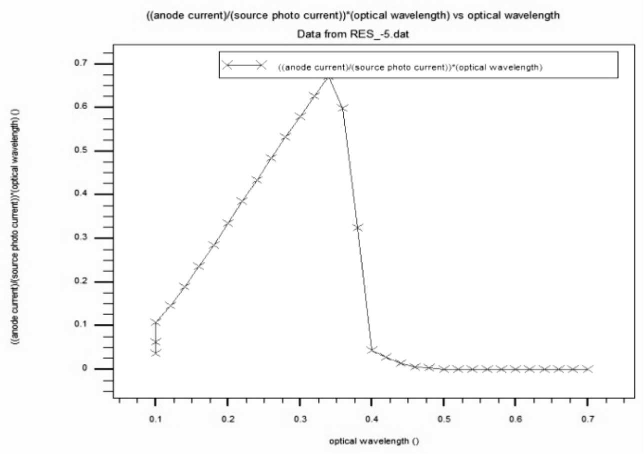

Fig.9. Responsivity curve of n-ZnO/p-GaN Heterojunction photodetector

5. n-ZnO/i-ZnO/p-GaN HETEROJUNCTION PHOTODETECTOR

The drawback of n-ZnO/p-GaN heterojunction photodetector is overcome by adding an insulating layer in between p and n region. The intrinsic layer reduces dark current and increases photo current. The n-Zno/p-GaN photodiode suffer from the following problem. The width of the depletion region is well below the absorption length, hence only a small fraction of photo carriers are generated within the depletion region. There is the reduction of quantum efficiency due to the collection of the photo generated electron hole pair generated outside the depletion region may be limited. Those carriers generated outside the depletion region will eventually diffuse into the depletion region and can thus contribute to photocurrent; this diffusion takes some time, which results in a tail in the impulse response function, which can limit the detection bandwidth. The above problem can be avoided with PIN structure. Most carriers are generated in the intrinsic region, because it is much thicker than the depletion region of PN structure. Another effect of the thick intrinsic region is reduced capacitance, which allows for the higher perception bandwidth. Sometimes the PIN structure heterojunction photodetector are made from different semiconductor material, where the photon energy greater than bandgap energy is only for the intrinsic region, but not for the p and n region. In that case any absorption outside the intrinsic region can be avoided.

5.1 STRUCTURE AND WORKING PRINCIPLE OF n-ZnO/p-GaN HETEROJUNCTION PHOTO DETECTOR

When the UV light hits the n-ZnO/i-ZnO/p-GaN photodetector, photons are absorbed in the intrinsic region and photo generated carrier pairs are produced. Strong electric field in the intrinsic layer forms a spatial separation between photo generated carriers, as a result less number of electron hole pair recombination will occur.

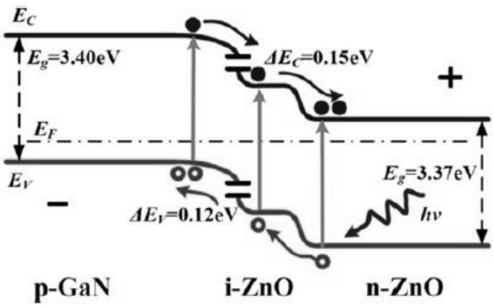

Fig.10. Band structure of n-ZnO/i-ZnO/p-GaN heterojunction structure [16]

The conduction band energy difference and valance band energy difference of ZnO/Ga are 0.15eV and 0.12eV respectively so the barrier height of electron and holes are almost same. As a result the photo generated electrons accelerate to n-ZnO, and photo generated holes move to p-GaN by the depletion region in the intrinsic layer; thus illumination current can be increased significantly. The Fig.10 shows the energy band diagram of p-GaN/i-ZnO/n-ZnO heterojunction photodetector

5.2 RESPONSIVITY OF n-ZnO/i-ZnO/p-GaN HETEROJUNCTION PHOTODETECTOR

The responsivity curve of n-ZnO/i-ZnO/p-GaN heterojunction photodetector is shown in the Fig.11. 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.

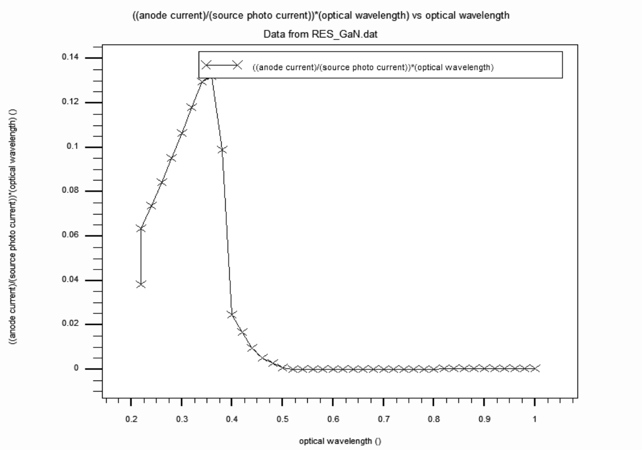

Fig.11. Responsivity curve of n-ZnO/i-ZnO/p-GaN heterojunction photodetector

6. RESULT AND DISCUSSION

The n-ZnO/p-Si heterojunction photodetector can detect both UV and visible light simultaneously over a single frame work and peak responsivity of 0.28 and 0.36A/W for UV and visible wavelength respectively at -5V reverse bias condition.The major disadvantage of n-ZnO/p-Si heterojunction photodetector was lower responsivity in the UV region. Si has lower bandgap compared with ZnO. So it’s does not provide sharp cut off between UV and visible region.n-ZnO/p-Si can be act as a dual detector. The ZnO with GaN substrate photodetector can be a best choice for solar blind detector. GaN have large bandgap compared with ZnO which 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.For a highly sensitive solar blind detector GaN is the better choice over silicon due to its larger bandgap leads to high UV to visible rejection ratio. The n-ZnO/p-GaN heterojunction photodetector have 0.678mA/W at zero bias condition. Peak responsivity of n-ZnO/p-GaN can further improved by adding an intrinsic layer in between n-ZnO/p-GaN and the responsivity peak is improved to 138.9mA/W.

Table.1. Comparison of GaN UV photodetector

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

7. CONCLUSION

The major drawbacks of simple homo junction photodetector are lower the responsivity and smaller switching ratio. Various methods are simultaneously applied for basic PN junction diode in order to improve their responsivity, illumination current, and switching ratio. One of the possible solution to improve the responsivity includes the structural changes; a PIN structure instead of PN structure which provide better responsivity due to increase in active area or sensitive area of detector, and also PIN structure reduce dark current and improve the illumination current. Another technique like proper selection of heterojunction materials improves the responsivity of detector. Different compound material can be able to detect a specific wavelength from entire electromagnetic spectrum like UV detector, IR detector, visible detector etc. The heterojunction photodetector plays a crucial role in optoelectronics sensing field. This analysis is mainly focused on ZnO based heterojunction UV photodetector. The ZnO/Si heterojunction photodetector can detect both UV and visible light. But the responsivity in the UV region is very low. For high sensitive UV application ZnO with GaN heterojunction photodetector are used. The n-ZnO/p-GaN heterojunction photodetector can detect UV light from visible and IR background. The responsivity n-ZnO/p-GaN is improved by adding an intrinsic layer in between n-ZnO/p-GaN. In future a buffer layer is added in between p-GaN and i-ZnO, which will acts as tunneling layer, leads to improve the responsivity in UV region.

REFERENCES

[1] Govinda Lakhotia, "An Investigation on TiO2-ZnO based Thick Film 'Solar Blind', Photo-Conductor for 'Green' Electronics", *Materials Science and Engineering: B*, Vol. 168, No. 1-3, pp. 66-70, 2010.

[2] U. Koch, A. Fojtik, H. Weller and A. Henglein, "Photochemistry of Semiconductor Colloids, Preparation of Extremely small ZnO Particles, Fluorescence Phenomena and Size Quantization Effects", *Chemical Physics Letters*, Vol. 122, No. 5, pp. 507-510, 1985.

[3] G.K. Paul, A. Bhaumik, A. Patra and S. Bera, "Enhanced Photo-Electric Response of ZnO/Polyaniline Layer-by-Layer Self-Assembled Films", *Materials Chemistry and Physics*, Vol. 106, No. 2-3, pp. 360-363, 2007.

[4] Henrik Fabricius, Torben Skettrup and Paul Bisgaard, "Ultraviolet Detectors in Thin Sputtered ZnO Films", Applied Optics, Vol. 25, No. 16, pp. 2764-2767, 1986.

[5] Anderson Janotti and Chris G. Van de Walle, "Fundamentals of Zinc Oxide as a Semiconductor", Reports on Progress in Physics, Vol. 72, No. 12, pp. 1-12, 2009.

[6] Tae-Hyoung Moon, Min-Chang Jeong, Woong Lee and Jae-Min Myoung, "The Fabrication and Characterization of ZnO UV Detector", *Applied Surface Science*, Vol. 240, No. 1-4, pp. 280-285, 2005.

[7] Ozgur Umit, Daniel Hofstetter and Hadis Morkoc, "ZnO Devices and Applications: A Review of Current Status and Future Prospects", Proceedings of the IEEE, Vol. 98, No. 7, pp. 1255-1268, 2010.

[8] R.Romero, M.C. Lopez, D. Leinen, F. Martin and J.R. Ramos-Barrado, "Electrical Properties of n-ZnO/c-Si Heterojunction Prepared by Chemical Spray Pyrolysis", *Material Science and Engineering:B*, Vol. 110, No. 1, pp. 87-93, 2004.

[9] Shashikant Sharma and C. Periasamy, "Simulation Study and Performance Analysis of n-ZnO/p-Si Heterojunction Photodetector", *Journal of Electron Devices*, Vol. 19, pp. 1633-1636, 2014.

[10] Y.F Gu, X.M. Li, J.L.Zhao, W.D. Yu, X.D. Gao and C. Yang, "Visible-Blind Ultra-Violet Detector Based on n-ZnO/P-Si Heterojunction Fabricated by Plasma-assisted Pulsed Laser Deposition", *Solid State Communication*, Vol. 143, No. 8-9, pp. 421-424, 2007.

[11] Lichun Zhang, Fengzhou Zhao, Caifeng Wang, Feifei Wang, Ruizhi Huang and Qingshan Li, "Optoelectronic Characteristics of UV Photodetector based on GaN/ZnO Nanorods Pin Heterostructures", *Electronic Materials Letters*, Vol. 11, No. 4, pp. 682-686, 2015.

[12] Meng Ding, Dongxu Zhao, Bin Yao, Zhipeng Lid and Xijin Xu, "Ultraviolet Photodetector based on Heterojunction of n-ZnO Microwire/p-GaN Film", *RSC Advances*, Vol. 5, No. 2, pp. 908-912, 2015.