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SIMULATION STUDY AND PERFORMANCE ANALYSIS OF n-ZnO/p-Si HETEROJUNCTION PHOTODETECTOR

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ABSTRACT

In this paper simulation study and analysis of n-ZnO/p-Si heterojunction photodetector are reported. A program in ATLAS simulator from SILVACO international has been developed and important parameters such as dark current, quantum efficiency, effect of temperature variation, thickness variations and doping density variations which affects the performance of n-ZnO/p-Si heterojunction photodetector have been evaluated. It has been observed that responsivity of photodetector increases with ZnO thickness and decreases with increase in donor and acceptor doping concentrations. Simulation results gives dark current of the order of 10^{-14}A which confirms its suitability for low noise applications. Photodetector has shown a very good quantum efficiency of 88% and 99% for UV, visible wavelengths respectively which confirms its UV-visible dual detection capability over a single framework.

Keywords: n-ZnO/p-Si heterojunction, photodetector, simulations.

I. INTRODUCTION

In recent years, ZnO has drawn global research interest due to its unique conductive, piezoelectronic and optoelectronic properties. The promising properties of ZnO such as wide band gap (3.37eV), large exciton binding energy (~60meV), large saturation energy and high thermal and mechanical stability makes it a suitable choice for photodetectors, solar cells, light emitting diodes, sensors and piezoelectronic devices [1-3].

Since ZnO is naturally having n-type conductivity, it is difficult to produce p-ZnO film due to self compensation effect of intrinsic defects and low dopant solubility. n-ZnO thin film based devices has got a wide attention in recent years and many p-type materials such as Si, GaN, $Sr_2Cu_2O_2$, NiO, $ZnRh_2O_4$ n-ZnO have been used to realize p-n heterojunctions [4, 5]. Among these materials use of ZnO thin films with p-Si substrate is a good choice to develop variety of optoelectronic applications. n-ZnO/p-Si heterojunction photodetector has the potential to detect both UV and visible wavelengths simultaneously over a single framework which is very advantageous in many industrial applications. Good optical and electrical properties, simplicity of fabrication, relatively low deposition temperature and low fabrication cost of n-ZnO/p-Si heterojunction is also the reason which has drawn a significant interest of researchers to use it in the area of photo detectors.

Some work on electrical and optical characteristics of n-ZnO/p-Si heterojunction photodetectors has been reported by researchers in past [6-9]. But no study on the performance estimation of n-ZnO/p-Si heterojunction photodetectors with temperature, thickness and doping profile variations is reported in best of our knowledge. This work reports the effect of temperature variations, thickness variation and doping profile variation on the performance of n-ZnO/p-Si heterojunction photo detector using ATLAS simulator from SILVACO international. This study and analysis also suggests the set of device parameters with which the efficient performance of n-ZnO/p-Si heterojunction photodetectors can be obtained when we are moving for actual fabrication.

II. DEVICE SIMULATION SETUP

A simulation program for proposed n-ZnO/p-Si heterojunction photodetector structure has been developed in ATLAS simulator from SILVACO international to obtain various electrical and optical characteristics. Fig. 1 shows the structure of the ZnO/Si hetero-structure which is a type II alignment hetero-junction according to Anderson model [10]. The working of the n-ZnO/p-Si heterojunction can be described as follows. When light of UV wavelength falls on the hetero-junction photodetector the photocurrent get generated due to electron hole pair generation in neutral n and p region of ZnO layer. At the same time separation of electron-holes in depletion region of ZnO layer due to electric field also contributes in photocurrent. For light of visible wavelength the ZnO layer behaves as a complete transparent layer and photocurrent get generated due to electron-hole pair generation in Si layer. In this way n-ZnO/p-Si heterojunction detects UV-Visible wavelengths simultaneous over a single frame work and behaves as a dual detector.

Figure 2 shows the energy band diagram for n-ZnO/p-Si heterostructure. Thickness of ZnO and Si is 500nm and 380μm respectively. Light is assumed to be falling from the top of the heterojunction. After defining the physical structure of device, material properties of ZnO and Si has been defined.

Different parameters required for simulation such as conduction band discontinuity (ΔE_c), valence band discontinuity (ΔE_v), effective density of states for electrons in the conduction band (N_c), effective density of states for holes in the valence band (N_v) and intrinsic carrier concentration (n_i) have been calculated using following formulas [10-12]:

$$\Delta E_C = \chi_{ZnO} - \chi_{Si} \quad (1)$$

$$\Delta E_V = (E_{g,ZnO} - E_{g,Si}) + \Delta E_C \quad (2)$$

$$N_C = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} \quad (3)$$

$$N_V = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} \quad (4)$$

$$n_i = \sqrt{N_C N_V}\exp\left(\frac{-(E_C - E_V)}{2kT}\right) \quad (5)$$

where, χ_{ZnO} and χ_{Si} is electron affinity for ZnO and Si, $E_{g,ZnO}$ and $E_{g,Si}$ is bandgap of ZnO and Si, h is Planck constant , k is Boltzmann constant, T is lattice temperature, q is charge of electron, m_e^* and m_h^* is effective masses of electron and holes.

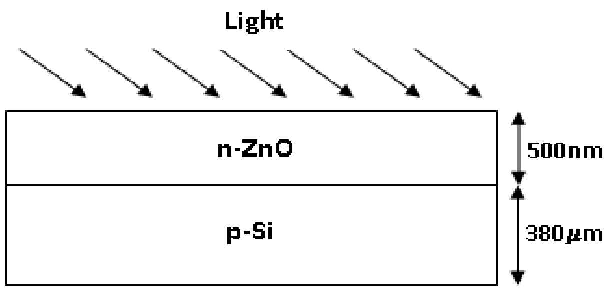

Figure 1: Structure of n-ZnO/p-Si heterojunction photodetector

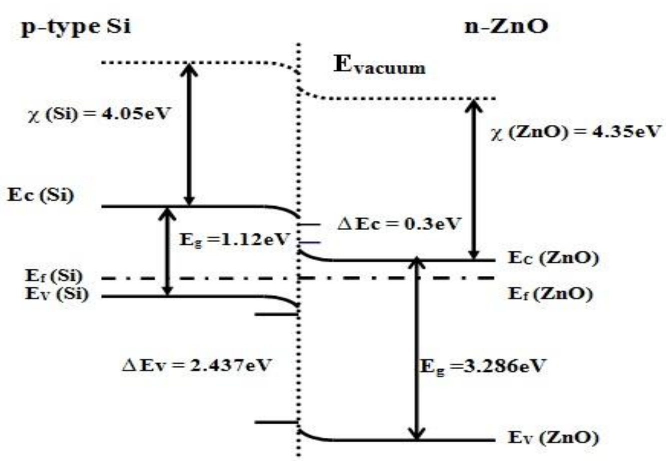

Figure 2: Energy band diagram of n-ZnO/p-Si heterojunction photodetector.

The set of material properties which are required for simulation includes the values of bandgap, electron affinity, dielectric constant, conduction band densities, valance band densities and electron/hole mobilities. Table I shows set of parameters that has been taken into consideration for the simulation of heterojunction photodetector. Doping is considered uniform for all the regions. The newton-richardson iteration method has been used to improve the efficiency of iteration. Concentration dependent model for mobility calculation and surface recombination mechanism at contacts has been considered in the simulation. For calculation of dark current AUGER, Band-to-Band and SRH model of recombination mechanisms have been considered [13-14].

Table 1: Values of parameters used for the simulation of n-ZnO/p-Si heterojunction photodetector

Parameter	Values
Donor concentration (N_D)	$1*10^{19}$ cm^{-3}
Acceptor Concentration (N_A)	$1*10^{15}$ cm^{-3}
Electron affinity (χ)	4.35 (ZnO), 4.05 (Si)
Effective density of states in the conduction band (N_c) [cm^{-3}]	$6.0*10^{19}$ (Si), $4.4*10^{18}$ (ZnO)
Effective density of states in the valance band (N_v)[cm^{-3}]	$2.2*10^{19}$ (Si), $7.1*10^{19}$ (ZnO)
τ_h and τ_n (sec)	$1*10^{-9}$ (ZnO) $1*10^{-3}$ (Si)
Dielectric constants (ε)	8.5 (ZnO), 11.9 (Si)
μ_n (cm^2/V.s)	60 (ZnO), 1000 (Si)
μ_p (cm^2/V.s)	10 (ZnO), 500 (Si)
Surface recombination velocity (S)	10m/s (electrons) 1000m/s (holes)
Effective mass of electron (m_e*)	$0.19*m_o$ (ZnO) $1.08*m_o$ (Si)
Effective mass of hole (m_h*)	$1.21*m_o$ (ZnO) $.56*m_o$ (Si)

III. RESULTS AND DISCUSSION

In this section simulation results of n-ZnO/p-Si heterojunction photodetector has been presented. Fig.3 shows current vs voltage graph for photodetector under dark and illumination condition. It can be seen from graph that under illumination condition photocurrent current increases. Under dark conditions dark current of the order of 10^{-14}A is obtained which confirms its suitability for low noise applications. Fig. 4 shows the internal and external quantum efficiency of the photodetector as a function of wavelength. Internal quantum efficiency is obtained from the ratio of available photocurrent to the source photocurrent and external quantum efficiency is obtained from the ratio of cathode current to source photocurrent. Plot of quantum efficiency confirms that of n-ZnO/p-Si heterojunction photodetector detects both UV and visible wavelengths simultaneously and has shown a very good quantum efficiency of 88% and 99% for UV and visible wavelengths respectively.

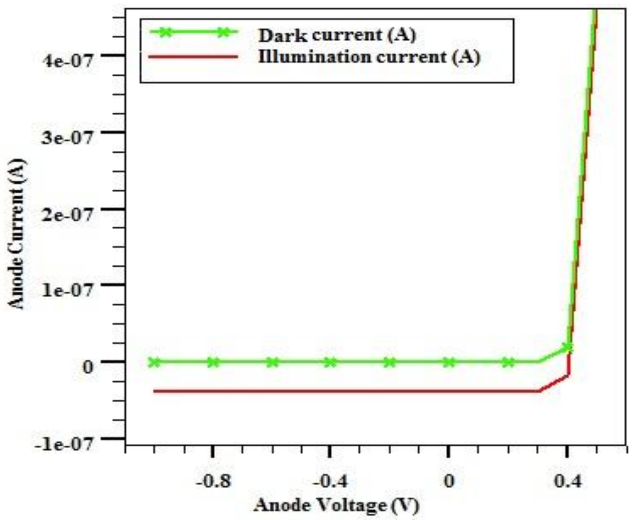

Figure 3: Current vs voltage plot under dark and illumination conditions

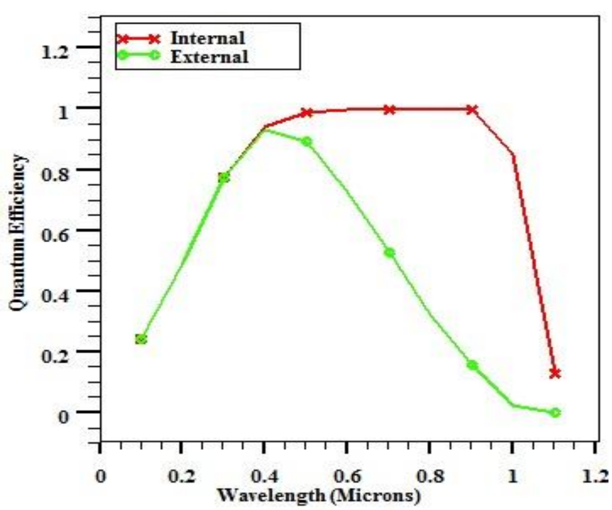

Figure 4: Internal and external quantum efficiency plot for the heterojunction photodetector

Effect of temperature on ZnO/Si photodetector has also been analyzed. Fig. 5 shows the variation in photocurrent when temperature is varied from 300K to 450K. It can be seen from graph that as temperature increases photocurrent of photodetector also increases. The extra current due to generation-recombination mechanism and/or the extra current due to the tunnelling mechanism through barrier are the probable reasons for rise in photocurrent with temperature [15,16]. This increase in photocurrent with temperature also affects the turn-on voltage of the photodetector. Turn-on voltage decreases with the increase in temperature and generation of more holes in p-region is the probable region for this phenomenon. Responsivity is an important parameter for a photodetector and can be described as follows:

$$R = \frac{q\eta\lambda}{hc} \tag{6}$$

where q is the charge of electron, η is quantum efficiency, λ is wavelength, h is Planck's constant and c is velocity of light. Fig.6 shows the effect of ZnO thickness variation on the responsivity of n-ZnO/p-Si heterojunction photodetector. Responsivity is being derived from external quantum efficiency. It has been observed that as thickness of ZnO increases responsivity also increases. Decrement in resistivity of ZnO layer with increment in ZnO thickness is the probable reason for this increased responsivity n-ZnO/p-Si heterojunction photodetector.

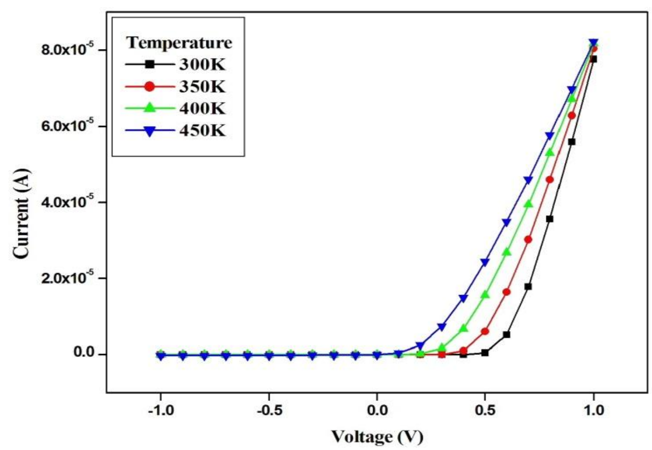

Figure 5: photocurrent vs biasing voltage plot with temperature variations (wavelength= 600nm, optical intensity=0.2W/cm^{-2})

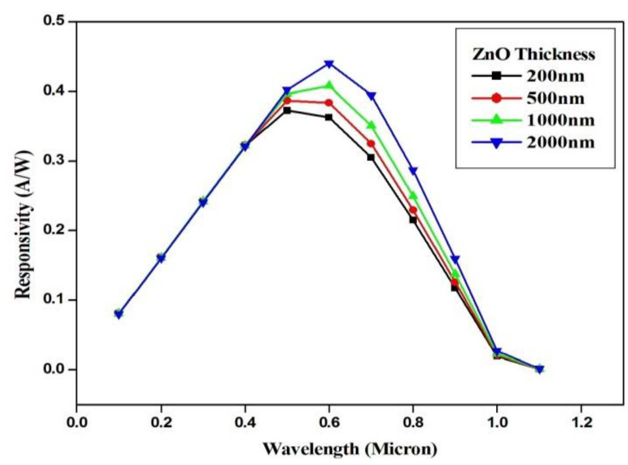

Figure 6: Effect of ZnO thickness variation on responsivity of n-ZnO/p-Si heterojunction photodetector (wavelength= 600nm, optical intensity=0.2W/cm^{2})

Figures 7 and 8 show the effect of donor and accepter concentration variation on responsivity of photodetector. As doping concentration increases from 10^{15} cm^{-3} to 10^{21} cm^{-3} responsivity decreases. A significant decrement in responsivity of photodetector has been observed when acceptor doping concentration is varied from 10^{15} cm^{-3} to 10^{21} cm^{-3}.

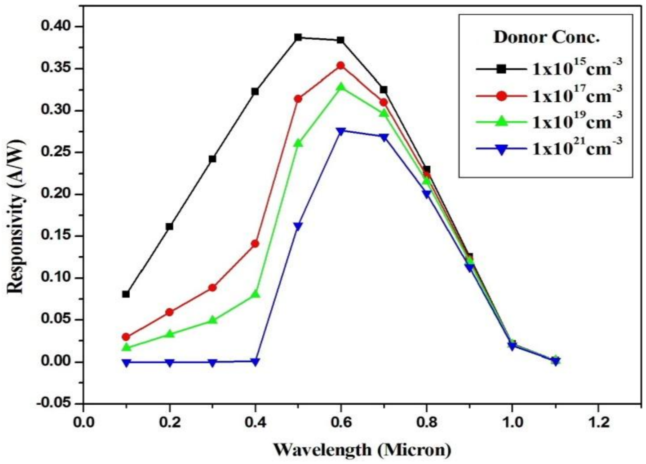

Figure 7: Effect of donor concentration variations on responsivity for n-ZnO/p-Si heterojunction photodetector (optical intensity is $0.2W/cm^2$, acceptor concentration is $1x10^{19}$ cm^{-3})

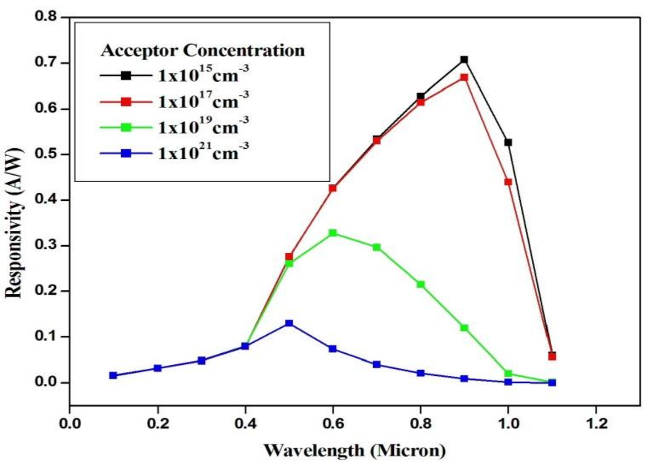

Figure 8: Effect of acceptor concentration variations on responsivity of n-ZnO/p-Si heterojunction photodetector (optical intensity=$0.2W/cm^2$, donor concentration is $1x10^{19}$ cm^{-3}, wavelength is 600nm)

IV. CONCLUSION

This work reports the performance analysis of n-ZnO/p-Si heterojunction photodetector using ATLAS simulator from SILVACO International. Results show that ZnO/Si heterojunction has shown very low dark current of 10^{-14} A and a very good quantum efficiency of 88% and 99% for UV-Visible wavelengths respectively. It has been observed that n-ZnO/p-Si heterjunction can detect both UV-visible wavelengths simultaneously over a single framework which can be very useful in variety of industrial applications. Effect of temperature variation, ZnO thickness variation and doping concentration variation on the performance of photodetector have also been analyzed. Results conclude that temperature thickness and doping concentration variations affect the performance of photodetector significantly and all these parameters need to be optimized before moving for fabrication in order to obtain efficient performance of device.

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