Performance Optimization and Analysis of ZnO based Ultraviolet Photodiode

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***Abstract*- In this paper a design approach for Zinc Oxide (ZnO) based p-i-n structure photodiode is demonstrated for ultraviolet (UV) detection. The peak sensitivity occurs at a range of 320nm to 340nm. The detection range can be further decreased by suitably alloying ZnO with MgO. Rigorous theoretical investigation has been performed for the device optimization to improve the responsivity. The optimization involves doping concentration and thickness calibrations of various constituent layers of the device. These results indicates that ZnO based photodetectors are good candidates for detecting ultraviolet radiation.**

***Index Terms*- zinc oxide, photodiode, ultraviolet, spectrum, responsivity**

I. INTRODUCTION

Photodiodes operating in ultraviolet (UV) regions are important devices that are widely used for many applications in commercial, civil and military fields. UV detectors are applied in missile warning systems, UV astronomy, ozone layer monitoring, high-temperature flame and fire detection, and environmental monitoring [1]. UV photodiodes deployed for these purposes can be made using ZnO, because it is an environment friendly material [2].

ZnO is one of the most promising II-VI group wide band semiconductor materials used for many photonics and electronics applications. It has direct band gap energy of 3.37eV at 300 K, large exciton binding energy of 60 meV, strong emission, large saturation velocity (3.2×10^7 cm s^{-1}) and high breakdown voltage that is about four times the value of GaAs [3-4]. Hence many high power and high frequency optoelectronics devices such as light emitting diode, photo-detectors, solar cell etc. are made utilizing these properties [5].

ZnO is a naturally n type semiconductor and has a very low solubility of dopants. Hence to realize ZnO based device there is an issue of fabrication of p-type ZnO with high hole concentration. With recent advancement various co-doping techniques have been used to develop p-doped ZnO [6-7]. This in turn gives a way to develop and design p-n ZnO homojunction devices.

II. RESEARCH METHODOLOGY

A. Device Structure

The material and design structure of ultraviolet photodiode used for study is as shown in Fig. 1. The structure consists of an intrinsic layer of ZnO sandwiched between two cladding layers. The top layer is heavily doped p-ZnO and bottom layer is heavily doped n-ZnO. This forms a p-i-n type structure. Ohmic p-contact and n-contact are placed at top and bottom layer to apply voltage bias to the device. The height and width of device is taken as 1um and 5um respectively.

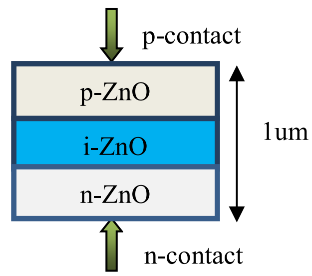

Fig.1. Device Structure.

B. Design study

This work is carried out using COMSOL Multiphysics software version 5.3. The design model uses semiconductor optoelectronics with frequency domain interface. This semiconductor interface is combined with the electromagnetic waves, frequency domain interface, and is used for modeling direct bandgap optoelectronics semiconductor devices.

Here p-contact is grounded and the n-contact is set to 2 V, which makes the device to operate in reverse bias. This mode of operation is known as photoconductive mode as absorbed light is used to generate current. Wavelength sweep from 400 nm to 160 nm is carried out keeping the incident power to be constant. Band gap of ZnO material is 3.3 eV which corresponds to wavelength of ~375nm. Therefore the incident photon energy is swept from just below the band gap energy to higher band gap energy upto 7.75 eV.

III. RESULTS AND DISCUSSIONS

The present study shows the impact of changing the doping concentration of both top and bottom layer as well as changing the height for optimization of device parameters. Different material parameters at room temperature were taken from various literatures for carrying out the study.

The parameters that were varied for carrying out the simulation study to optimize the best outcomes of the device are summarized in Table I.

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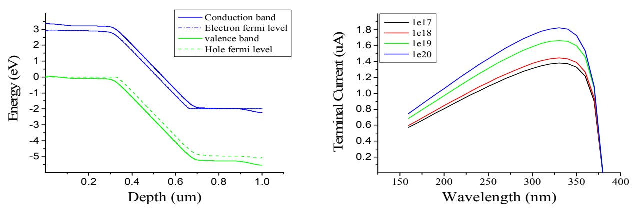
TABLE I
SIMULATED PARAMETERS USED IN ZNO p-i-n PHOTODIODE STRUCTURE

Simulation parameters	n-ZnO	i-ZnO	p-ZnO
Doping conc. (cm^{-3})	1e17,1e18, 1e19, 1e20	Intrinsic	1e17,1e18, 1e19, 1e20
Thickness of layer (um)	0.05, 0.1, 0.15, 0.2, 0.25, 0.3	1.0	0.05, 0.1, 0.15, 0.2, 0.25, 0.3
Thickness of structure (um)	1 , 1.5 , 2, 2.5, 3		

A. Doping Concentration

The resulting energy level diagram of device is as shown in Fig. 2(a). In the intrinsic region the quasi electron Fermi level lies below the conduction band and quasi hole Fermi level lies above the valence band. This implies that valence band is full and conduction band is empty so in this region absorption of photons takes place. The current through the device as a function of wavelength for various doping concentration of p and n region is shown in Fig. 2(b). Towards the longer wavelength at the end of sweep range there is much less current passing through the device. This is because the longest wavelength corresponds to energy which is below the bandgap of ZnO, hence there is no absorption of photon in active regime creating electron hole pair. The total device thickness and n-p height is kept constant at 1um and .2um respectively while carrying out this study.



(a) (b)

Fig.2. (a) Device energy diagram and (b) Current output as a function of wavelength for different doping concentration.

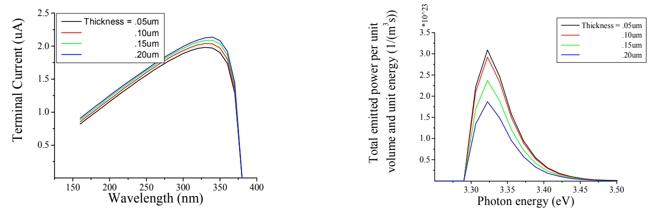
B. Thickness variation of n and p layer

The second study is done keeping the doping concentration fix at 1e20 cm^{-3} and changing the thickness of n and p region. As the thickness of diffusion region increases the minority carrier moves towards the depletion region i.e. electron from p-side and hole from n-side. This movement constitutes diffusion current from n-side to p-side. Hence overall current increases as shown in Fig. 3(a). The resulting photo current I_p from n side to p side is given by (1)

$$I_p = eA(L_h+L_e+W)G \quad (1)$$

where e = charge of electron, A= cross sectional area illuminated by photon, L_h = diffusion length on p-side, L_e = diffusion length on n-side ,W = width of depletion region and G = electron hole pair generation rate

Also the total spontaneous emission falls with increase in diffusion length as most of electrons and hole contribute towards photo current rather than combining radiatevly as shown in Fig. 3(b).

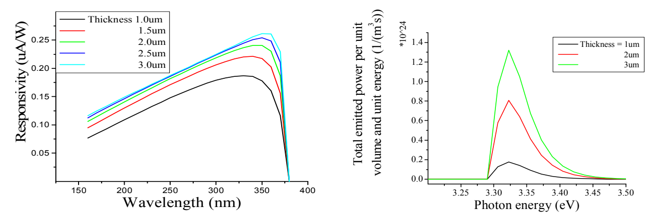


(a) (b)

Fig.3. (a) Current output verses wavelength and (b) Spontaneous emission from the device for different n and p layer thickness.

C. Total thickness

The final study is done by changing the thickness of device keeping doping concentration fixed at 1e20 cm^{-3}. This increases the active region area where photons energy is absorbed hence increase in the terminal current of device is observed as shown in Fig. 4(a). The spontaneous emission occurring at wavelength 330nm for various thickness of device is shown in Fig. 4(b).



(a) (b)

Fig.2. (a) Responsivity and (b) Spontaneous emission for different thickness of device.

IV. CONCLUSION

The present study shows some key aspects of designing ZnO based photodiodes for ultraviolet detection. The peak sensitivity of detection was observed at 330nm. At high doping concentration of 1e20cm^{-3} the terminal current shows highest value of 1.8uA. Higher doping of n and p layer leads to higher terminal current. Also changing the overall device thickness increases the responsivity of the device.

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