DESIGN AND CHARACTERIZATION OF SILICON QUADRANT DETECTOR (QD) FOR ROBUST POSITION SENSING

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Refractive Index

In the name of Allah, the most Beneficent and the most Merciful

Certificate of Approval

Title of Thesis: Design and Characterization of Silicon Quadrant (QD) Detector for Robust Position Sensing

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Accepted by the Faculty of Engineering and Technology Department of Electronic Engineering, International Islamic University Islamabad, Pakistan in partial fulfillment of the requirement for the degree of the MS Electronic Engineering with specialization in Advanced Electronics.

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DEDICATION

This Thesis is dedicated to my

Beloved Parents

and

My Special one (A)

Certificate

This is certifying that the work contained in this thesis entitled:

"***Design and Characterization of Silicon Quadrant Detector (QD) for Robust Position Sensing***" has been carried out by ***Waqas Ahmad*** under the registration ***349-FET/MSEE/S-14*** in Advanced Electronics Laboratories under my supervision. In my opinion, this is fully adequate in scope and qualifies the degree of the MS Electronic Engineering with specialization in the Advanced Electronics.

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ABSTRACT

Research in silicon based quadrant detector technology has recently seen an important push to develop the robust silicon based detectors which are used as the position sensors. The thrust is to manufacture the low cost and high efficiency detectors which have the CMOS process compatibility. In this work, a new design and post fabrication characterization of the PIN photo diode quadrant detector is envisaged. The simulation tool Silvaco TCAD (and its variants) are used to design and simulate the processes of the device. Device's output characteristics are also simulated to understand the design proficiency. Investigations on electrical and electro-optical properties of the post fabrication device are also made at length. Electrical measurements such as I-V characteristics, Responsitivity, C-V characteristics, transient time, transient photo voltage with respect to the time and photo voltage with respect to the light intensity and the optical characteristics like Psi (Ψ), Delta (Δ), Refractive Index, and Extinction Coefficient are analyzed in order to evaluate the designed and processed device structure for potential application in position sensing and other detection mechanism.

CHAPTER 1

INTRODUCTION

1.1 Introduction

CMOS technologies are used for implementation mature, cheap and reliable integration technologies since several decades. It has major advantage over the III-V compound semiconductor. CMOS technology has used to fabricate the optoelectronics devices like that Photo diode, PIN Photo diode, Avalanche Photo diode and Photo Transistor for the single chip application. Photo diodes and Photo Transistors aye widely used for the photo detectors. They divided in the further section like that PN Photo Diode, PIN Photo Diode, and Avalanche Photo Diode. PN Photo diode is very common used for the photo detection and it is very simple implementation into the standard CMOS technology. The Quadrant Detector (QD) is position sensitive detectors based on the photovoltaic effect. The operation of quadrant photo detector is very simple. When the light falls on the detector then quadrant detector generates the output current. In this way, quadrant detector is used to find the position of the spot. It is usually used to find the relative position of the light spot projected on its surface [1]. It is composed of four p–n junction photodiodes separated by small gaps [2]. Quadrant Detector has four junctions which placed symmetrically with respect to the center shown in Fig.1. When a light beam is projected, the photo currents will be generated.

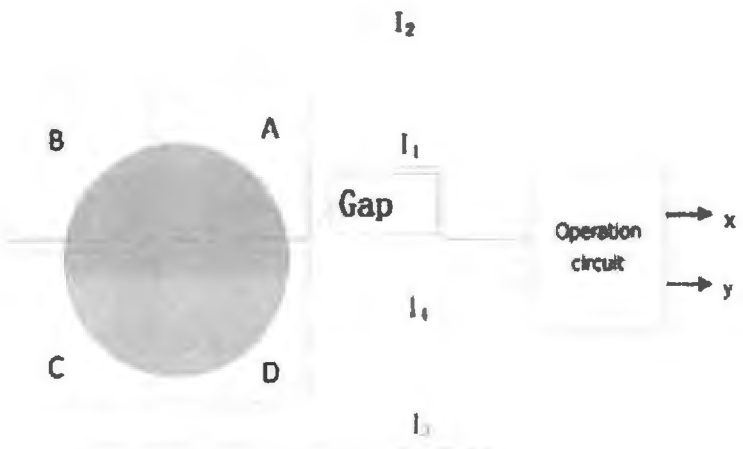

Fig.1 Diagram of Quadrant Detector [1]

Quadrant detector also called position sensitive which are used to detect the position when the light is projected on the spot and it is useful to find the vibration and displacement measurement triangulation and astigmatic error detection. There are two types of position sensitive detectors, the lateral effect Position Sensitive Detector and Four quadrant position sensitive detectors. In the lateral effect position sensitive detector, It is consists of p-n junction having two electrodes which are differentiate by anode or cathode shown in Fig 2. These two electrodes connect to each other in parallel form. P-N junction operated in reverse biased. In the depletion region, the light beam formed due to the electrons-hole pair and electrons and holes in the detector side are separated due to the electric field. Due to the lateral effect, the carriers moves toward the contacts and it is generated the higher current which is closer to light beam and its compared to opposite contact. The phenomena of difference the current of the contacts, we can measure the position of the light.

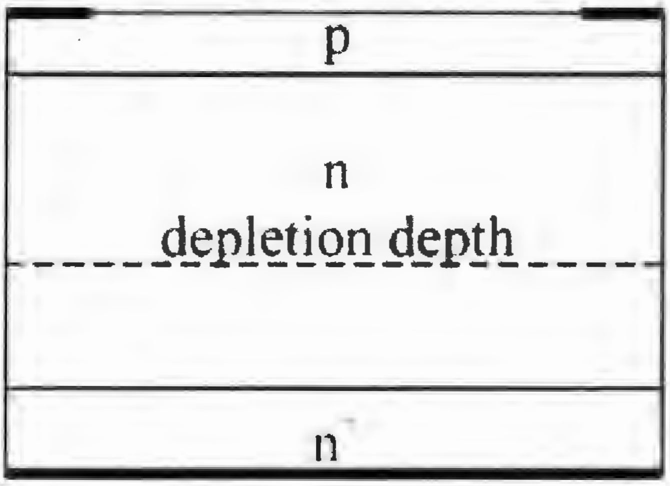

Fig 2. Structure of Psition Sensitive Detector [3]

While four quadrants PSD composed by the additional p+ region on the surface as compared to the lateral effect PSD as shown in Fig 3. The additional p+ region are separated by the small gap which shows that p-n junction has the four electrodes and impedance of inter electrode increased gradually. This novel sensor has higher noise effect than the lateral effect PSD because signal is depend upon the size of the light spot [3].

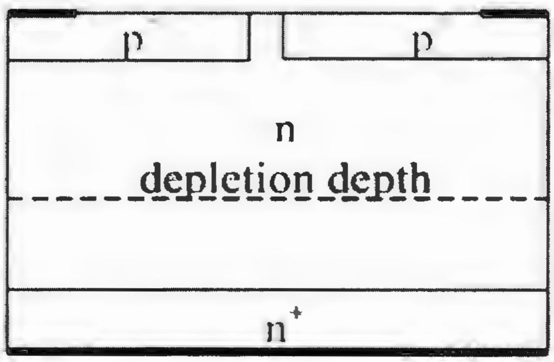

Fig 3. Four Quadrants PSD [3]

Four quadrant detectors is a common used position-sensing detector. Due to its simple signal processing, lower inherent noise level, high sensitivity and high response speed advantages. The quadrant detector low cost based sensor which has various application for example tracking the laser beam, particle tracking, measure the Gaussian laser beam measurement, autocollimators, optical tweezers, ellipsometers, precise optical alignment, wave front sensing, angle measurement, laser guided weapons and robust in nature [4].

1.2 Variability of Photo Detectors

Different photo detectors are used to detect the light and convert its electrical signal. The PIN diode and avalanche photo diode are the best detectors which detect the optical power. Both detectors have insensitive and very small change in wavelength. The design and fabrication of PIN diode cost is relatively low, good reliability and it gives good performance [5]. P-I and N region can be arranged in diode by vertically or in same plane. The planar structure of PIN diode shown below [6].

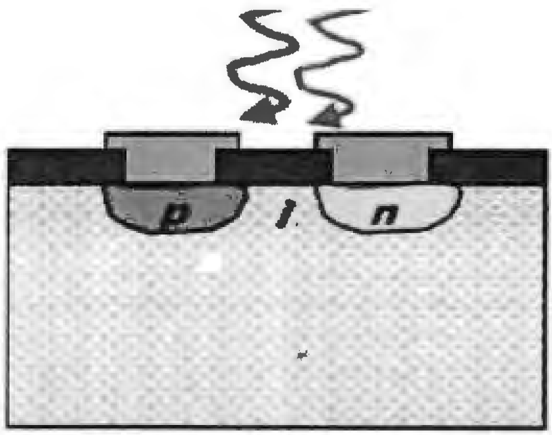

Fig 4. Planar Structure of PIN Photo diode [6]

My research focus on to design planar based four PIN photo diode and its electrical and optical characteristics using the trade off simulators. It can be fabricated using the CMOS technology where P-I and N regions doped with impurities using the ion implantation or diffusion process.

1.3 Problem statement

The goal of this research work is to design, process fabricate and characterize the silicon based photo diode quadrant detector both electrically and electro-optically to access the process parameters used for the optimization of their next generation fabrication protocols.

1.4 Objective

There are a few objectives to be achieved in this research

- Detail study of photo detectors
- Study and analysis of the quadrant photo detector and its fabrication and measurements
- Design the structure of quadrant detector on trade off simulators
- Characterization of electrical and optical properties of quadrant detector
- Electrical and electro – optical measurements include Hall, I-V/ C-V, Q-DLTS and spectroscopic, Ellipsometry techniques in the Advanced Electronics Labs at IIUI

1.5 Scope of the Work and Thesis Outline

This research is focused on to the design of quadrant photo detector and its electrical and optical characteristics to yield the desirable attributes for potential position sensing. This research consists of two parts: (a) Process simulation and Device simulation and (b) post fabrication characterization of the device. This is dealt in detail with the state of the art simulation and experimental facilities in the Advanced Electronics Laboratories at IIUI. The work presented here in this thesis is also divided in general introduction, background theory related to the knowledge necessary to understand the problem area, literature review, experimental parts and results, the discussion and conclusion on the results and the ideas to shape up the future work.

CHAPTER 2

BACKGROUND THEORY

2.1 Photo Detectors

Photo detector is an optoelectronic device which covert light energy into the electrical energy. Photo detectors generally used in optical communications system. It has various applications in every field of science like that light sensor, diagnostic tools, digital radiography and nuclear medicine. The basic operation of silicon photo detector is to convert the light into the electrical energy. In the photo detector, to increase the depletion region a reverse bias voltage is applied and it's generated the electron hole pair. Due carrier drift which is in opposite side generated a signal on the collecting electrodes. Presence of electric field in the depletion region the electrons pair produced outside and that's why no signal will be generated at the electrodes. Photo detector performance depends upon interaction of dept of photons and charge carrier in the depletion region. By the increasing the bias voltage, time performance can also be increased [7].

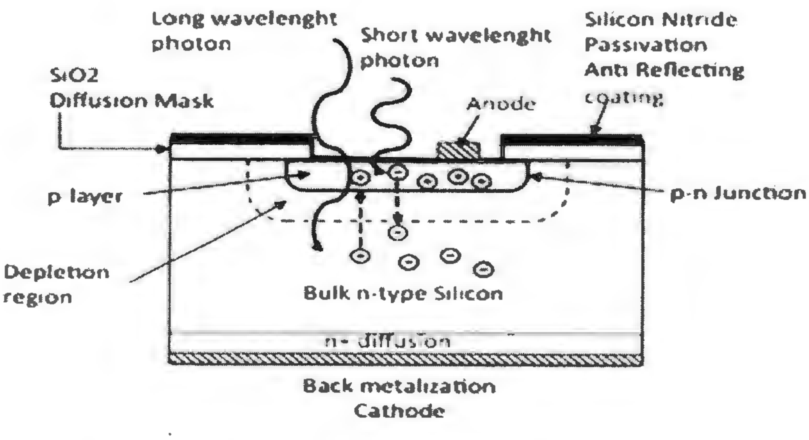

Fig 5. Basic Structure of Standard Silicon Photo Diode [7]

Some optical devices are very similar to photo detectors which are used in solar cells which has same function as convert heat energy into the electrical energy. Photo diodes and photo detectors are two good examples of photo detectors. LED is an also example of photo detector but it has different function which is that its convert current or voltage into the light [7].

2.2 Properties of Photo detectors

Photo detection is very emerging field in the area of the electronics devices and its detections. Silicon photo diode has efficient, low cost and give good performance in the photo detection in the different range of wavelength. Silicon photo detector has unique feature is that it has 90% surface reflection, response time approaching 30 psec and wavelength approached more than 850 nm [8].

The quantum efficiency of the detector is defined as number of electrons-hole pairs generated per incident photon and its defect free materials.

$$\eta = (1-R)\,[1-\exp(-\alpha w)] \qquad [9]$$

Where R is the surface reflectivity, α is the absorption coefficient and w is the width of the absorption layer. High quantum efficiency achieved for low surface reflectivity and extensive absorption area. By dielectric coating, surface reflectivity can be reduced [9]. The performance of detection can be determined if we know the quantum efficiency. The sensitivity of photo detector, noise equivalent power and responsitivity depends upon the quantum efficiency [10].

i. Responsivity

It is the unique property of photo detector in which is defined as output current is divided by the incident light.

$$R = \frac{Iph}{Popt} \qquad [10]$$

In the above equation Ip is the output current and $Popt$ is the optical power. It is linearly independent of the quantum efficiency and it is depends upon the quantum efficiency of the device [10].

ii. Noise Equivalent Power

In the photo detecting device, the noise power is defined as the result of collection of light in the signal to noise ratio is equal to 1 and other words rms noise current divided by the responsitivity and its unit is W/$\sqrt{Hz}$. It is depends on the frequency of light and normally photo detectors are characterized by the single value of NEP. It is given the performance value of the photo detectors. It is also used for comparing the performance of the photo detectors [10].

iii. Detectivity

It present the noise level in the photo detector and it is not depends upon the detective area.

$$D = \frac{\sqrt{A}}{NEP} \qquad [10]$$

it is also used for comparing the performance of the photo detector like that Noise Power Equivalent but it is not suitable to find the response of the photo detector to an intensity spectrum [10].

iv. Dark Current

It is the relatively small electric current that is present in the absent of the light and flow through the photo sensitive devices. Due to dark current, photo detector can operate under an applied bias and generates electrical signals in the absent of light. The performance of the dark current will be increased if applied large bias voltage across the photo detector. It has capability to detect the small signals from the photo detector [10].

v. Noise Spectrum

It depends upon the electrical frequency. It is also known as the current plotted or noise voltage. It is used to find the magnitude of the noise if we know the electrical frequency of the photo detector. It is also used to determine the performance of the SNR to frequency. To find the noise power of the system, the term power spectral density is used which is described as the noise content as the function of the frequency. Mathematically it is expressed as

$$P_N = \int_f S(f)\, df \qquad [10]$$

In the above equation P_n is the noise power over a bandwidth range, S (f) is the power spectral density, and f is the bandwidth [10].

2.3 Photo diode

Photo diode commonly used for the purpose of light detection. It is the type of semiconductor which has junction of oppositely doped regions (pn junction) on a semiconductor substrate. This creates regions of opposite doping and creates the space free charge region and it has high impedance. Mostly silicon and germanium are used to fabricate the photo diode and it has high impedance which is used for light detection with high sensitivity and low temperature. Light is used as an input source in the photo diode and in the reverse bias condition, when the no light then the current will be the zero at the junction and when the light is present it is acts as to be a switch or relay [11]. The operation of photo diode is that when the light falls on the pn junction, it creates electrons-hole pair because energy of photon higher than the band gap energy of the material. It operates in photoconductive mode or photovoltaic mode. Photovoltaic mode is used when determine the performance of the dark current whereas photoconductive mode is used to determine the performance of the fast switching [12].

2.4 P-N Junction

It is very easy to understand the pn junction because it is very simple of all semiconductor devices due to its fast switching and small weight and size. It is the hot topic to research area in the semiconductor devices. Mostly it has application in solar cells, detections of light and transistors. It has good sensitivity and has low cost. The properties of silicon can be changed if changing their carrier concentration through the diffusion or ions implantation. To make P and N type semiconductor, impurities atoms added like that

P-N junction. Hence the potential reduced and enhance the from p region to n region and enhanced the electron diffusion from n region to p region. Due to this phenomena the depletion region is reduced when the diode is act an in the forward bias [14].

While P-N junction operates in the reverse biased condition, it enhanced the electrons and holes towards the contact. Hence it enhanced the electrons and ions in the depletion region and very small saturation current flows [15].

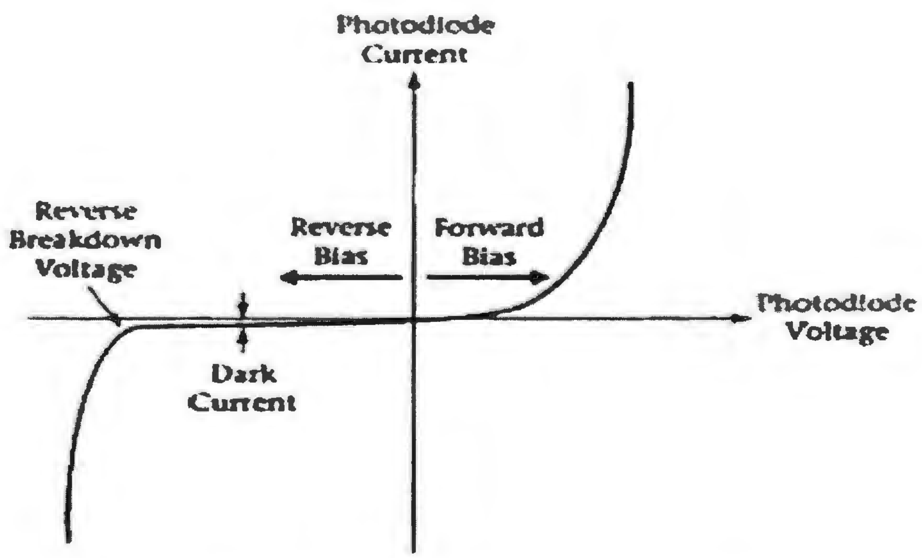

Fig 7. IV Characteristics of PN Photo Diode [15]

2.5 Avalanche Photo diode

It is the type of the P-N junction which has high internal gain and operated at high electric field. In the reverse bias mode, when the voltage is applied then electric field increased and that's why charge carrier in the depletion region also increased. It is commonly used in the optical communication. It is very similar to PIN photo diode but the difference is that it is absorbed each photons and generated the more electrons hole pair. The structure of the avalanche photo diode is very similar to PIN photo diode but the difference is that it has guard ring which avoid the surface break down mechanism [16].

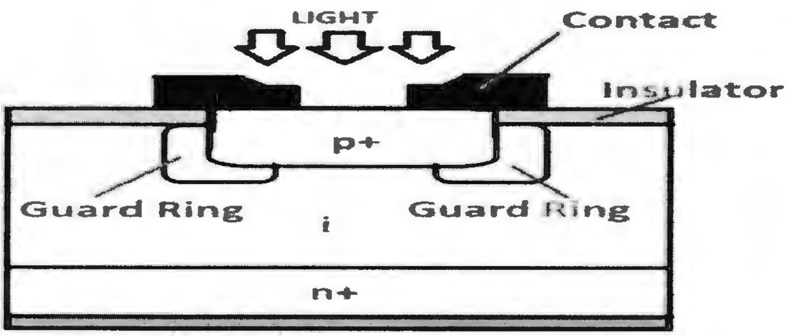

Fig 8. Basic Structure of Avalanche Photo diode [16]

It is mostly operated in the reverse bias mode that why it has strong electric field across the intrinsic region. When it is in the depletion mode, reverse bias generate the depletion region the diode that enhance the junction where photons are absorbed. These photons generate the electrons hole pair in the depletion region. Charge carrier in the depletion region has own sufficient energy which is produced new electron hole pair [16].

Guard ring is used in the avalanche photo diode which prevents the high electric field concentrations of the edge of the contacts. Guard ring is use to achieve the high performance in the photo sensitive area leakage current and achieving best reliability and improving the quantum efficiency and signal to noise ratio [16].

The current and voltage characteristics of the avalanche photo diode show in fig below. It has three different types of mode, Forward bias, Reverse bias and Avalanche breakdown. In the forward bias mode, the frequency response in the forward bias is not so good that's why it is not used in the optical communication and it is also called photovoltaic mode. In the reverse bias condition, a relative current generates as the change in the optical power and it is also called photo conductive mode. While in the avalanche breakdown, that is occur both in semiconductor and insulator martial [16]. Avalanche photo diode is also called the position sensitive in which it is used for the collection of the charges at different anodes. Normally in this mode it is placed at four corner squared device which is used to gain the information of the position of the photons. The noise level of the avalanche photo diode depends upon the temperature and the bias voltage.

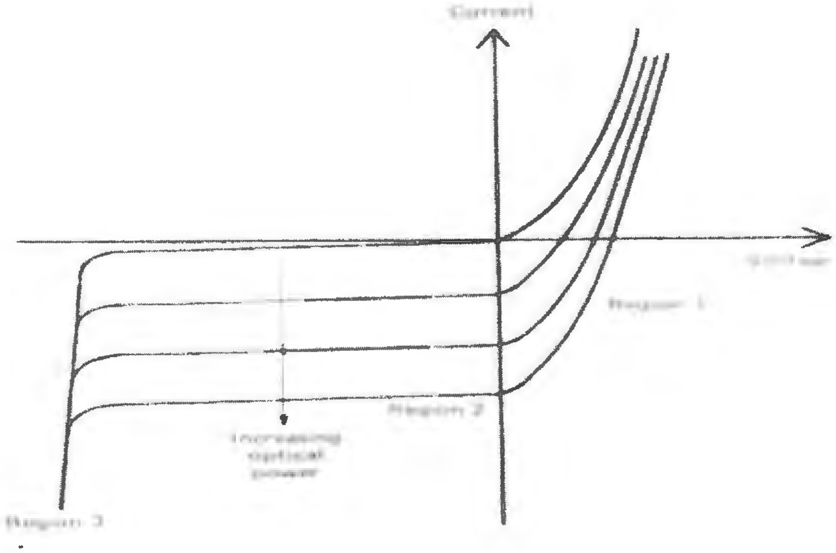

Fig 9. IV Characteristics of Avalanche Photo Diode [16]

Mostly it is used for stabilizing the signal; therefore it is used for improving the signal to noise ratio [7].

It has ability to reduce the miniaturized for micro scale devices. It has disadvantage is that it operates at high voltage and fabrication cost is too much make it very costly. It needs the composite temperature and standard voltage to maintain the circuit. Avalanche photo diode gives better performance in quantum efficiency greater than 90% at peak wavelength of response [10].

2.6 PIN Photo Diode

PIN photo diode is based on the P-N junction where P and N junction has highly doped regions. P I and N photo diode can be structured in different ways by vertically of planar as sown in fig. The planar PIN photo diode has low cost, has good efficiency, as compared to the vertical PIN photo diode [6]. In the PIN photo diode. Intrinsic region increased to gain the high efficiency and photons produced the more electrons hole-pair. PIN photo diode has capability to increase the transient time and decrease the junction capacitance. The speed of photo diode depends upon the three factors, diffusion, and drift and junction capacitance. In the diffusion, the charge carriers are produced to outer of the depletion region which are close enough to diffuse it. In the drift time which is in the diffusion region, it can be reduced to by increasing the intrinsic width of the junction and the junction capacitance which is reduced by the strong reverse bias [10].

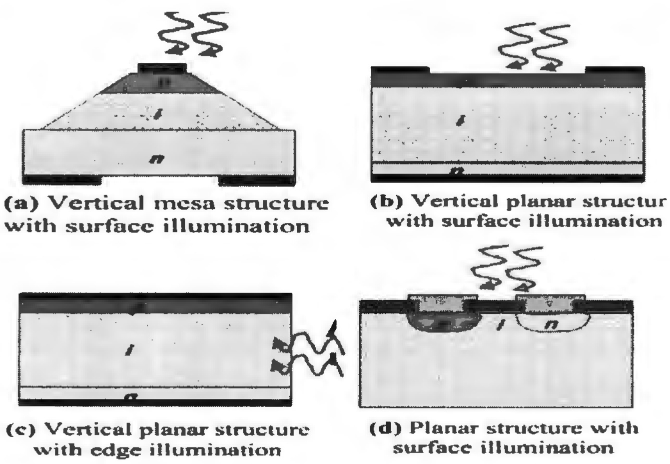

Fig 10. Basic Structure of PIN Photo diode [6]

Pure intrinsic silicon is used for the fabrication of PIN photo diode. In this structure, heavily doped the P and N near the intrinsic region, therefore it is referred to as the P, I and N diode. In the PIN photo diode, junction capacitance is inversely proportional to the depletion regions. Therefore depletion regions absorb more photons. To achieve the best frequency response of the PIN photo diode, mobility of electrons should be greater than the holes. The response time of PIN photo diode is given by

$$T_{PIN} = I^2 / u\ (V_0 + V_b)$$

It means that PIN photo diode show fast time if high bias voltage applied [19]. As compared to the other optical detectors Silicon PIN photo diode has low cost, good efficiency, small in size, better resolution and it can operate at room temperature. It is used to measure the position of the light and its pixels used for the image sensor. It is also used for measure the short distance in optical communications and measure the optical storage due to the dark current. By reducing the surface reflectance, the performance of the PIN photo diode can be enhanced [20].

2.7 Photo Transistors

Like other photo detectors, Photo transistors based on the photo electric effect. In this phenomenon of photo electric effect, the energy of the photons greater than the gap energy of the silicon and its absorbed and electrons-hole pair produced. A depletion layer generated in the PN junction between the two regions and electric field produced in this region. Electrons hole-pair separated in the depletion layer due to the electric field. It is produced the photo current through the junction [21]. It has two versions: with two terminals (Collector and Emitter) and three terminals (Collector, Emitter, base). Three terminals transistors also called the npn transistors which is shown in Fig.

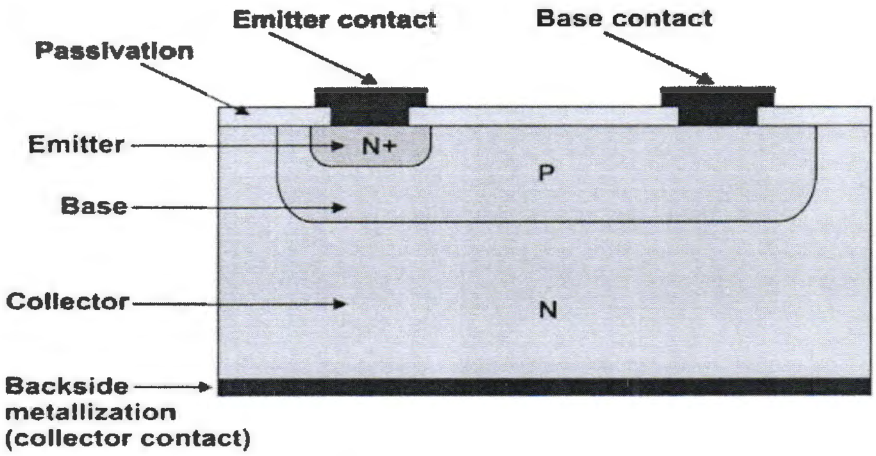

Fig 11. NPN Photo Transistor [22]

A photo transistor with two terminals has the same structure as the three terminals but it has not base contact. When positive voltage is applied between the collector and emitter, then it is operated in the biased mode. That's why base emitter junction is forward biased and collector base junction is reversed biased. The collector base junction has the lager junction as compared to the base emitter junction to gain the high sensitivity. The time response of the photo transistors is quite similar to the other photo detectors devices like the PN and PIN Photo diodes. The photo transistor has high sensitivity as compared to the other photo detectors due to its inherent current gain. It is the much smaller to the photo diode, therefore the current gain of the photo transistor range from hundred to thousand. The current gain of the photo transistor is given by

$$H_{FE} = Ic / I_b \qquad [22]$$

In the above equation I_c is the emitter current, I_b is the base current. If the photo transistor connected between the base and collector of the bipolar transistor then it is act as the photo diode. In this way, current is absorbs of the photo diode is fed to the base of the bipolar transistor. Hence this current is also called the transistor base current [22].

Photo transistor has advantages to other photo detector because it has no need to high voltage to gain the current amplifications. Photo transistor has bandwidth less than the bandwidth of the other photo detector like that PN and PIN photo diode due to the capacitance between base and emitter and between base and collector. The major drawback of the photo transistor is that slower response time as compared to the photo diode [23].

CHAPTER 3

LITERATURE REVIEW

3.1 Literature Review

C. Lu et al described the innovative method to sense the light spot of QD. They investigated spot energy distribution, dead area to the dynamic range, the spot movement mode and the detection sensitivity. They developed technique in which they achieved the better results in measurement. In the same spot size, the ability of sensitivity of Gaussian distribution is better than the uniform distribution and diagonal mode is better as compared to the cross mode. The measuring range of QD is 400 μm, and the resolution is 50 μm during experiment [1].

X. Hao et al investigated that when the quadrant detector set in the inclined plane at the angle of 45°. The device sensitivity increased by θ factor 1.4 and gave linearity [2].

K. Bertilsson et al designed a four quadrant position sensitive detector. The design overcomes the major drawback to effectively reduce the atmosphere turbulence. In this design, they increased the linearity which is essential to sensing the whole range. The designed QD is limited to sense the small area and appropriate for use in detectors up to 1mm in size [3].

M. Chen et al investigated the four quadrant detector whose shape is circle and elliptic in which they studied the relationship between the light spot position and output voltage in case of laser spot [4].

P. S Menon et al designed and characterized the PIN photo diode at trade off simulator Silvaco. They designed the PIN Photo diode at Silvaco Athena with two dimensional physical structures with different doping concentration and analyzed its electrical characterization. It is concluding that when intrinsic region is increased. There is decrease in the generation of the photo current [6].

M. G Bisogni et al review the CMOS based photo detectors and its electrical and optical properties. They designed and investigated the analog solid state photo detectors for positron emission tomography. The main attention of their research on the single photon multiplier which is used to designed and fabricates the scanners [7].

W. F Muhammad et al designed the photo detectors doped with indium and aluminum and analyzed its photo electronics properties and its possible effects doping, diffusion time, reverse voltage. Under estimation it is found that its shows good rectification under if it is diffused with the 30 minutes with the temperature of 1050 °c. It has low leakage current and giver better electronics properties if the device doped with the 150 nm indium and 200 nm of aluminum [8].

R. A. Yotter et al presented the review of the photo detectors and its electrical and optical properties. They give the importance and its application in the biological and optical field. They described the optical characteristics and analyzed the photo detection in terms of the dark current, noise equivalent power, responsivity, and response time and quantum efficiency. Avalanche photo diode, Photo multiplier and charged coupled devices are commercially used in lenses and detection of the light [10].

H. Melchior et al described the basic principles the photo detectors like that photo multiplies, photo diodes and avalanche photo diode. These photo detectors used to detect the light intensity with very short wavelength. Recently designed and implantation of the photo multiplier show better results than the other photo detectors. It shows the high gain, good efficiency. They presented the review of the silicon and germanium based photo detectors and analyzed its electrical and optical properties like that speed of response, quantum efficiency, sensitivity and internal gain [11].

M.A. Othman et al designed the CMOS based PN photo diode for the application of the 5GHZ optical communications. They designed the photo diode at Silvaco software and analyzed its current to voltage characteristics in terms of the changes in the width and the light [15].

M.A Othman et al described the review of the avalanche photo diode in terms of the optical communications. It is used to gain the high electric field and to obtain the high bit rate in optical communications. In relative to PIN photo diode, the avalanche photo diode has internal high gain. Avalanche photo diode has internal guard rings which is used to remove the high electric field and gives the better efficiency as compared to the PIN photo diode [16].

Haapalinna et al developed the method to measure the linearity in the photo detectors which based on the automated instrument. The technique is very simple in which absolute linearity of photo detectors measured. They designed the silicon photo diode and measured its linearity at 3×10^{-5} up to 7 mW of optical power [17].

Kundu et al presented the properties of the PIN diode and its applications in the microwave switching. They analyzed the resistance of the switch in microwave and its electrical properties which depends on the intrinsic region. The switch shows low resistance and higher frequency which based on the semiconductor material. GaAs based switch shows low resistance and lower isolation as compared to others. It is also used as single pole single through switch [18].

Alexandre et al presented the two structures of the photo transistors and analyzed its electrical properties using the VHDL –AMS language. They analyzed the spectral response of the photo transistors and investigate the linearity with respect to the power of the incident light [19].

B. Schmidt et al presented the design and fabricated the one or two dimension position sensitive photo detectors. The silicon planar technology was used via ion implantation for silicon doping. The PIN diode has chip dimensions from $25\times25mm^2$ (difference-photodiodes, quadrant-photodiodes) up to $14\times14mm^2$ (quadrant-detectors) and $5\times40mm^2$ (one-dimensional full area PSPDs) [22].

H. Wang et al fabricated the UV photo detector having low temperature, low cost and a simple method. It was composed of two layer n type titanium dioxide nano-rods which were fabricated by the hetero thermal method. The feature of this UV photo detector has to work without any external power source and displayed better sensitivity to UV light [23].

C. Mattsson et al designed a structure of quadrant which has several advantages, It has better electrode resistance s compared to the lateral effect resistance and it is suitable impressive effects than a conventional four quadrant. The designed structure is applied to detect the window less than 0.5× 0.5mm² and the typical deviation of the error is around 9 mm (2.2%). The position error is reduced to 6 (1.5%) and 2 (0.5%) mm by using the technique of 2-d correction function and modest analytical expression [24].

Z. Sadygov et al proposed three separate designs of micro pixel avalanche photo diode. The first one design is the silicon wafer in which matrix of independent p-n junction with surface resistors created. Due to resistors suppression of the avalanche process it's released each micro pixel to the metal grid. The second design based on the prototype has ability to work on the single type photon detection mode in which the local suppression of the avalanche process is carried out due to the limited conductivity of individual surface drift channels formed along the silicon–silicon oxide boundary. The third design based on deep buried multilayer pixels with an individual suppression of the avalanche process is also fabricated and characterized with in independent vertical channels [25].

M. Li et al designed and fabricated the metal photo detectors based on the silicon. Silicon dioxide layer was grown to reduce the dark current and passivity the surface. Dark current for the detector (0.75×0.5 cm²) with the added a-Si film was reduced from 0.137 μA to 2.61 μA at 5 V and 2 orders less as compared to standard silicon based film. Schottky diodes for QD fabricated at lower temperature and improved by cryogenic metallization process. As the temperature of the metallization decreased the dark current and speed enhanced. Schottky barrier height and ideality factor for the LT samples were increased from 0.399 eV to 0.481 eV, and 3.76 to 4.64, respectively, compared to that of the RT sample at 150 K. The results in this specific design show that thermionic field emission and current transport are in forward current region [26].

G. G. A. Salgado et al studied the porous silicon photo detector acquired by the electrochemical etching of p type none polished crystalline silicon. The samples which obtained at different conditions are characteristic by Photo Luminance (PL). The results showed the finest intensity in photo luminescence and adjusted at 625nm [27].

J. Q. Qian et al proposed the method which measures direction and rotor speed of quadrant photoelectric detector. This technique is well suited to reduce the noise and outside disturbance. The measurement range is 1–200,000 rpm which also reduced the effect of change of optics facular intensity [28].

L. P. Salles et al designed the 2-d position sensor based on the architecture of the quad cell and gave solution to overcome the nonlinear response in quad core cell to radically symmetric light spot. They achieved the desired output by the changing the quad cell perimeter and adding the appropriate regions which have different sensitivity [29].

M. McClish et al designed the position sensitive solid state photo multiplier (PSS-SSPM) which is based on the CMOS process. On micro pixel level, the device shows the 3-D information. PS- SSPM fabricated by its energy, timing resolution, and 3-d resolution. The device has position sensor with different micro pixel geometries and different micro electrical properties. [30].

T. Coura et al proposed the CMOS photodiode and improved the process yielding in low cost. They used the 1.6µm CMOS process in which they designed the photodiode with dual efficiency optical position sensitive detector. Every feature of the photodiode has n-well/ p-epi circularly surfaced junction combined with the p-n well/p-epi junction. It gives the 4% efficiency of the peripheral regions. Quantum efficiency improved 18% as compared to the conventional junction [31].

W. Sun et al presented the design for unitary photo detector and a single combination optical head (OPH) which is applied in laser application such a Blue-ray disc, digital versatile disc etc. The design is based on the discrete three laser wavelength beam and it is integrated on the optical unit [32].

M. A. Abbasi et al fabricated the Ultra Violet photo detector on fluorine doped tin oxide having additional feature of the hetero junction carried out the p-NIO and n-ZNO nanostructure have SEM and X- ray diffraction results show that nanostructure have good crustal quality and uniformity. The UV photo detector yielded produced the photocurrent of around 3.4 mA and a responsivity of 2.27A/W at -3 biasing voltage [33].

L. V. Schalkwyk et al fabricated and characterized AlGaN based solar blind ultraviolet four quadrants Schottky detector. By annealing, an ohmic layer structure was deposited. Au was coated on the Schottky contacts and then annealed. The detector had held onto a commercial chip carrier and wires were epoxy attached from the ohmic and Schottky contacts to the carrier strips [34].

Y. N. Chang et al designed the five photodiode detectors that can measure the solar power using the solar power sensor. The solar power sensor is designed with the four trapezoidal sides with an upper with rectangular sides formed on the top which had a column sensor [35].

S. Hirota et al proposed the photo multiplier tube (PMT) which has high quantum efficiency and designed the hybrid photo detector which has the next generation underground large water Cherenkov detector [35, 36].

Z. P. Barbaric et al derived the quadrant photo detector which is based on the new relationship. They derived the simulation which is based on the Matlab and analyzed its accuracy and its efficiency of the laser tracker system. The new proposed technique is that new displacement signal along the axes of the rotated coordinate system are dependent on the both of the center spot and attuned to laser tracking. Its gives the higher sensitivity of QPD. Because it's higher sensitivity, it provides better accuracy of laser tracking system [37].

J. Contreras et al investigated the ability of color sensing of amorphous silicon which is based on the 32 linear arrays. They showed its ability to distinguish between the Blue, Red and Green (BRG) and derived colors. By ignoring the white color, the proposed detector can detect the red color by combination reflection of the surface of the white and red color [38].

J. Sun et al explained that Resonator-quantum well infrared photo detectors (R-QWIPs) were the advance level of the quantum well infrared photo detector. To gain the best performance, the thickness of the resonator was reduced; they proposed the two optimized inductively coupled plasma etching process in which they developed the R-QWIPs detector. The substrate of this detector was completely removed and hence achieved the desired dimensions [39].

N. Beyraghi et al proposed innovative current mode four quadrant multiplier. The fabrication based on 0.35μm standard CMOS technology and the designed multiplier was simulated in HSPICE simulator [40].

J. Xu et al proposed a photo detector which is based on the reduce oxide graphene in plane micro super capacitors and CdS nano-wires. The micro super capacitors electrodes were used as the source and drain of the CdS photo detector. It is configured like as visible light photo detector system without using any external power [41].

N Katic et al designed the sensing device using 0.18μm CMOS technology which is cost effective. They investigated the difference between the conventional and combed shaped photodiodes in terms of its light responsivity, response speed and quantum efficiency. They developed the sensing device photo detectors three transistor active pixel topology. They measured the responsivity, response speed and quantum efficiency for each structure. The results show that CMOS technology is well-matched BJT in time domain applications. They achieved the better responsivity by combining the lateral and vertical BJT. They achieved the fast response by using the Darlington pair which configured with BJT which is used in the time domain imaging applications [42].

D. H. Son et al designed and fabricated the silicon PIN diode high resistivity, 100 orientation, n type and 380μm thick on the 5 inch silicon wafer. They used the technology of radioactive source to measure the energy resolution and signal to noise ratio to check the performance of the PIN diode Am-241, Cs-137, Sr-90. They measured the energy resolution of these parameters. AM -241 energy resolution of 59.9 KeV was measured to be 23% and Cs-137 are at lower region while Sr-90 radioactive source measured at 31.2 [43].

N. I, Shuhaimi et al used the Sentaurus TCAD tools to design the Silicon PIN diode. They investigated the I.V performance as well as effects in the variations of the undoped regions. The width of PIN diode is varied while thickness is at fixed at 40μm. They studied the I-V characteristics and its performance at different width 70μm, 80μm and 90μm. They analyzed that as the width increased; the current level is also increased [44].

E Abiri et al describe the various applications of PIN diode. They presented the PIN diode which is very similar to conventional PIN diode but difference is that layer is used at the centre of the layers in the PIN diode. They designed the diode which has four pins which is fabricate of series of resistance and capacitance. It has many applications such as modulators and demodulators, amplifiers, high frequency multipliers and resonators [45].

W. M. Jubadi et al used the Sentaurus TCAD technology to simulate the four different intrinsic layers of PIN diode thickness 5μm, 20μm, 30μm and 50μm thickness and investigated the I-V characteristics of PIN diode. They investigated I layer thickness and its effects on PIN diode. The result which gain from simulation shows that as the thickness of I layer is thin then the more forward current flow in the PIN diode [46].

A.W. DiVergilio et al used to spice simulations to present three terminals PIN diode. The structure which they proposed predicts the accurate behavior of the diode. The diode works at forward conductive state which shows that its accuracy in simulations [47].

Z. Zainudin et al designed the PIN diode silicon on insulator at Athena and analyzed its electrical characteristics on the Atlas Silvaco software. They analyzed the performance of the PIN diode silicon on insulator and simple PIN diode and realized that it's produced lower leakage current as compared to the simple PIN diode. However, SOI shows poor performance in the temperature variations [48].

A. Aditya et al analyzed the properties of different materials like that SiC-4H, SiC-6H, Si, Ge, GaAs, SiC-3C, GaN-wZ, GaN-zB, InAs and studied its total resistance, intrinsic resistance and junction resistance and studied it's what effects on the intrinsic regions using the same parameters [49].

CHAPTER 4

EXPERIMENTAL TECHNIQUES

The following techniques are used to design and characterizations of the Silicon Quadrant detector which are given below:

Designs and Simulations

- **Silvaco**
  - Athena
  - Atlas

Electrical Analysis

- **ASMEC Analysis**

Optical Analysis

- **Ellipsometry**

4.1 Silvaco

In this project we used Silvaco TCAD tool to design the PIN Photo diode and explain its electrical characteristics. Silvaco is the simulator tool of TCAD process for device simulation. Silvaco tools consist of the Athena and Atlas. Athena is used for the design for the physical structure and Atlas is used for the electrical characterization of the design. Silvaco found in 1984 and 11 sub office in worldwide and head quarter in Santa Clara, California [50].

4.1.1 Athena

It is the process simulator that has capabilities to design the numerical, physically based two dimensions structure which used in the semiconductor. It has included SUPREM-IV simulator with many new capabilities. ATHENA is known to accurately predict the dopants distribution, layer by layer topology, and mechanical behavior in device structures [51].

It is used in combination of different tools like that Deck build, Tony plot, Dev-Edit, Mask view and Optimizer. In the Deck build tool, it is provide the codes which are used in the command and it is used in the run time environment. Tony plot shows the graphs which obtained due to the simulations. Dev-Edit is used to mesh define in the structure and improvement. Mask view is used as an editor of the IC layout and the Optimizer is used as to optimization of the across the multiple simulators. Athena is used also as the input of the Atlas device simulator. Athena gives the 2-d physical structure of the device which is used as an input by the Atlas and Atlas gives the electrical characterizations of the structure [52].

Athena has three major advantages

- It is easier to design the 2-d structure
- It gives the insight
- It is based on the theoretical knowledge

➢ It is cheaper than experiments

➢ It is much quicker than other simulator

The next Figure shows that the Athena frame work architecture

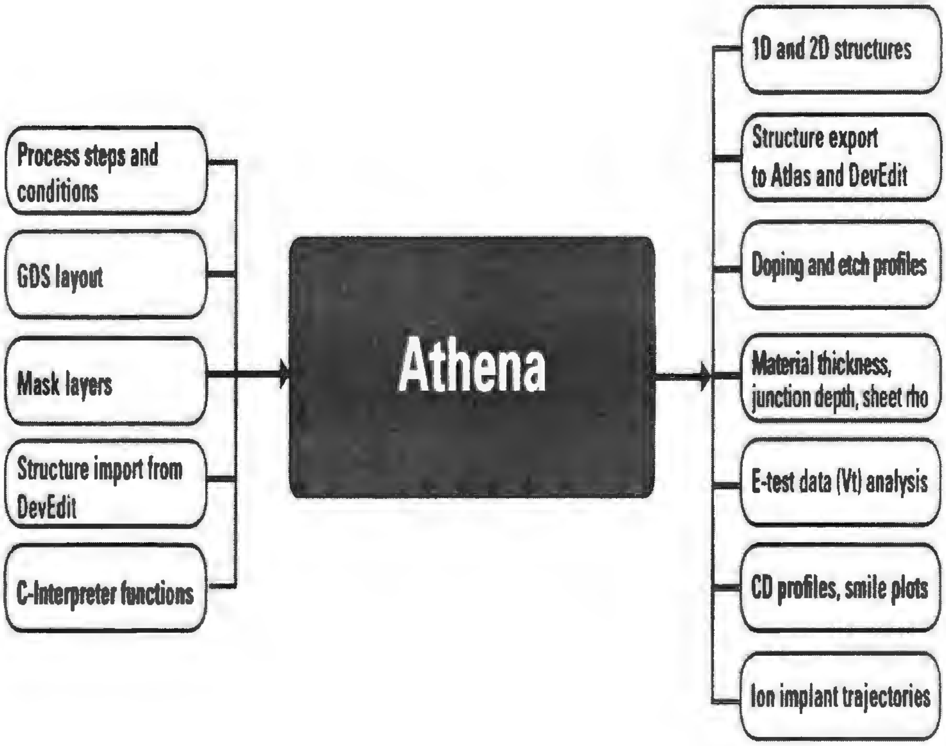

Fig 12. Inputs/Outputs of Athena [51]

4.1.2 Atlas

It is the two or three dimensional simulator that is used to get electrical characterization of the device. It is simulate the electrical, optical and thermal behavior of the semiconductor. It used to analyze electrical characterizations and behavior of the device [53].

The main advantages of the Atlas are [54]

- The 2-d structure which is simulated by Athena is used as an input by Atlas
- The combination of Atlas and Athena are used to find the process parameters of the characterization of the device
- It is used to solve to problems regarding to the maximum combinations of break down, Power dissipations, Speed, Leakage density etc
- It is used to get the electrical and optical characterizations of the Silicon material, Organic material and all types of the electronics devices like that CMOS and Optoelectronics
- It is much quicker, easier and time effective process simulator

The simulation problems following the given steps [54]

- 2-d physical model to be simulated by Athena or other tools
- The physical models to be used in Atlas
- To solve the physical equations numerical method is used
- Bias conditions are necessary to get the electrical characterization

The following figure shows that the working of the device simulator

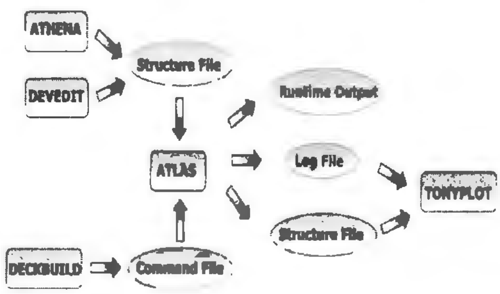

Fig 13. Flow chart of Atlas Simulator [54]

Frequently, it is used with the combination of the Deck build in the run time environment which is based on the two types of operations interactive and batch mode operations. In the interactive mode, it shows the executions of the command in atlas and shows the error, warning messages and other parameters. In the batch mode, it is also called the non-interactive mode in which prepared command is necessary for running the in batch mode [54].

Atlas has two types of input parameters and three types of parameters which are shown in Figure 13.

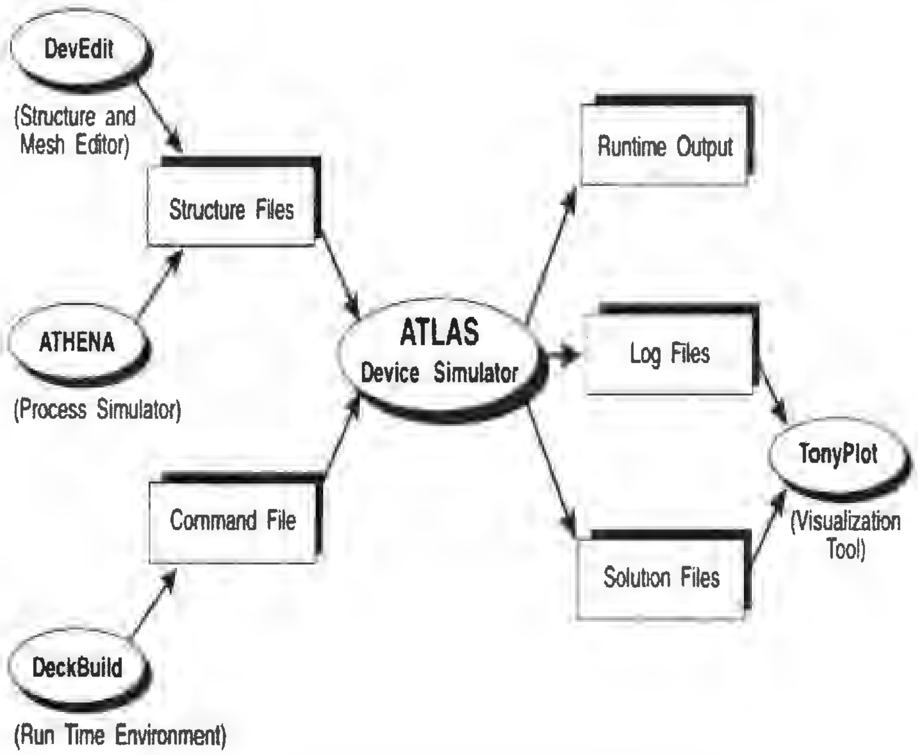

Fig 14. Atlas Inputs and Outputs [54]

Command file is known as the first input file that is used in Atlas to execute and structure file is known as the second input file that defines the structures in the atlas [54].

Run time output file is known as the first output file of the Atlas in which it is shows the error, warning messages and progress. The second file is called the log file which is used for the analysis of the current and voltages and last output of the Atlas is the solutions file which stores the data of 2d and 3d structures [54].

In Atlas, there are different methods to solve the problems of the semiconductor devices.

a. Gummel Method

It is fully decoupled which is used to solve the each unknown equations until to achieve the stable solutions. It is effective where the systems of the equations are weakly coupled [54].

b. Newton Method

It is fully coupled in which is used to solve the all unknown equations. It takes the long time to solve the equations as comparatively to the Gummel method. It is helpful when the systems of equations are strongly coupled [54].

c. Block Method

It is fully coupled and decoupled in which is used to solve the some equations. It has the faster simulations over the Gummel and Newton method [54].

In ATLAS, there are five groups of commands which are necessary to get the desired results. If these five statements are in not correct order then we did not achieve the desired results.

These five statements are shown in next Figure.

Group	*Statements*
1. Structure Specification	MESH REGION ELECTRODE DOPING
2. Material Models Specification	MATERIAL MODELS CONTACT INTERFACE
3. Numerical Method Selection	METHOD
4. Solution Specification	LOG SOLVE LOAD SAVE
5. Results Analysis	EXTRACT TONYPLOT

Fig 15. Flow of Process Simulation [54]

4.1.3 Luminous

It is the advance version of device simulator which is fully integrated with atlas. It is used to get optical characterizations of the planar and non planar semiconductor devices. It has ability to analyze the coherent effects in the layer devices. The beam propagation technique is used to get the optical properties like that refractive index, coherent effects, transient time and diffractions. It is applicable to various devices technologies like that Charge Couple devices and imaging devices, solar cells, photodiode, photoconductors, avalanche photodiode, photoconductors, phototransistors and high speed and communications photo detectors.

4.1.4 Process used in Simulations

- Mesh Define
- Mesh Initialize
- Oxidation
- Diffusion
- Etching
- Annealing
- Metallization

Mesh defines: Simulation accuracy and process of the time is directly depends upon number of nodes in the grid. A finer grid is necessary to obtain the accurate electrical characterization [51].

Mesh initialize: The substrate is formed either in p-type or n-type with its points, nodes, triangles, background, doping or some additional parameters [51].

Oxidation: It is the process of grow the thin layer of SiO_2 on the surface of the wafer which is used as the passivation layer [55].

Diffusion: It is process of the transfer of the chemical properties from the region from the high concentration to the region of the low concentration. Basically it is used to change concentration of the conductivity and type of the semiconductor material [56].

Etching: It is process to remove the unwanted materials which is formed by the doping or diffusion. Anisotropic etching or isotropic etchings are two methods which are used for the etching purpose mostly. Dry or wet etchings are also two techniques which are also used for special applications [57].

Annealing: It is the high temperature process which is reduced the stress in the crystals structure of the wafer [58].

Metallization: It is process of the electrical contacts between the circuits of the semiconductors materials. Mostly Aluminum is used for the purpose of the metallization. But other alloys also used for the metallization [59].

4.2 ASMEC Analysis

It is the abbreviation of the Automatic System for Material Electro Physical Characterization which is very sensitive equipment. It is used to measure current at the range of the Pico Ampere. It has Cryogenic cylinder which is used to observe the sample and it is connected to the ASMEC which is further connected to the data to analyzing the data. The next Figure shows the ASMEC system.

Fig 16. ASMEC System

ASMEC has many applications which are given below:

- Kinetics of free and trapping charges
- C-V Characterization (Pulse and line scanned)
- I-V characteristic
- Charge-DLTS
- Photo-stimulated Internal Field Transient Spectroscopy (PIFTS)
- Electrical Excitation
- Optical Excitation
- Iph(t)
- Vph(t)
- Q(t)
- Q(t)
- I(t)
- Emission/Recombination Rate
- Minority Carrier Concentration
- Minority carrier Life time
- Built-in Voltage
- Resistivity/Conductivity
- Activation Energy
- Concentration of non-compensated donors and acceptors
- Dielectric constant
- Charge Analysis

- Carrier Concentration/Deep Level concentration
- Failure mode Analysis

The specifications of ASMEC are given below:

Current Sensitivity	1pA
Charge Sensitivity	5×10^{-16}
Range of Bias Voltage	-13.5V to +13.5V
Range of Rate window	10µs-200s
Temperature	72K-500K (Extendable)
Interface	Probe-station /External Acquisition
Deep level concentration sensitivity	5×10^{-7}

Table of Specifications of ASMEC

4.3 Ellipsometry

Ellipsometry technique which is non-destructive and non-invasion to obtain the optical properties of the samples by means the reflected light waves. It is very useful technique to measure accurately because it is not depends upon the absolute intensity and it is used to measure the relative change in measurement [60].

It is used to measure the any physical property of the optical systems and its measure the little change in polarization when intensity of the light incident on the sample. That is why it is used in much different application [60].

Normally, it is used to find the dielectric properties of the like that refractive index, dielectric functions of the thin films. It is also used to get the optical properties like that roughness, thickness, doping concentrations, electrical conductivity of the materials [61].

4.3.1 Basic Principle

It is used to measure the change of the polarization when the intensity of the light incident n the sample and it is reflected and then it is compare to the model because it is model dependent technique and the model explains the sample structure. Basically, it is used to find the properties of the sample like that thickness, refractive index and dielectric functions. It is used the polarized light to get the characterizations of the semiconductor devices. When the light undergoes to the sample then its reacts with sample and changes its polarizations. Usually, the measurements in the form of the Psi (Ψ) and Delta ( ) [61].

The basic diagram of the ellipsometry is given below:

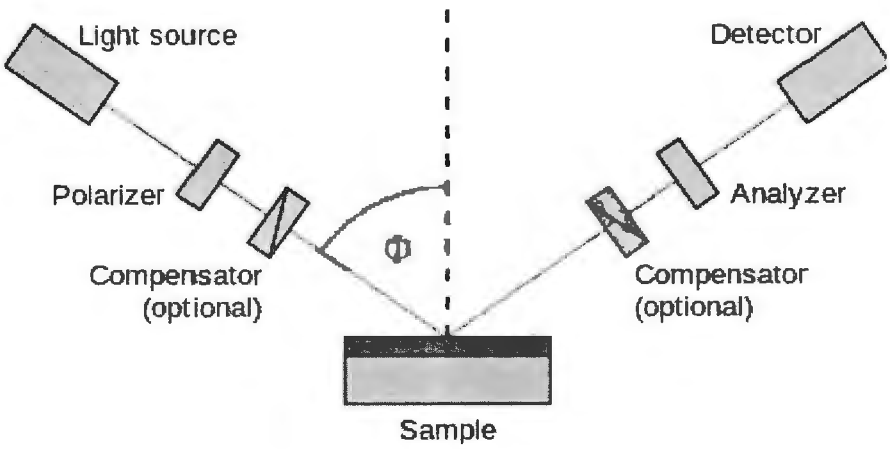

Fig 17. Diagram of Ellipsometry [61]

In this Fig 17, light source is linearly polarized by the polarizer. Then the polarized light source passes through the compensator and then its falls on the sample. Then its reflects due to the sample and its pass through the compensator and second polarizer which is also called the analyzer and reach on to the detector [61]. There are three different designs of the ellipsometry which are Nulling ellipsometry, Rotating Analyzer and Photo elastic modulator ellipsometer [62].

4.3.2 Nulling Ellipsometry

It is simple and based on the nulling principle. When the light incident on the sample. Then analyzer is rotated to find the minimum light which is entered to the detector. The drawback of this design is that it is not suitable for the precise measurement and cannot obtain to real time measurement. The diagram of the nulling ellipsometer is given in below [62].

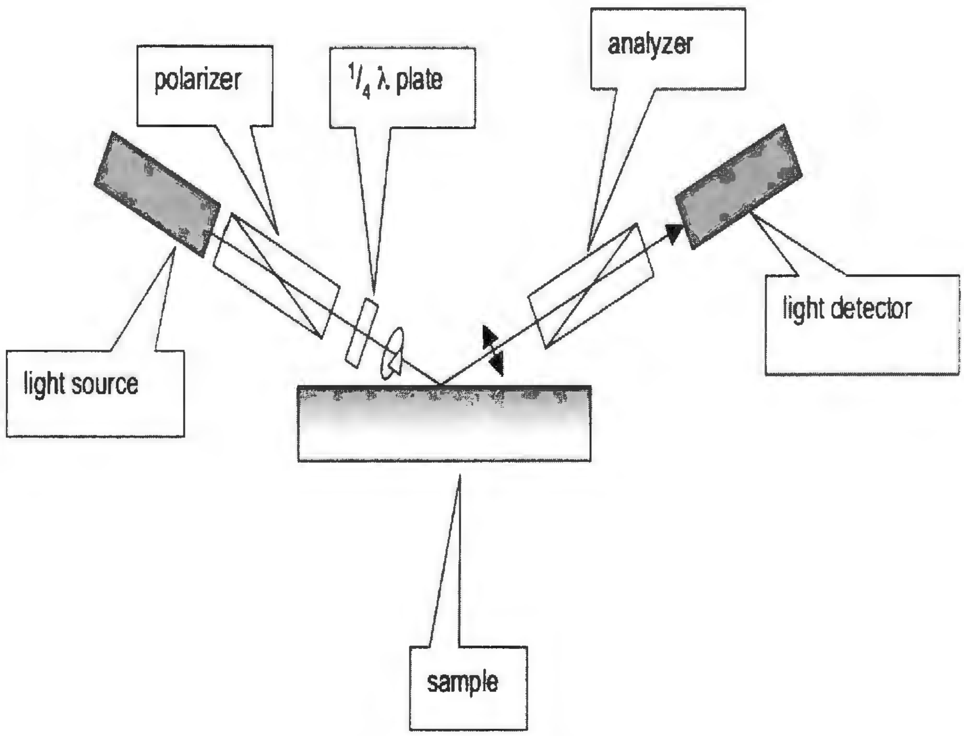

Fig 18. Diagram of the Nulling Ellipsometry [62]

4.3.4 Photo elastic modulator Ellipsometers

It is latest ellipsometers which is referred to as the solid state ellipsometers because it has no moving parts for the data acquisition. It is fast and more accurate and gives the precise data as compared to other designs of ellipsometers. It is the sensitive to other designs because it has faster technique for the measurement and its sensitivity ad very sensitive to ultra thin films. The diagram of Photo elastic modulator ellipsometers is given below [62].

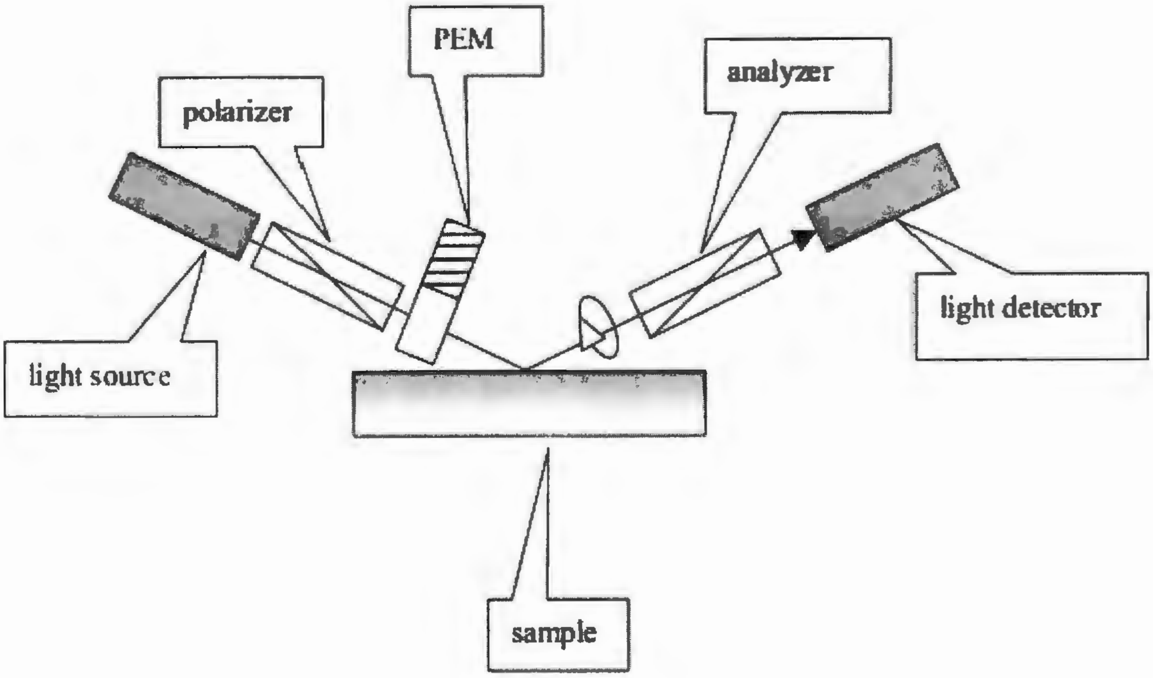

Fig 20. Diagram of Photo elastic Ellipsometers [62]

4.3.5 Metrology Grade Spectroscopic Ellipsometer

It is the tool to find the optical characterization of silicon based materials. It is based on the step scan analyzer measurement mode. It is used to find the thickness of the films, Psi, Delta, and Refractive Index (N) and Extinction Coefficient (K).

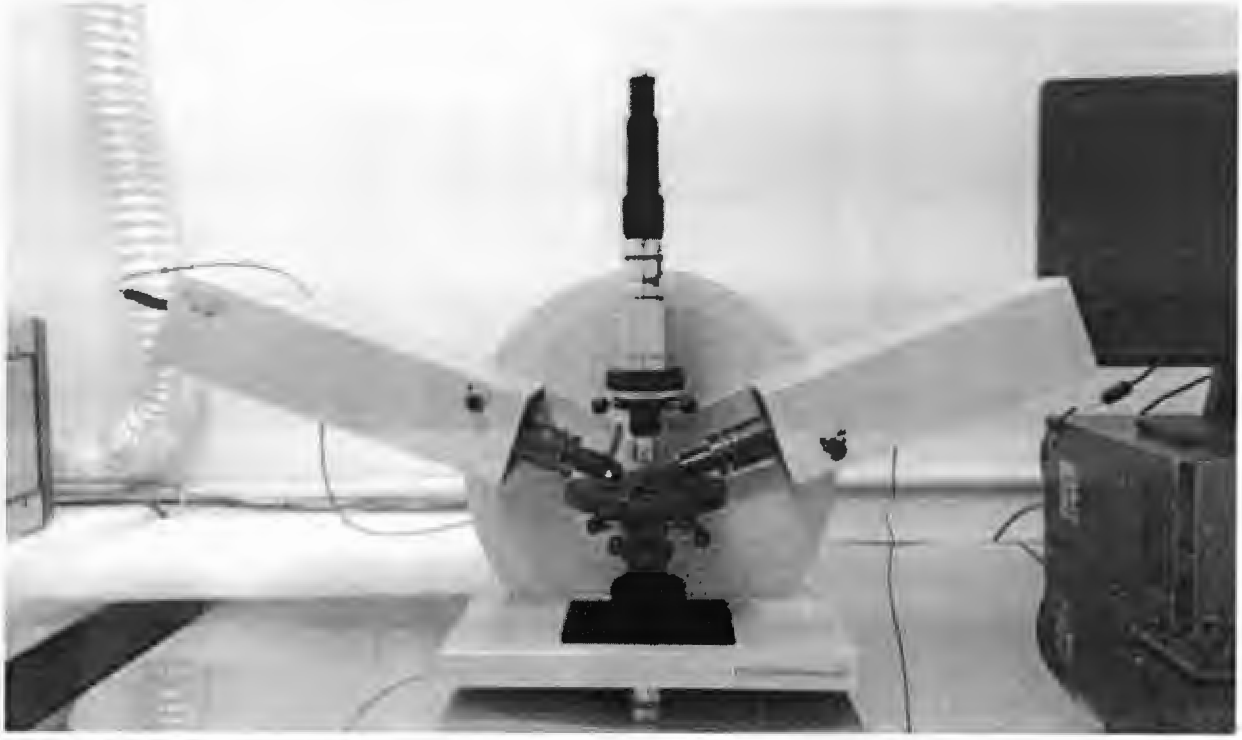

Fig 21. Metrology Grade Spectroscopic Ellipsometer

It has many applications which are given below

- Thickness of thin films
- Refraction Index
- Extinction Coefficient
- Refraction
- Transmission

- Conductivity
- Depolarization
- Crystals modifications
- Conductivity
- Scattering

CHAPTER 5

EXPERIMENTS, RESULTS AND DISCUSSION

5.1 Simulation of PIN Photo Diode

In this project we used Silvaco TCAD tool to design the PIN Photo diode and explain its electrical characteristics. Silvaco is the simulator tool of TCAD process for device simulation. Silvaco tools consist of the Athena and Atlas. Athena is used for the design for the physical structure and Atlas is used for the electrical characterization of the design. The following process is used to design the PIN Photo Diode at Silvaco Software.

5.1.1 Mesh Define and Initialize

It is the parameter of the size of the design. X-direction shows that the length of the device and T- direction shows that the depth of the device. The dimension of the device is 2500 × 22 and Silicon with concentration of phosphorous 1000 ohm/cm^2 and 2 dimensional. So it is lightly doped N- type as shown in Fig below:

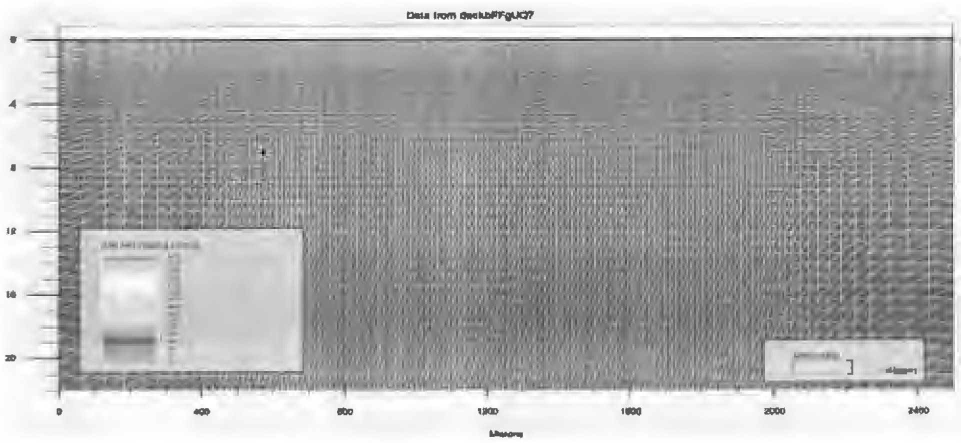

Fig 22. Mesh Initialize 2-d view

5.1.2 Deposition of oxide layer

0.6 µm oxide layer deposit on the silicon wafer for the masking purpose. It is also used as a passivation layer.

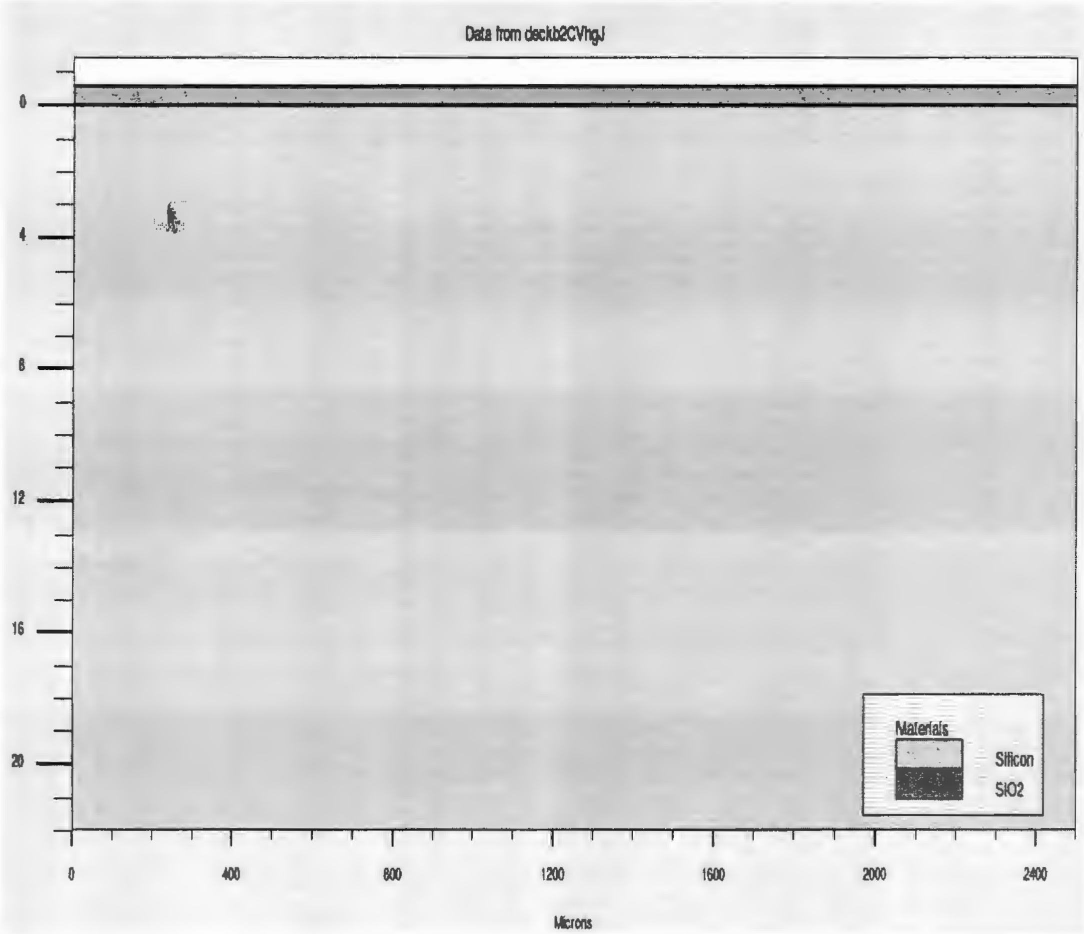

Fig 23. Structure formed after deposition of oxide layer

For making the P well and N well, it is necessary to make the geometrical etching at the silicon based wafer to form the P well and N-well. Firstly we will make the P-well. For this purpose, geometrical etching will be done.

5.1.3 Geometrical Etching for making the P-Well

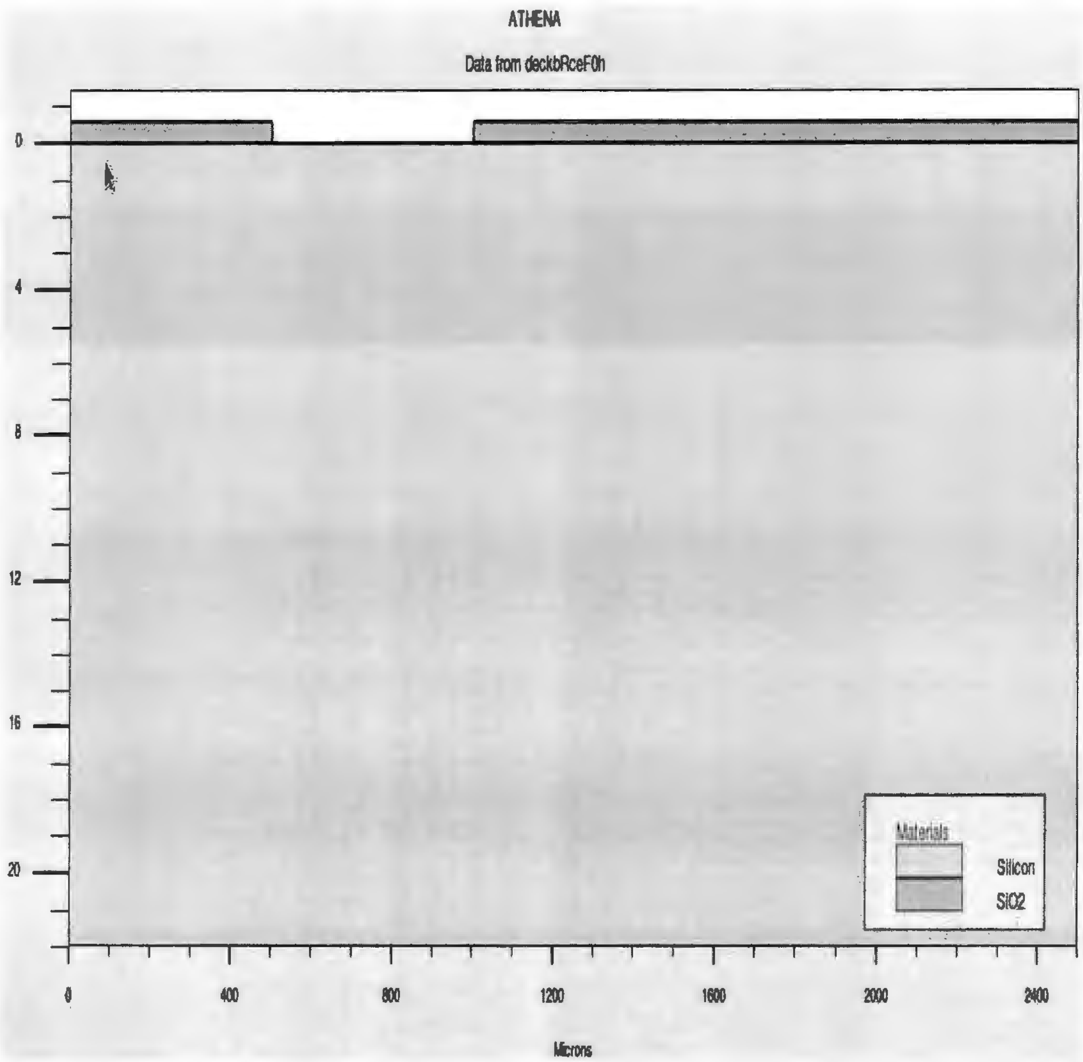

Fig 24. Geometrical Etching for making the P-Well

The next step is to deposit the nitride layer. It is also called the cap layer. It is deposit on the silicon wafer because the concentrations of the boron atoms only diffuse into the P-well and not diffuse the whole wafer which is shown in next Fig.

5.1.4 Deposition of Nitride layer for making the P-Well

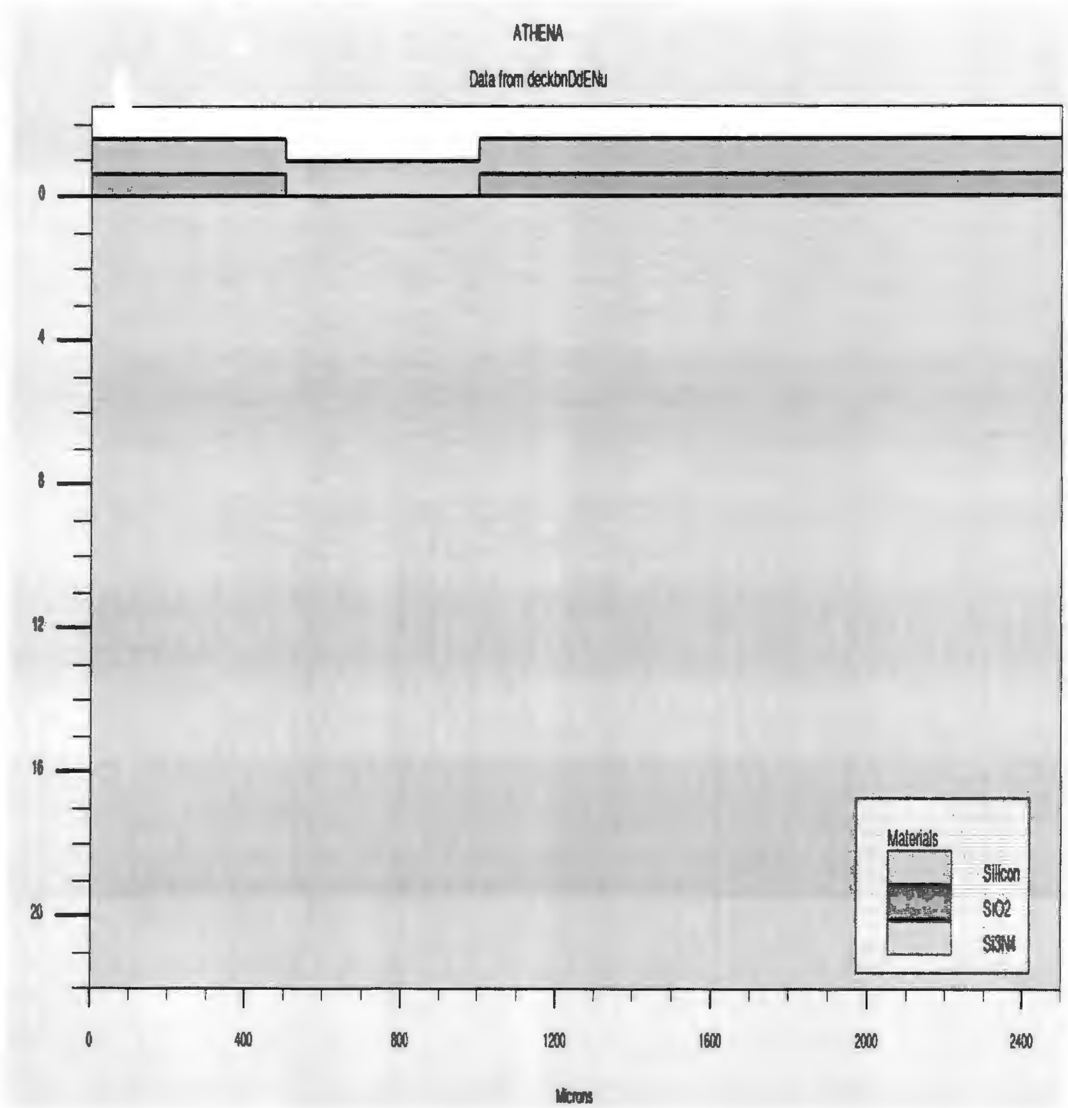

Fig 25. Structure formed after deposition of Nitride layer

The next step is to etch the nitride layer. For this purpose, Geometrical etching will be done for the purpose of the P-Well.

5.1.5 Etched Nitride layer for making of the P-Well

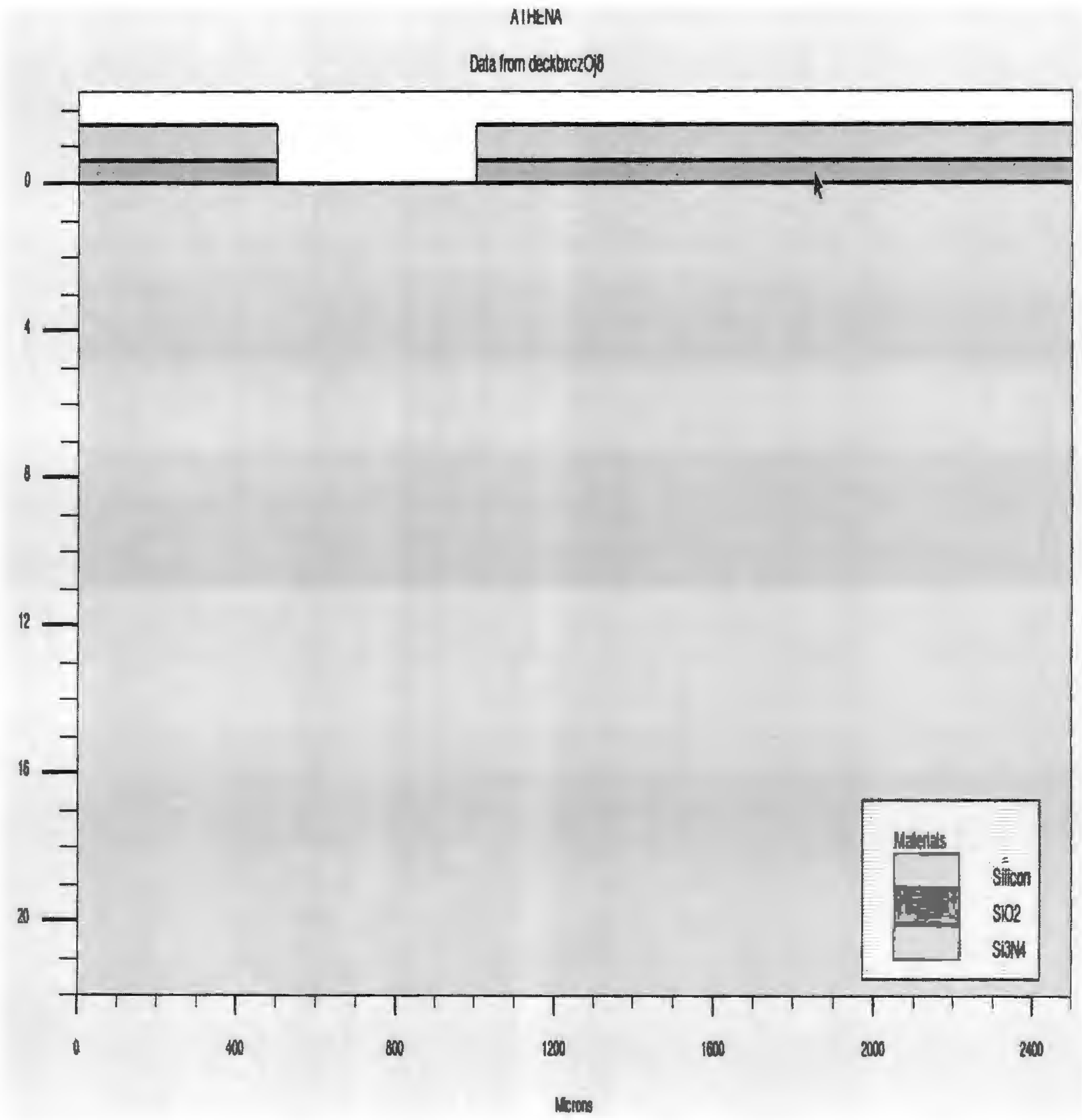

Fig 26. Etched Nitride layer for making the P-well

The next step is to diffuse the Boron atom with the concentration of 8.09 $\times e^{16}$ with the temperature of 1200 °C and 120 minutes.

5.1.6 Diffusion the Boron Impurity for making the P-Well

For making the P-Well. It is necessary to diffuse the Boron atom with the concentration of 8.09 $\times e^{16}$ with the temperature of 1200 °C and 120 minutes.

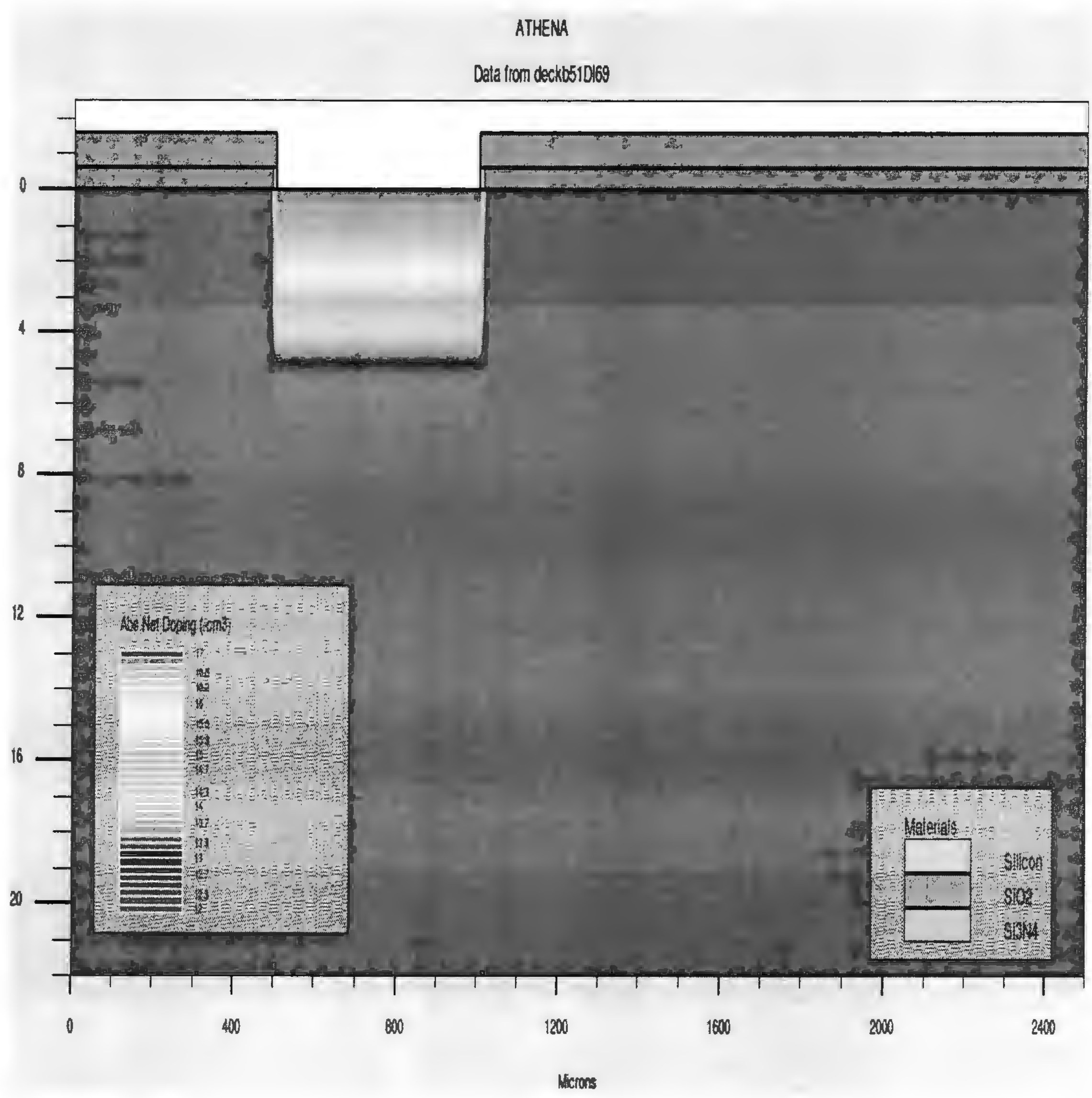

Fig 27. Diffusion the boron impurity for making the P-Well

The next step is to etch the nitride layer from the whole wafer from making the N-Well.

5.17 Etched the Nitride Layer

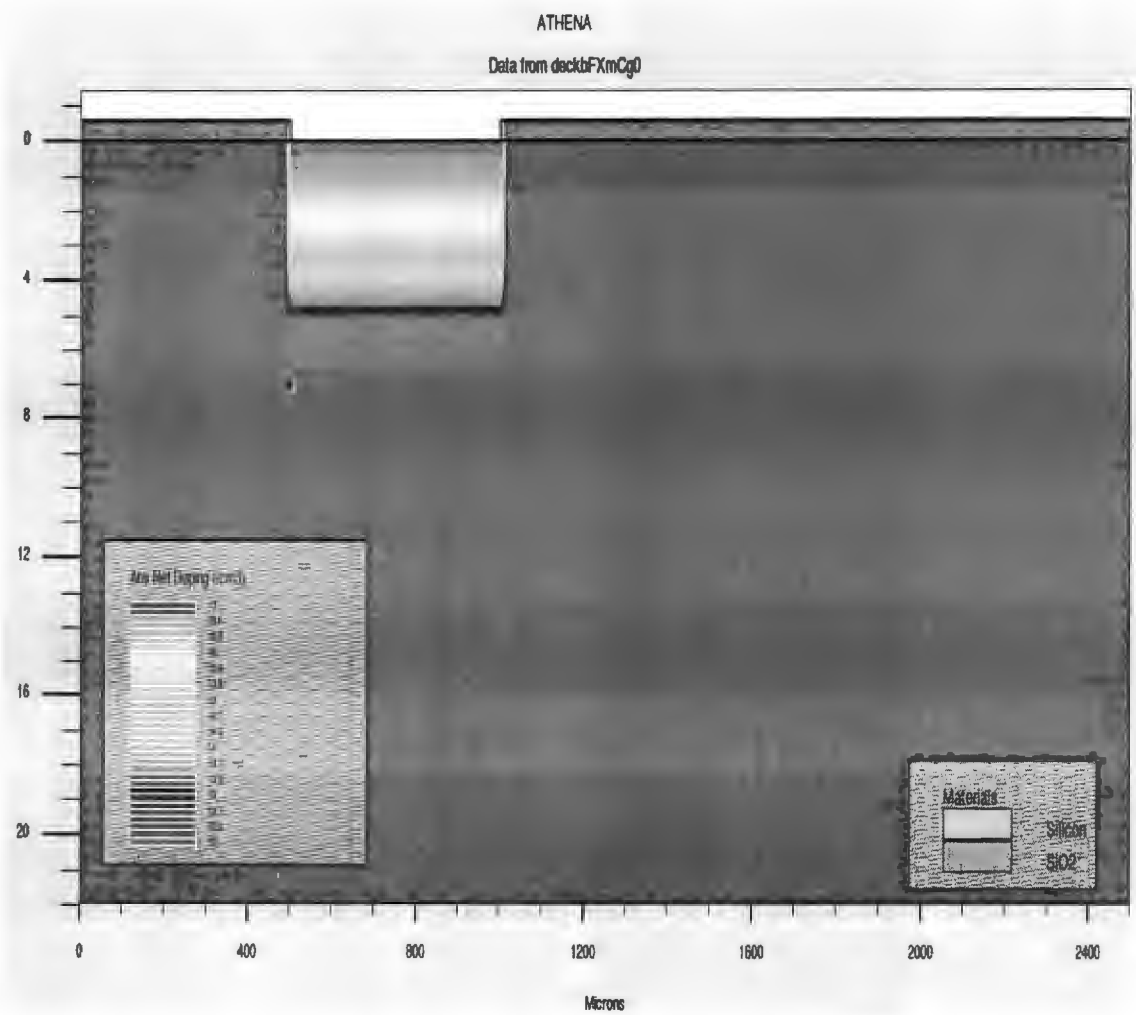

Fig 28. Etched the nitride layer from the whole wafer

The next step is etching the oxide layer from the whole wafer for making the N-Well.

5.1.8 Etched the Oxide layer for making the N-Well

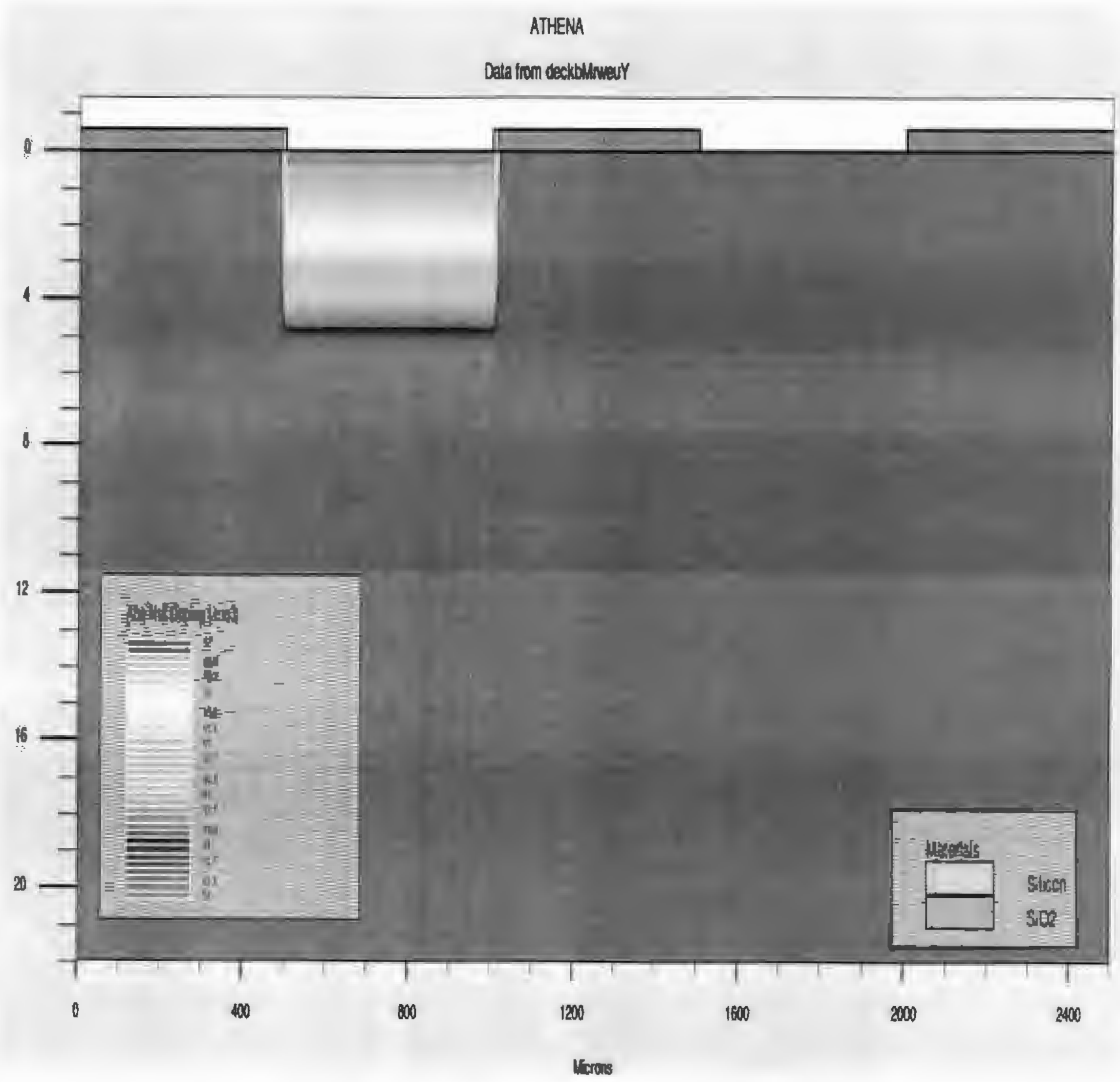

Fig 29. Etched the oxide layer for making the N-Well

The next step is to deposit the oxide layer for masking purpose and then deposit the nitride layer on the silicon wafer for making the N-Well on the other side on the Silicon wafer.

5.1.9 Deposit the Nitride layer for making the N-Well

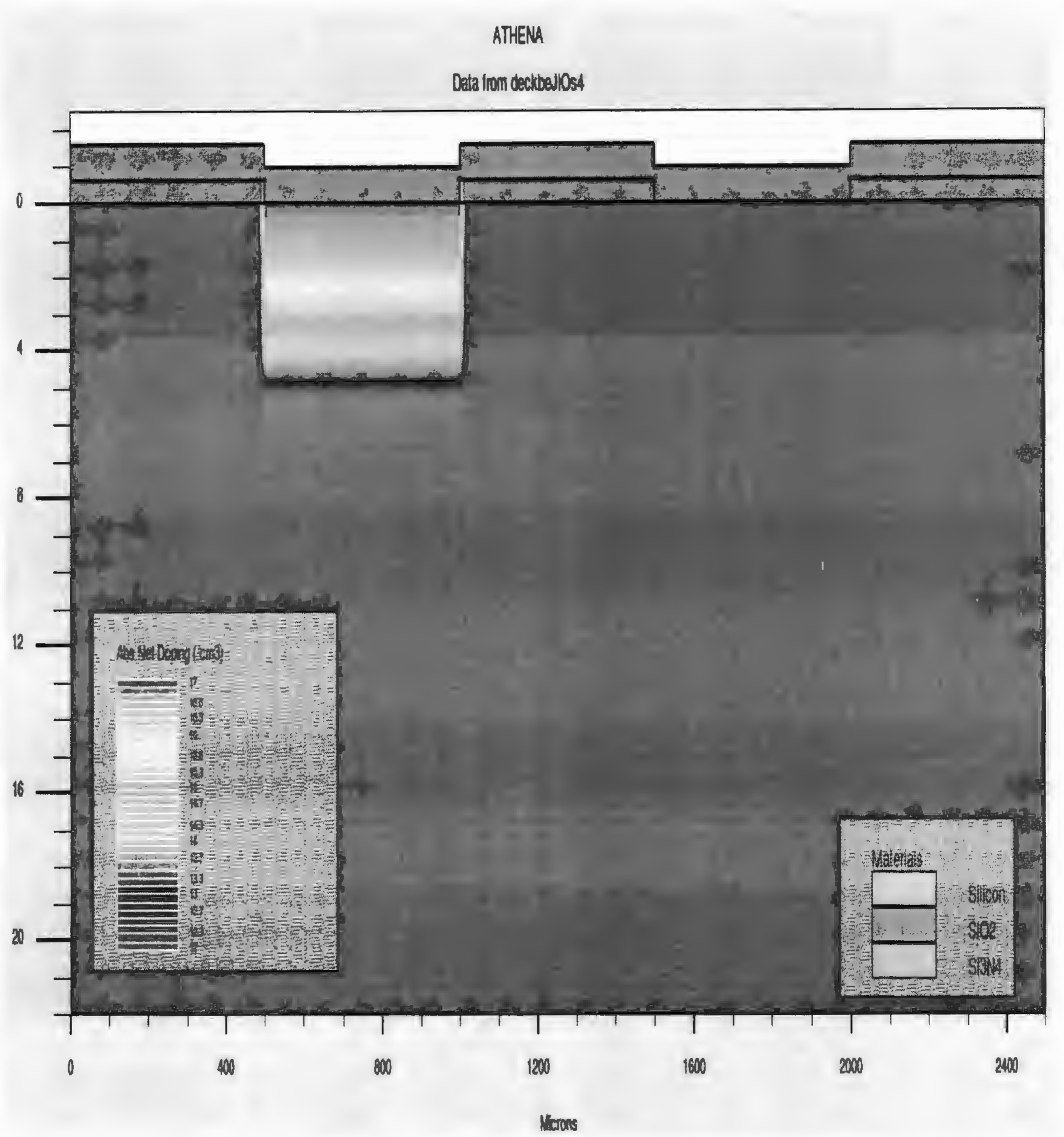

Fig 30. Structure formed after the deposit of nitride layer for making the N-Well

The next step is to etch the nitride layer for the making of the N-well as shown in next Fig.

5.1.10 Etched the Nitride layer for making the N-Well

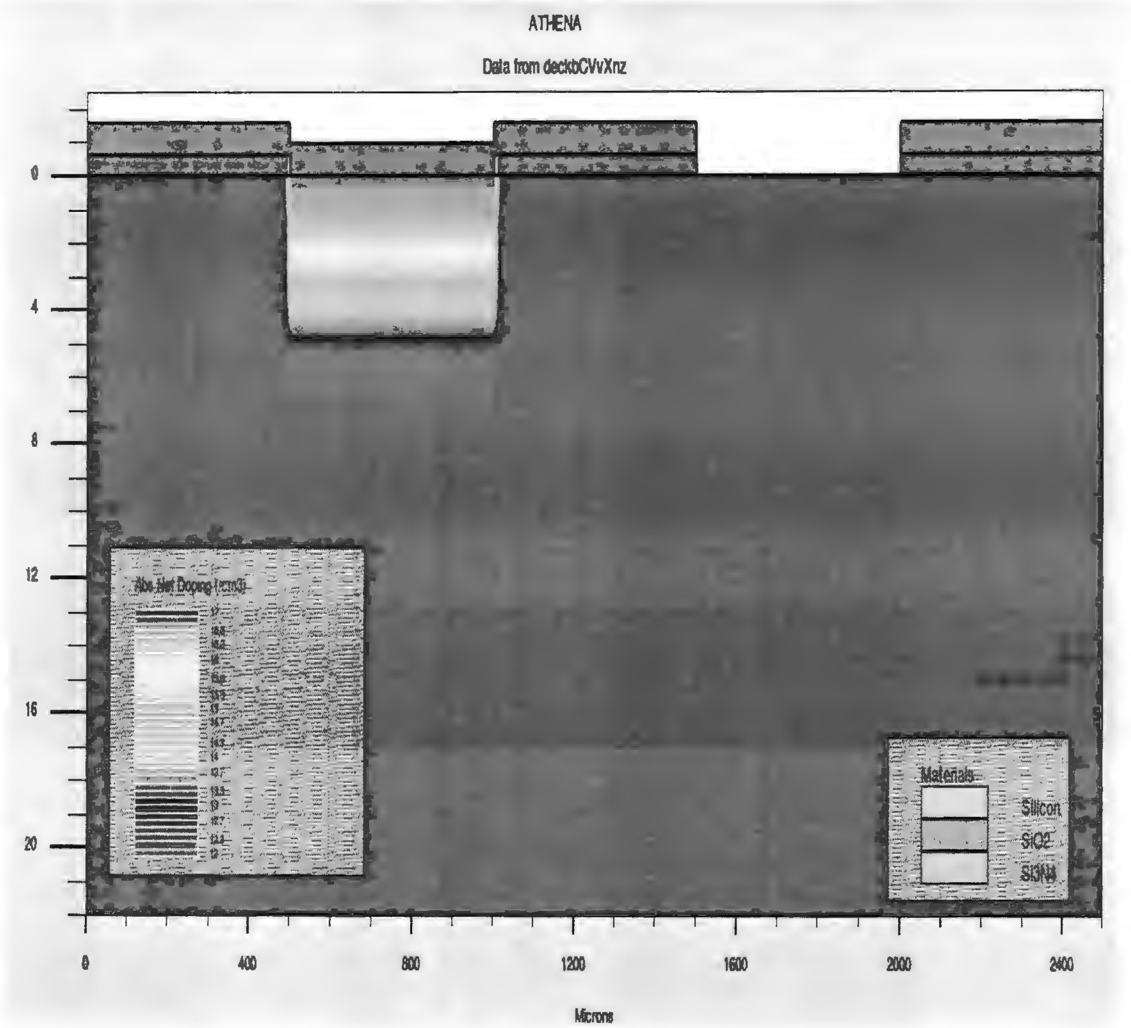

Fig 31. Etched the nitride layer for making the N-Well

5.1.11 Diffusion the Phosphorus Impurity for making the N-Well

For making the N- Well, the right side of the silicon wafer is diffused with the Phosphorus with the concentration of the $8.02 \times e^{18}$ with the temperature of the 1150 °C and time 70 minutes.

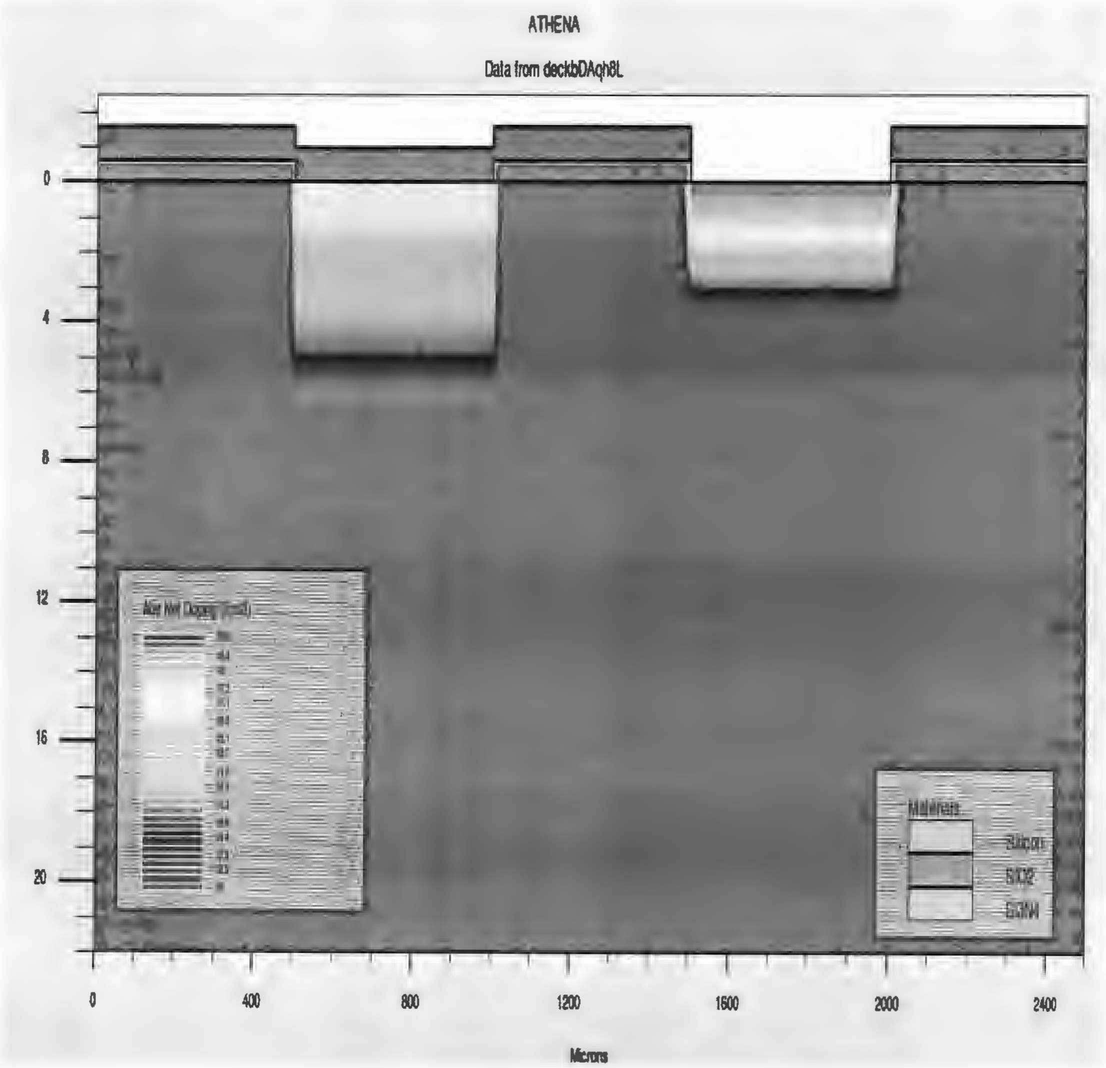

Fig 32. Diffused the Phosphorus for making the N-Well

5.1.12 Deposition of Aluminum for making the Electrodes

It is process of the electrical contacts between the circuits of the semiconductors materials. Mostly Aluminum is used for the purpose of the metallization. But other alloys also used for the metallization.

The next step is to deposit the aluminum for making the contacts as shown in Fig.

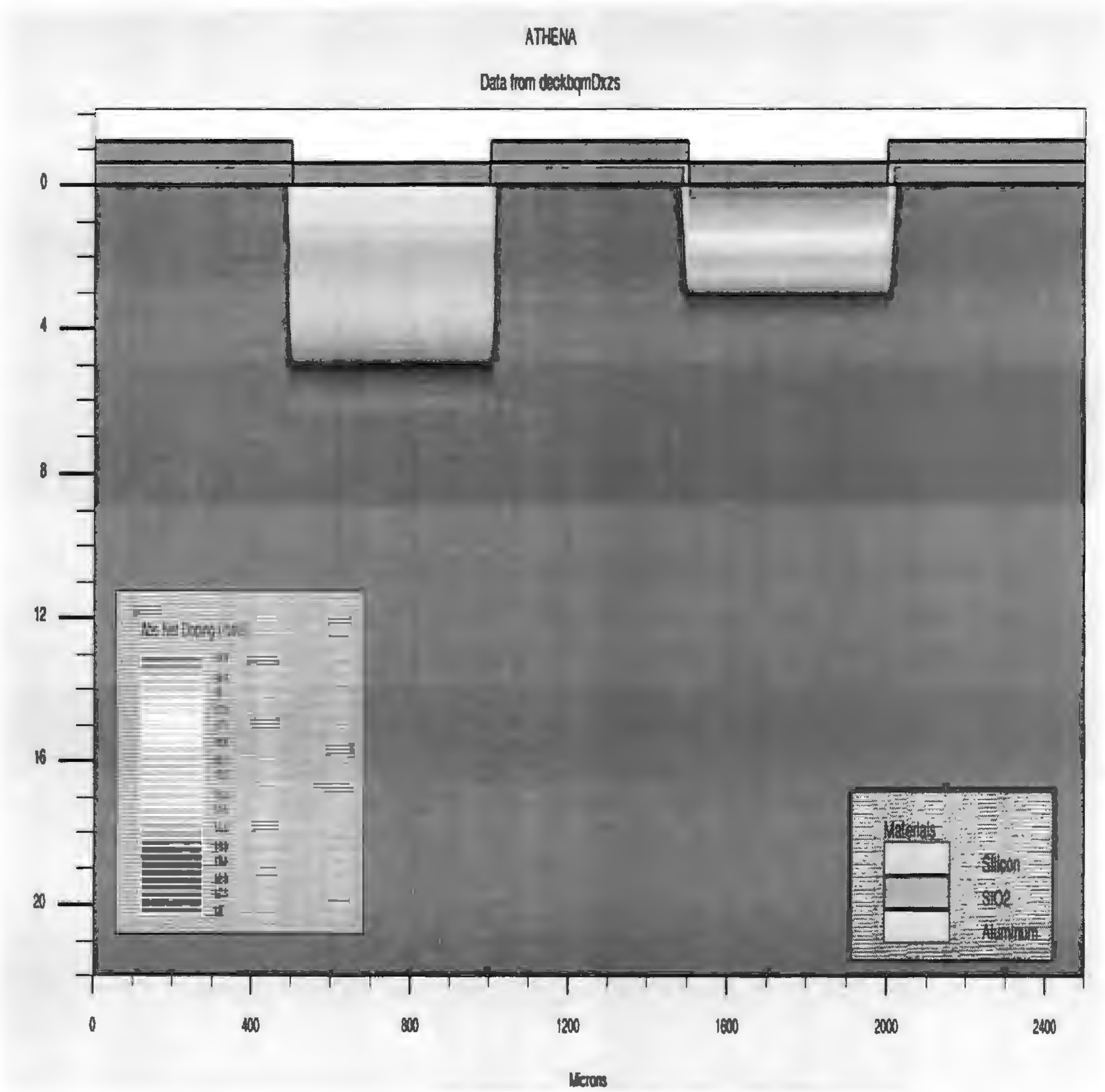

Fig 33. Deposit of Aluminum for making the Electrodes

5.1.13 Setting the Electrodes

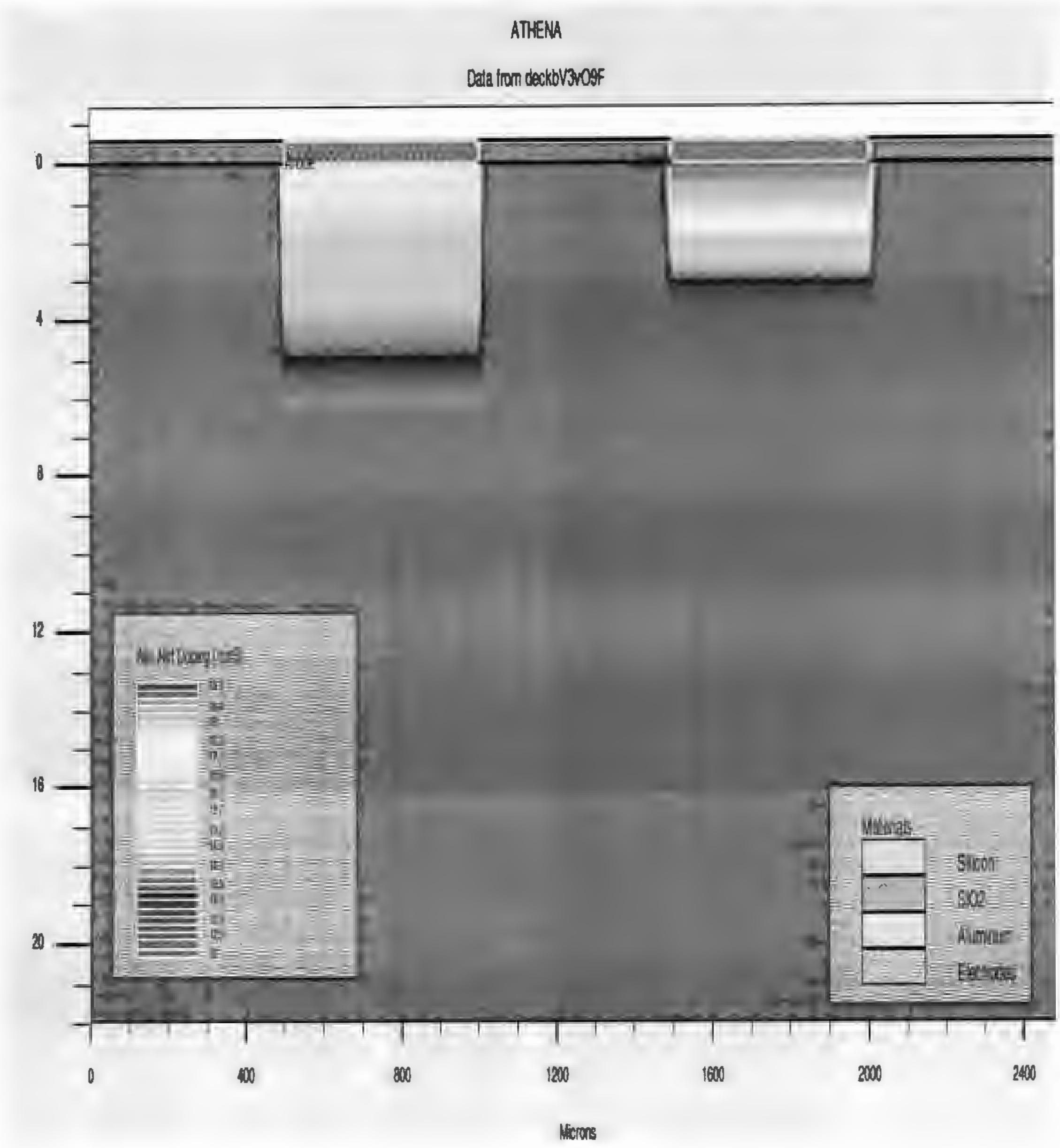

Fig 34. Structure formed after the metallization

5.1.14 Annealing and Final Structure of PIN Photodiode

It is the high temperature process which is reduced the stress in the crystals structure of the wafer. The next step is annealing the Aluminum at temperature of 500 °C and diffused time at 30 minutes. The final structure of the PIN Photo diode is given below in Fig.

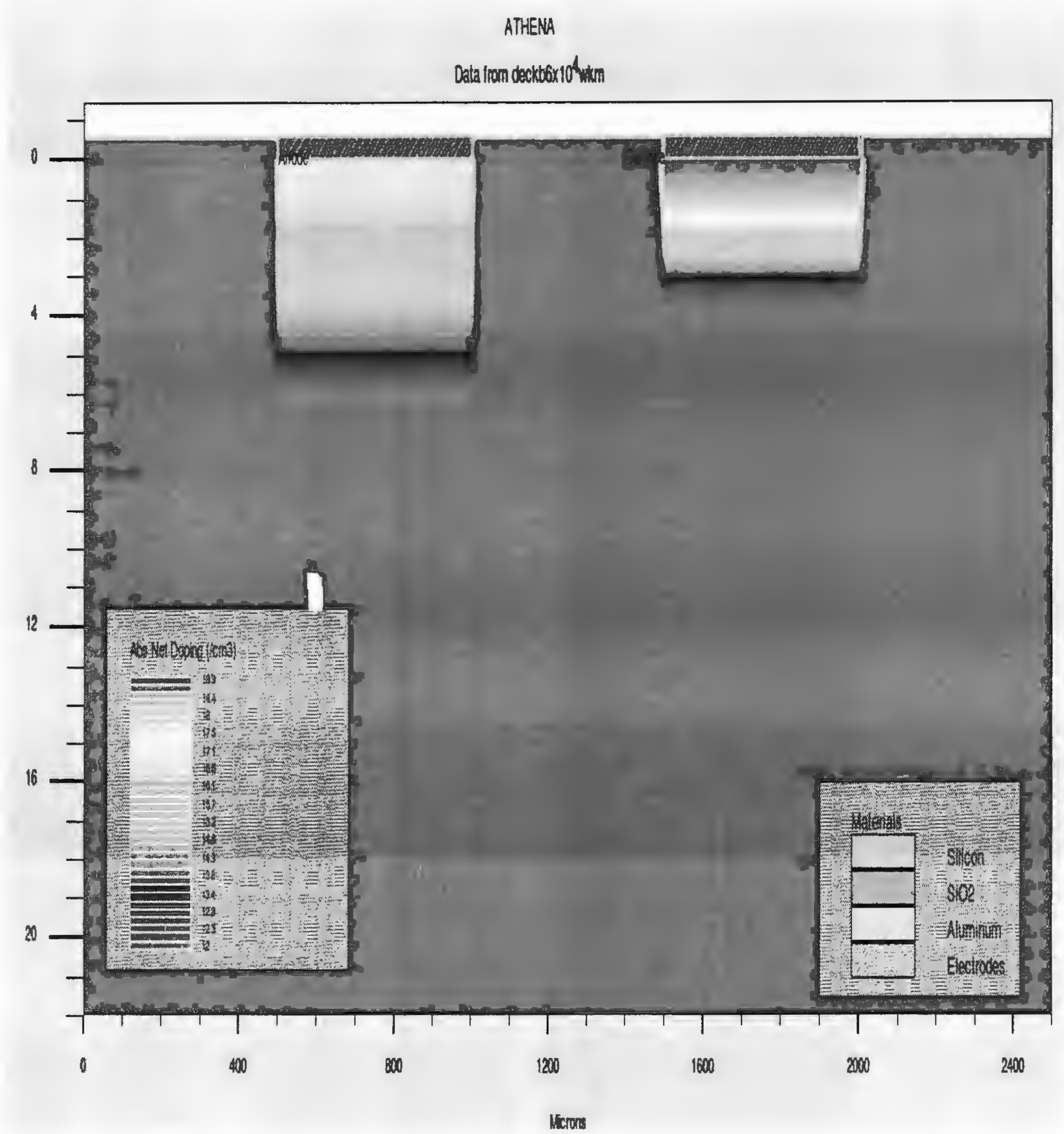

Fig 35. Final structure of PIN Photo Diode

5.3 Electrical and Optical Characterization with Commercial Simulator

ATLAS is the module of the Silvaco simulator which is used to obtain the electrical characteristics of the device. ATLAS simulates the electrical, optical and thermal behavior of the semiconductor with the special reference to the output efficiency of the manufactured device [53].

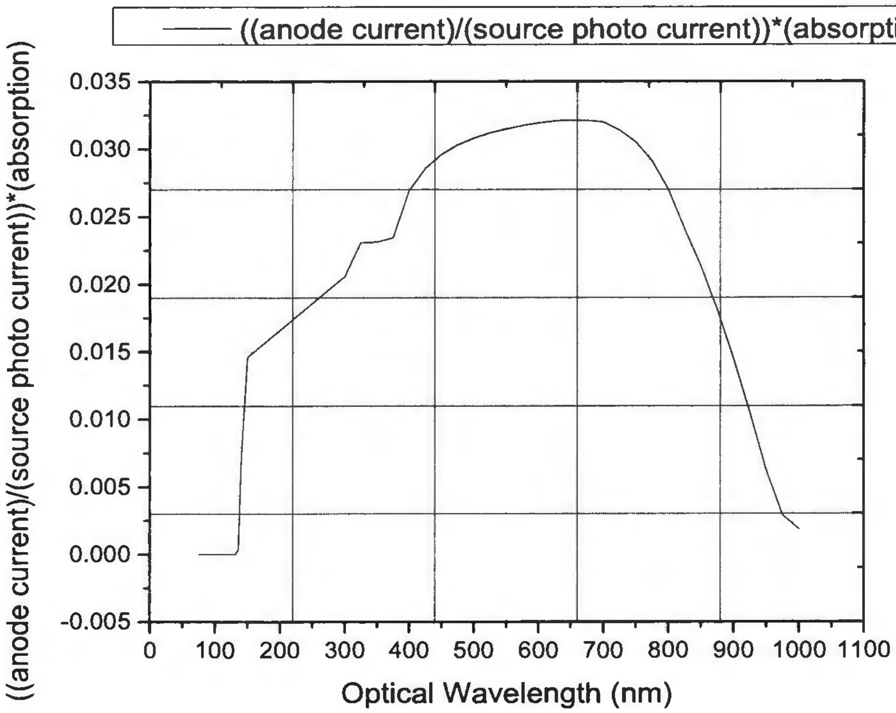

Fig 36. Graph between (Quantum Efficiency) optical wavelength and source photocurrent/absorption

In Fig 36, the internal quantum efficiency of the PIN Photo diode is presented which is defined as the number of the charge carriers composed by the device to the number of the photons of a given energy on the device from outside and then absorbed by the device. It is influenced by the absorption coefficient. As we can see from the graph, the internal quantum efficiency varies with the wavelength.

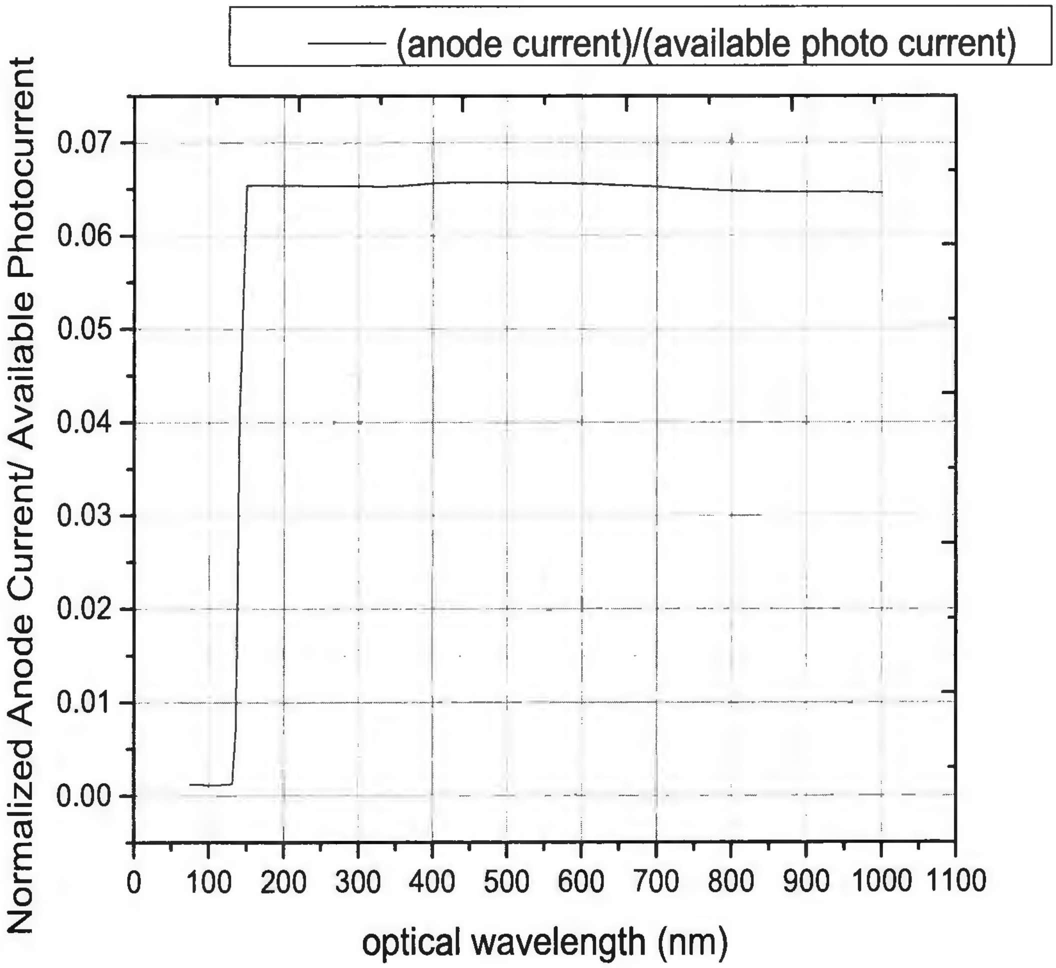

Fig 37. Graph between (Quantum Efficiency) optical wavelength and anode current

Fig. 37 reveals the correlation between the optical wavelength and the current dynamics. When the light is incident on the device it creates the single photon yielding the electrons-hole pairs. These electron-hole pairs would contribute to the photo detector's output current. This can be seen that after certain rise, it is independent to the energy of the photons striking at the surface of the device. High quantum efficiency as can be seen from Fig. 37 is ensured from this correlation.

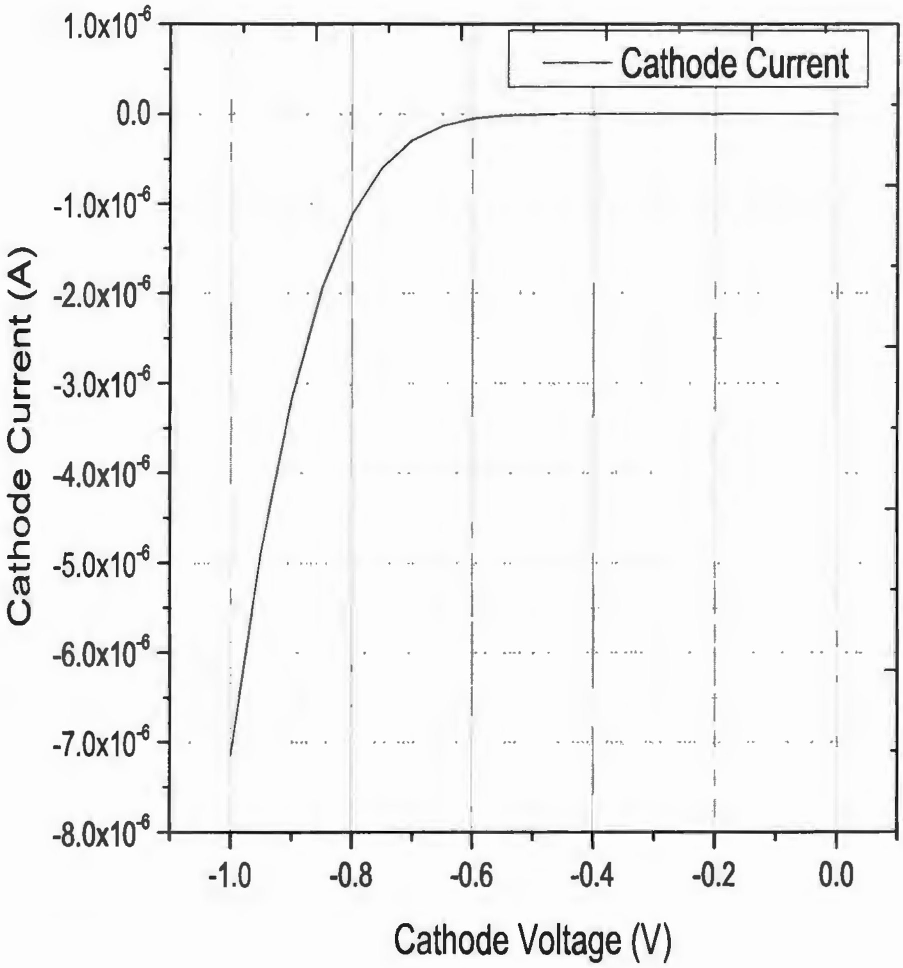

Fig 38. Graph between current to voltage

The relationship of cathode current to cathode voltage is shown in the Fig 38. It is referred as the dark current of photo detector. The reverse bias is applied here to get a very small reverse saturation current. The device current is also noticed to get decreased as the voltage increases on the cathode terminal of the detector.

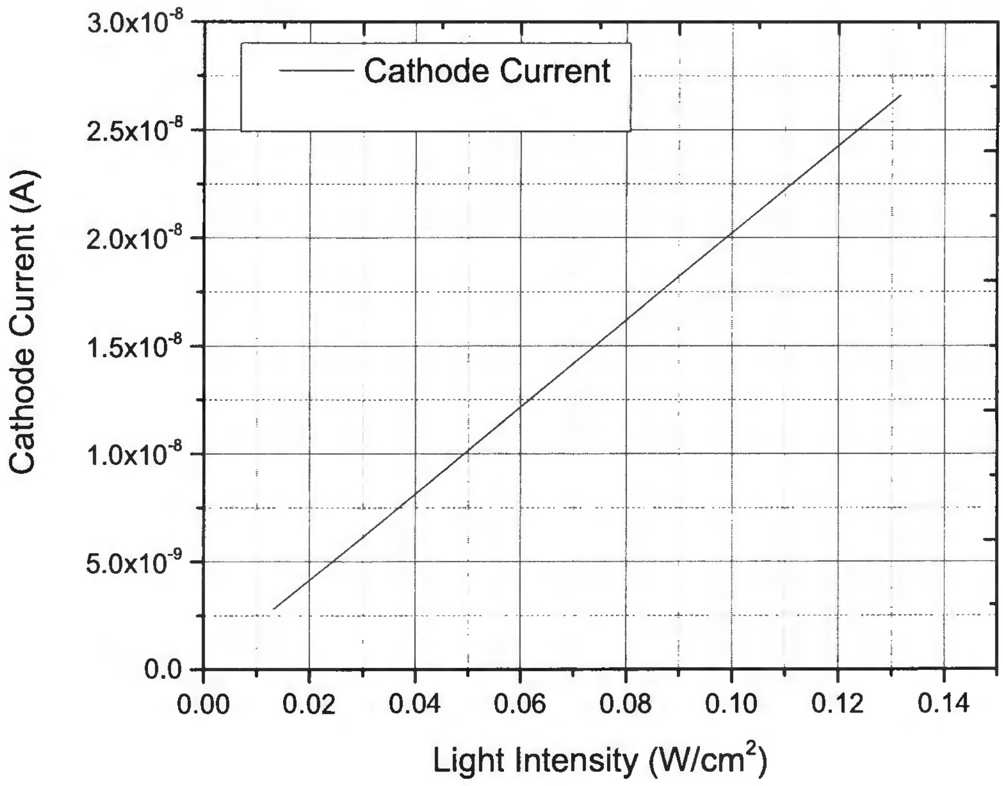

Fig 39. Graph between light intensity and cathode current

Fig. 39 exhibits the relation between the light intensity and the current on the cathode. It is visible that when the light has no impact on the device, it shows almost negligible current with the increase in power, an increase in the current (produced photo current) is evident.

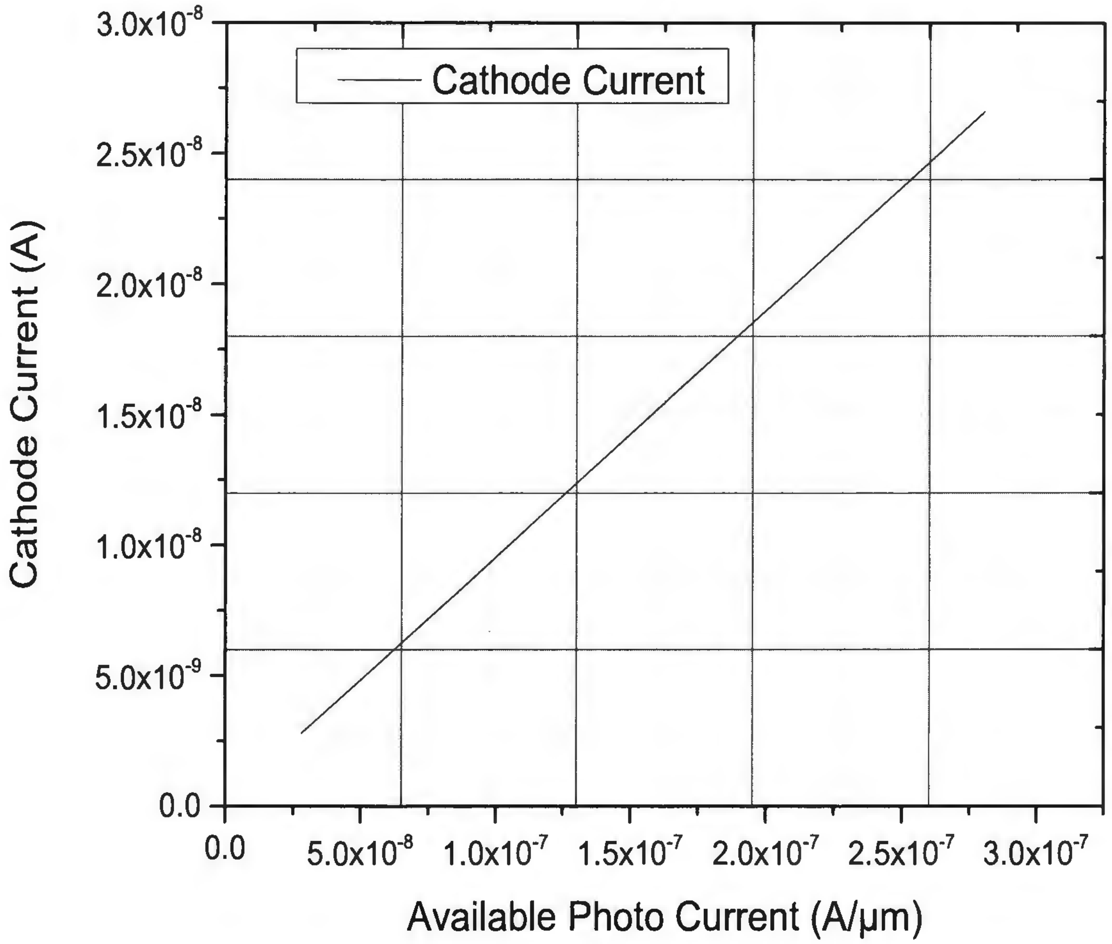

Fig 40. Graph between photocurrent and cathode current

Relationship between the photo current to cathode current is exhibited in Fig. 40. The figure shows that the detection of the device is very high when the light is incident on the PIN photo diode part of the quadrant structure. This generates the photo current and has capability to detect even at very narrow scales. This can be seen from this graph that when the photo current increases, then the cathode current increases linearly.

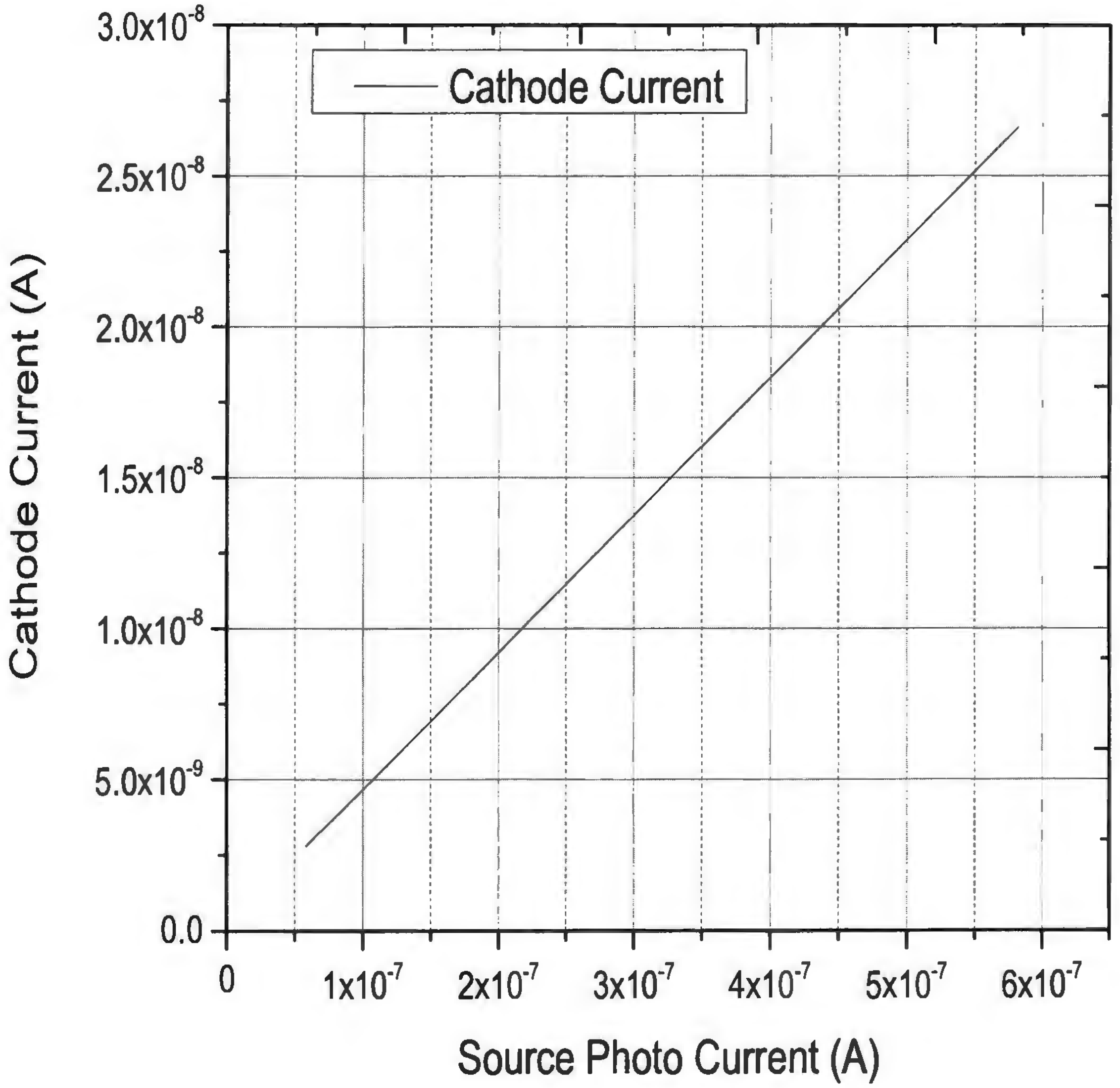

Fig 41. Graph between source photocurrent and cathode current

Correlation between the source photos current to cathode current is depicted in Fig. 41 for the case when the light is incident on the PIN photo detector. The generation of the photo current increases when the light is incident on the detector, which in turn increases the cathode current in a linear fashion.

5.4 Electrical Characterization of Quadrant Photo Detector with ASMEC

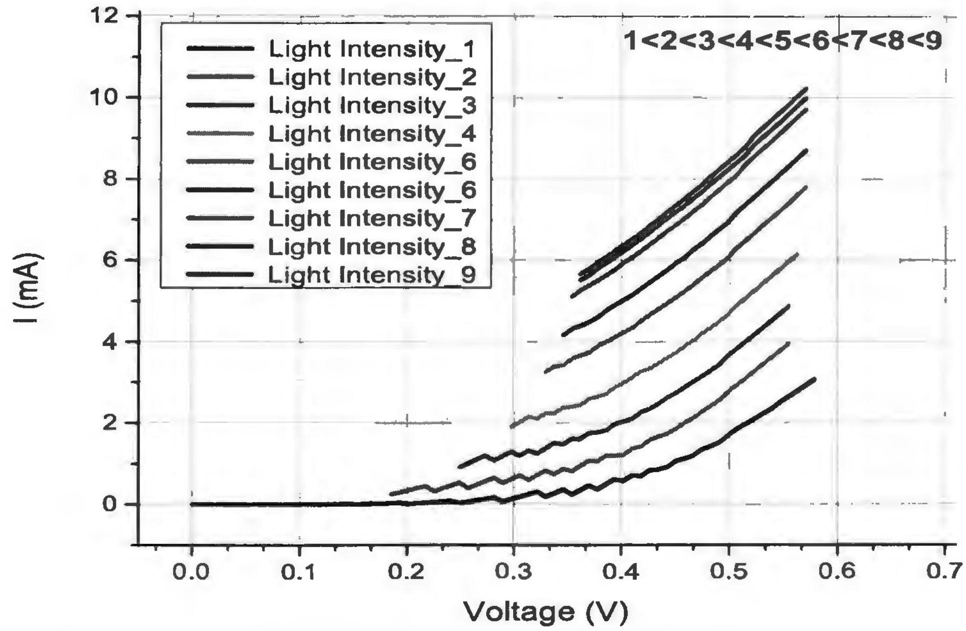

Fig 42. Graph between current to voltage in the presence of the light intensity

Fig. 42 shows that the relationship between the current and voltage for variety of light intensities. The currents and voltages are measured from anode to cathode. We see that when no light is incident on the device, then it yields no current, this can be approximately near to the dark current region of the device. But when the incident light is applied on the device, it produces the negative voltage and produced the photo current. For example, we may take the case of the light intensity 2 which starts from 0.2 voltages. As we increased the intensity of the light, then an increase in the voltage with respect to the current is noticed and thus the generation of photo current starts. If we increased the light intensity to a maximum, then a maximum photo current is seen to be generated. This is evident from the case 9. The intensity of the light 9 shows maximum photo voltage and hence generates a maximum current.

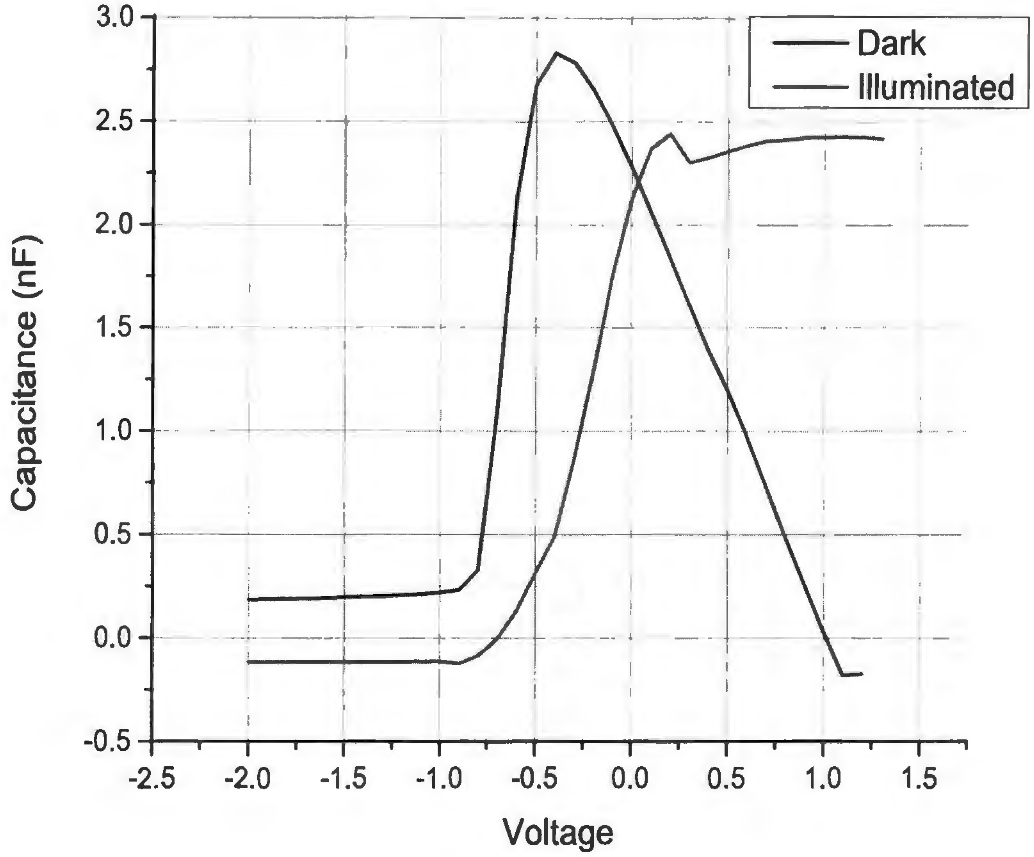

Fig 43. Graph between voltage to capacitance in the presence of Dark and Illuminated

Fig. 43 shows the relationship between the measured capacitance against the voltage. This works in three different modes: accumulation, depletion and inversion. During the dark measurements, there is no inversion layer seen. In the accumulation mode, there is a decrease of current possibly related to the competing electron mobility and increase in the carrier recombination. In the depletion region, carrier recombination goes smaller as the voltage is applied. In the inversion layer, the current is comparably lesser than the accumulation.

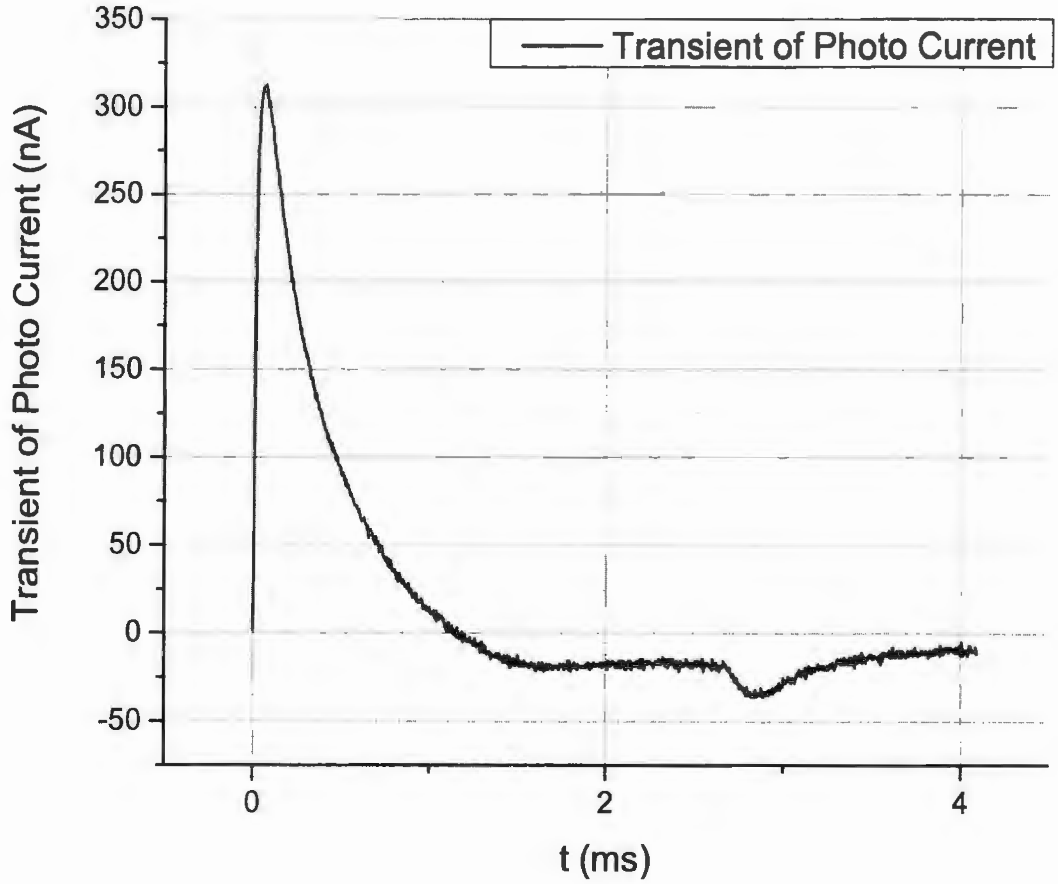

Fig 44. Graph of transient of photocurrent with respect to time

Fig. 44 is a plot between the transient photocurrent and time. Transient photo current is the time in which generates electrons-hole pair are generated in the device. There is no light intensity incident on the device, no current is generated. But when the short light pulse is incident on the active part of the device and it is absorbed throughout the depletion layer and generates the electrons-hole pair that tends to decay exponentially.

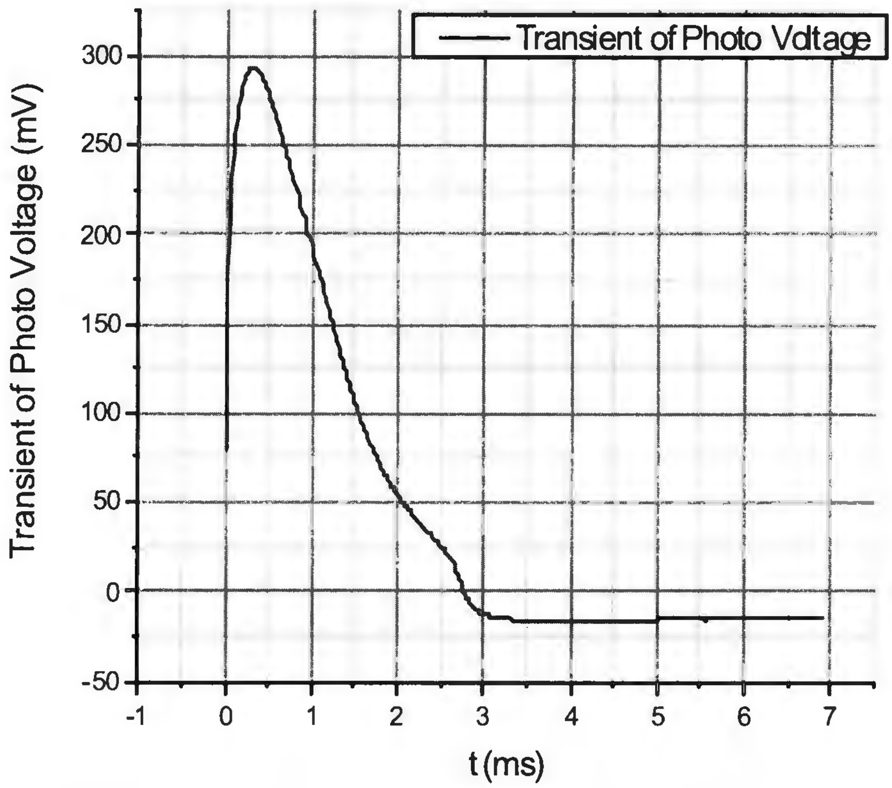

Fig 45. Graph of transient of photo voltage with respect to the time

Fig. 45 shows the relationship between the generation of the photo voltage and the transient time. This relates to the creation of the voltage or the electric current when the light falls on the device. In this figure, device at 0 t (ms) has exhibited the generation of the minimum voltage. As the light pulse is incident on the active device region, then it creates the pulse of electric current due to the photo electrons-hole pair. The responsitivity and the detection of the light and non-zero transient photo voltage is signature of the efficiency of the device utility for the photo detection and the position sensing.

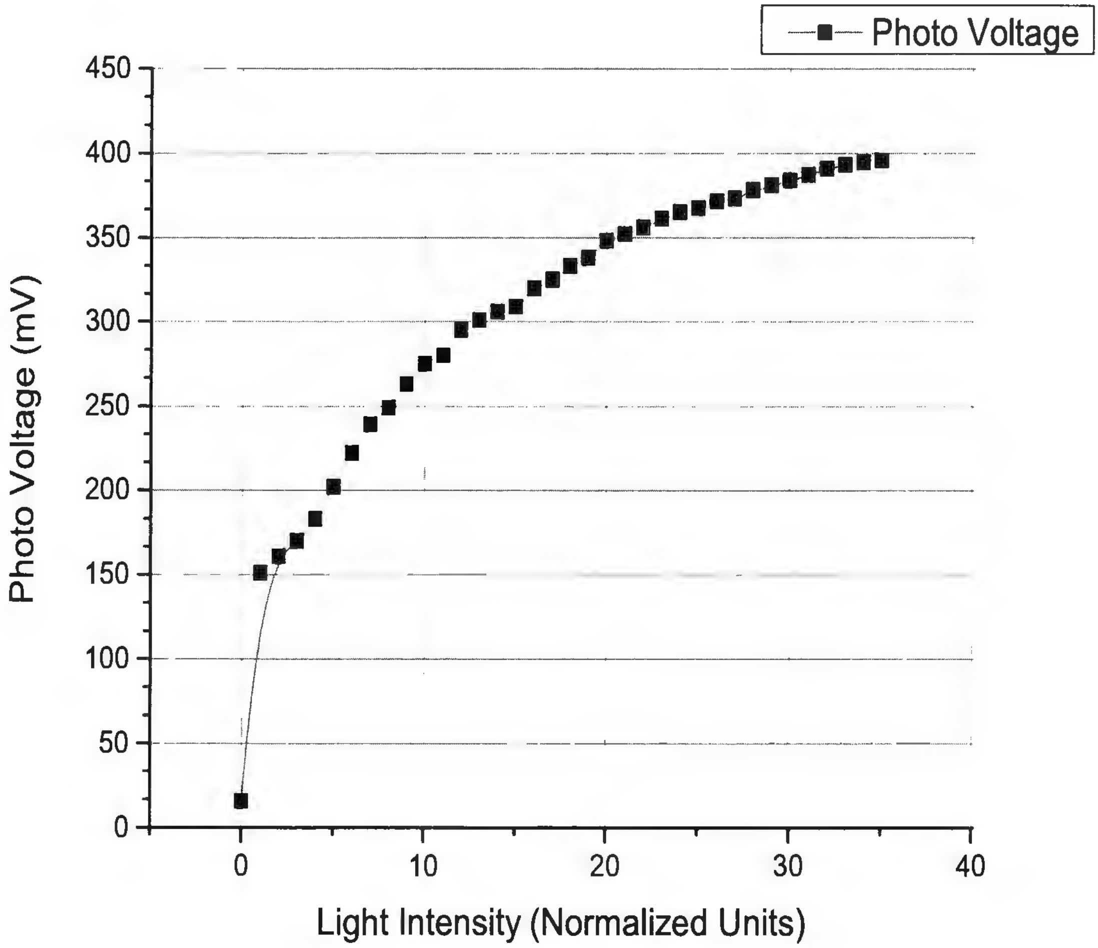

Fig 46. Graph between the generations of the photo voltage in the presence of the light intensity

Fig. 46 shows the relationship between light intensity and photo voltage. It is evident that photo voltage of the device is very little at zero intensity of the light. When the light intensity incident on the device, it creates the electrons-hole pair in the potentially in the intrinsic region of the PIN structure and generates the photo voltage. As the light intensity is increased, the generation of the photo voltage gets increased. The normalized units are actually the units of the intensity controlled lamp used domestically.

5.5 Electro-Optical Characterization of the Quadrant Photo Detector

The electro-optical analysis of silicon based quadrant detector is vital to investigate its design effectiveness and efficiency. Metrology Grade Spectroscopic Ellipsometer is used to obtain characteristics of the device structure. Using this sophisticated machine, we have measured the profiles and values of the Psi, Delta, Refractive Index (n) and Extinction Coefficient (K). Metrology Grade Spectroscopic Ellipsometer is used to perform this analysis on each quadrant and center point of this quadrant photo detector.

5.5.1 Center Point of Quadrant Detector

Metrology Grade Spectroscopic Ellipsometer is used to find the optical properties at the center point of the silicon based quadrant detector as shown in Fig. 47 below:

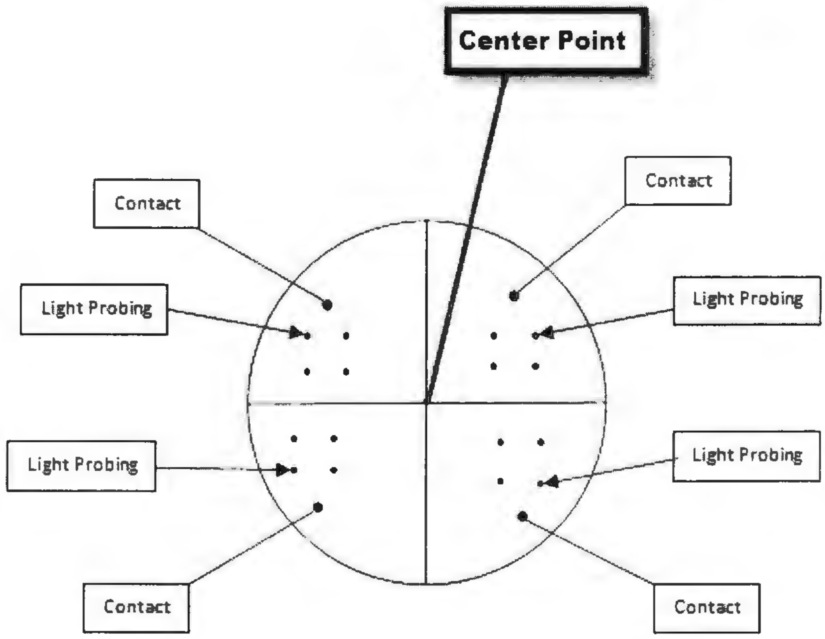

Fig 47. Center Point of Quadrant detector

The centre of the device is a sensitive region undergoing several processing conditions during fabrication and may impact. The activity of the other active device region connected through the centre. The properties that are directly linked with the sensing and detection mechanism are desirable to be investigated at this particular space-point of the device.

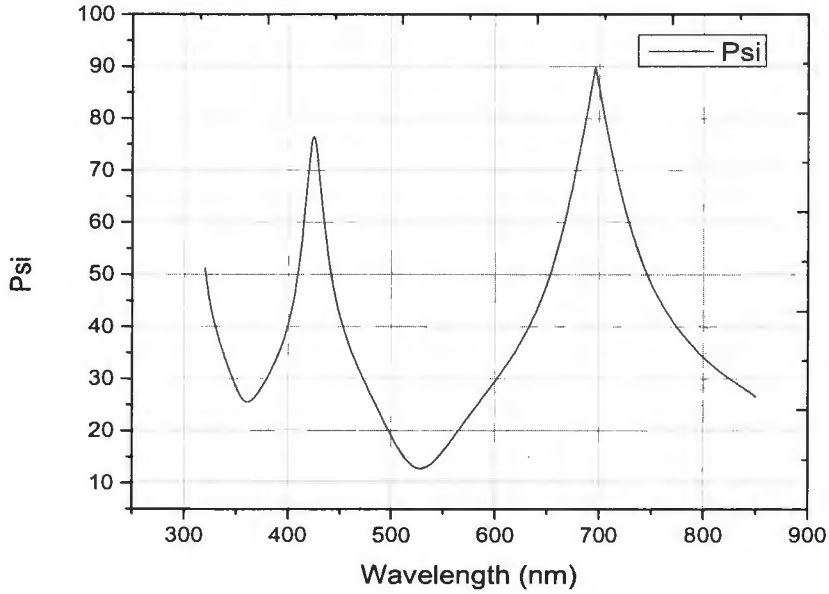

Fig 48. Graph between Psi and Wavelength (nm)

Psi is measured with respect to the wavelength by the Ellipsometry tool. When the light strikes through the center point of the silicon quadrant detector then it interacts with the layer beneath and changes the values contributing to each edge connected to the central point (four active device regions connected through a central point-specific geometry for position sensing dynamics) as shown in the Fig. 48. The value of the Psi describes the change in polarization when the light interacts with the surface.

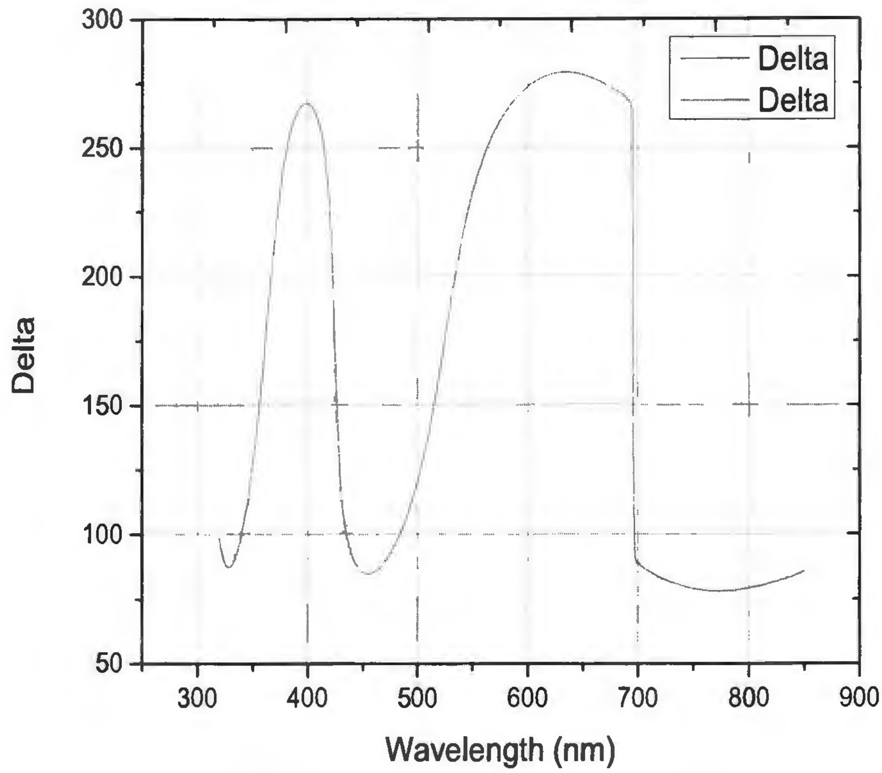

Fig 49. Graph between Delta and Wavelength (nm)

In the Fig. 49 above, the values of Delta is measured with respect to the optical wavelength. This is a very sensitive to measure the change of polarization particularly in scenarios when the output characteristics of the device reflect. The attribute of the sensing the certain position in space and time. Sensitivity comes from changes in delta. When the center point of silicon quadrant detector is exposed the light then the light changes its properties and gives different values depicting change in polarization with respect to change in the light-matter interaction at the specifically defined space charge region of almost-uniform distribution.

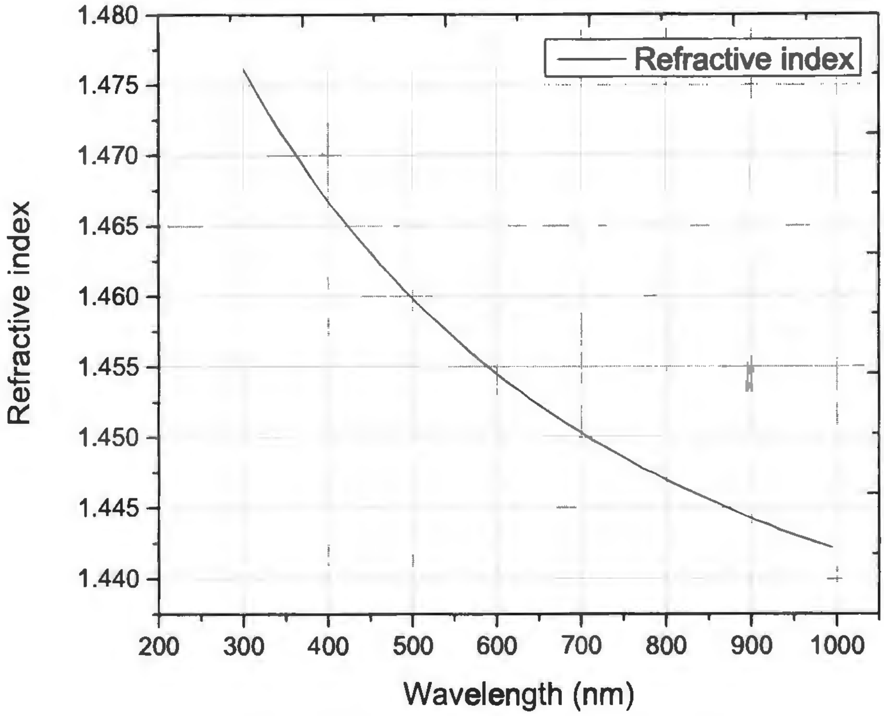

Fig 50. Graph Between Refractive index and Wavelength (nm)

From Fig. 50 above, refractive index (n) of the active region is measured with respect to the wavelength. Refractive index is defined as how the light propagates through the medium. This is important attribute impacting the sensing capability of the device while in operation. When the center point of the silicon quadrant detector is illuminated then the refractive of index varies with the varying wavelength. When light is incident on the center point of the quadrant detector then due to polarization it gives higher value at relatively lower minimum wavelengths. As the wavelength increases the refractive index decreases exponentially.

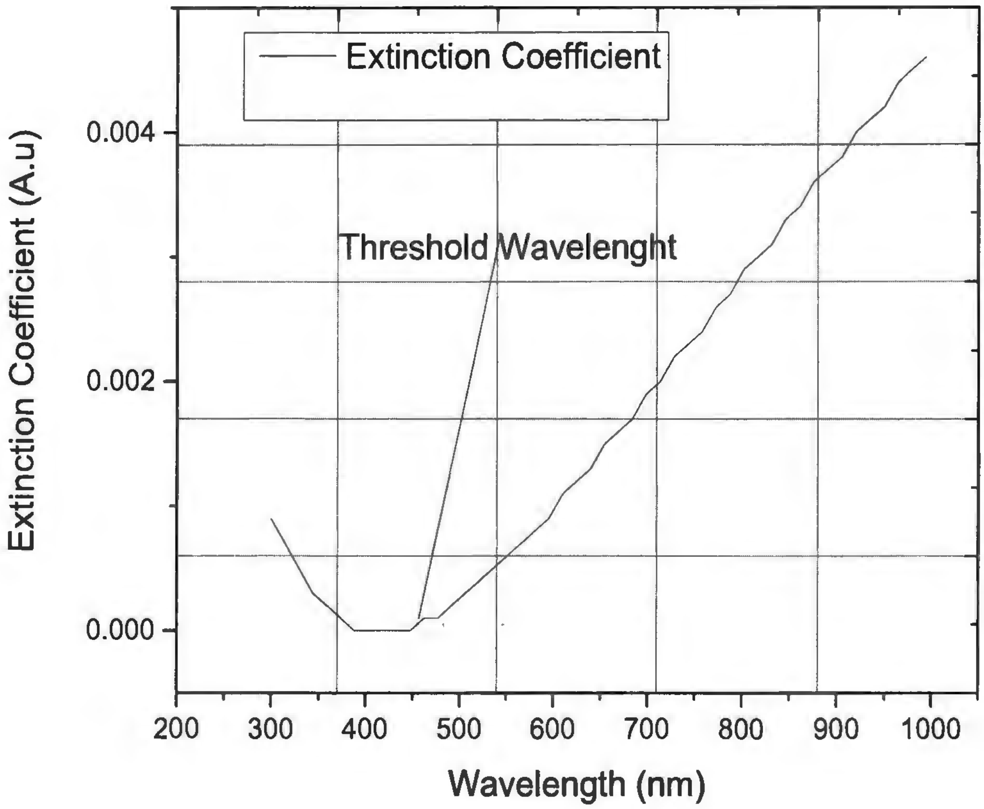

Fig 51. Graph between Extinction Coefficient and Wavelength

Ellipsometry is also used to evaluate the Extinction Coefficient (K) of the center point of the silicon based quadrant detector. It is defined as the measure of the absorption of the light in the medium. It is depended on the material and also on the wavelength on the incident light. When the sample is illuminated it gives different values and increase linearly after the threshold wavelength as shown in the Fig. 51.

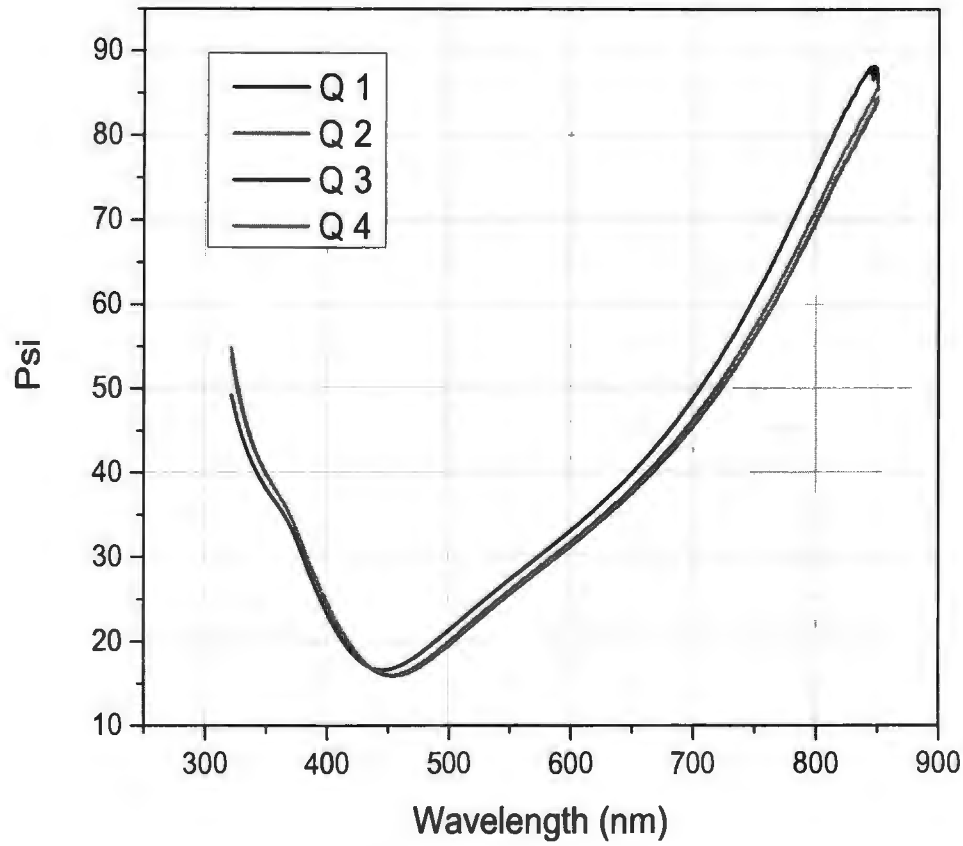

Fig 53. Graph between Psi and Wavelength at each region of Quadrant Detector

Psi value is measured with respect to the wavelength (refer to Fig. 53) at four regions of the quadrant detector is indicated by Q_1, Q_2, Q_3 and Q_4. All four regions behave similarly and follow the similar trend while varying the wavelength from the 280nm to over 800nm. This signifies the uniformity of proven definition beneath each active region, which may resell in active accurate information collected while undergoing a sensing or detection operation under certain bias/ external perturbation.

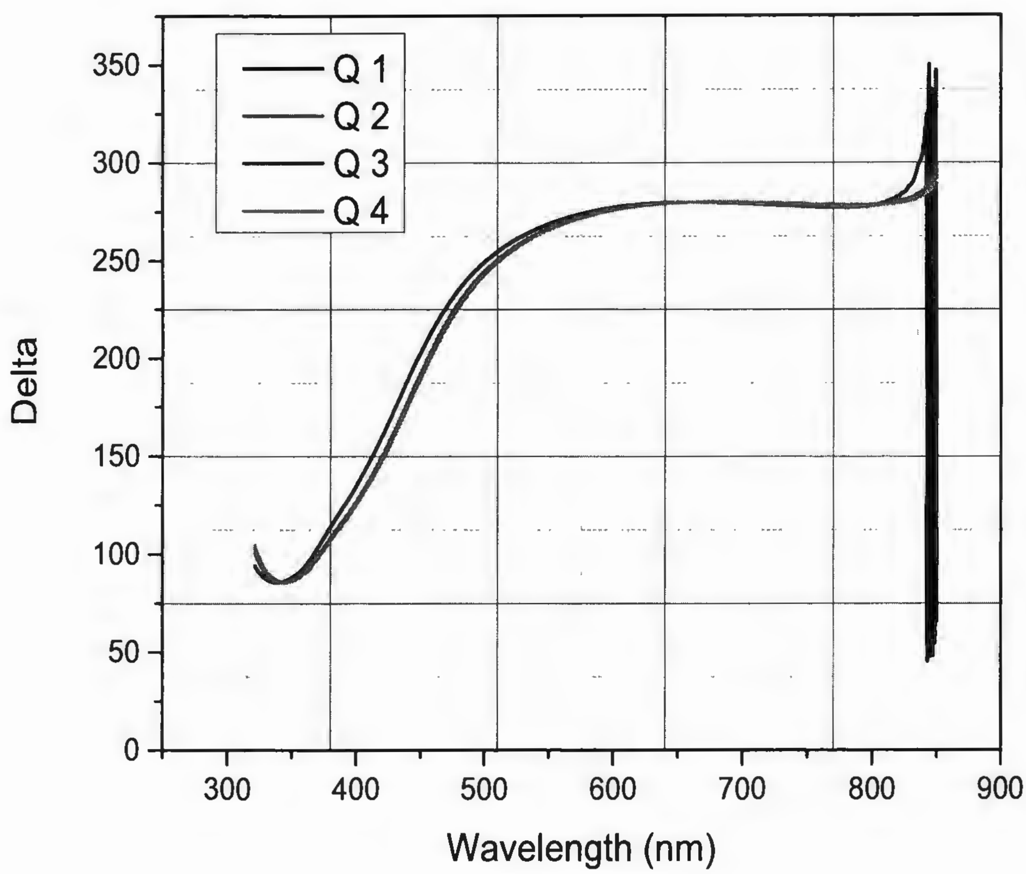

Fig 54. Graph between Delta and Wavelength at each region of Quadrant Detector

Similarly values of Delta are measured with respect to the varying wavelength at each specified region of the quadrant detector as depicted in Fig. 54. When the light interacts with the each quadrant detector it changes the behavior of the variation in a similar fashion in all such cases. The difference in the values of the measured properly in very little indicating on the design uniformity of the device.

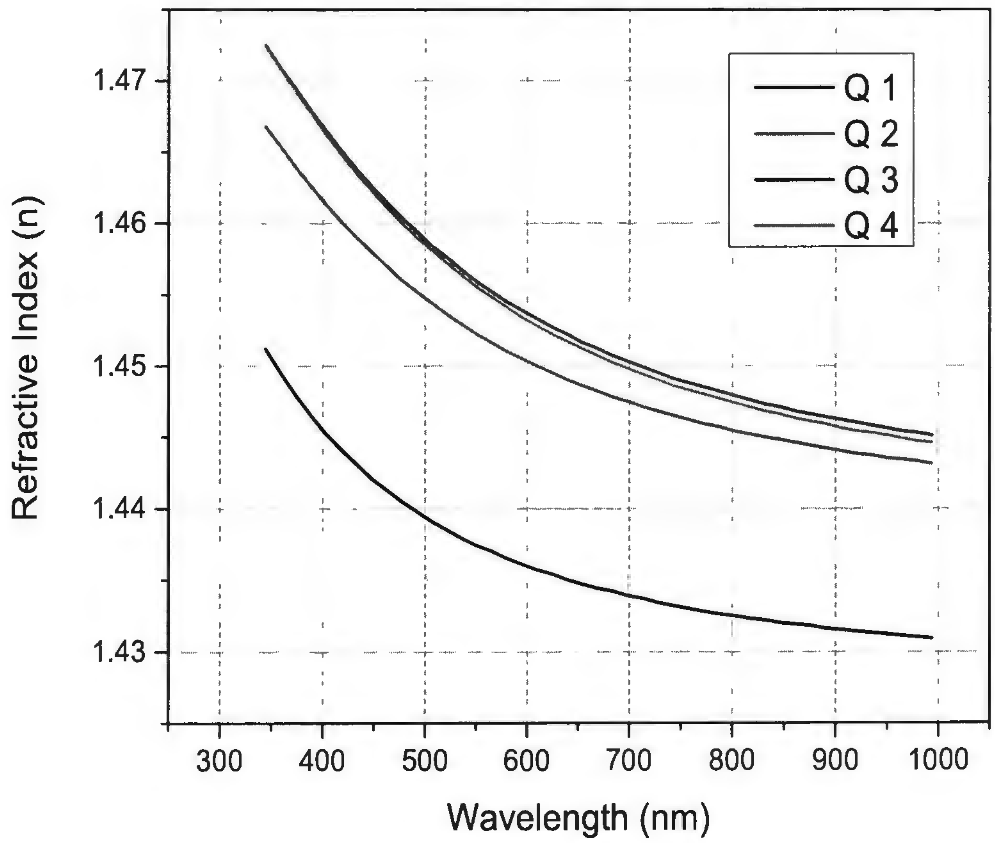

Fig 55. Graph between Refractive Index and Wavelength at each region of Quadrant Detector

Refractive index (n) is measured with respect to the wavelength at each point of the silicon quadrant detector in the Fig. 55. Refractive index decreases with increasing wavelength when the light is incident on a specific quadrant of the detector. This is extent of the propagation of light through the mediums in each quadrant. The propagation behavior seems to follow a similar metrics in each active region with a little variation of its magnitude in each case.

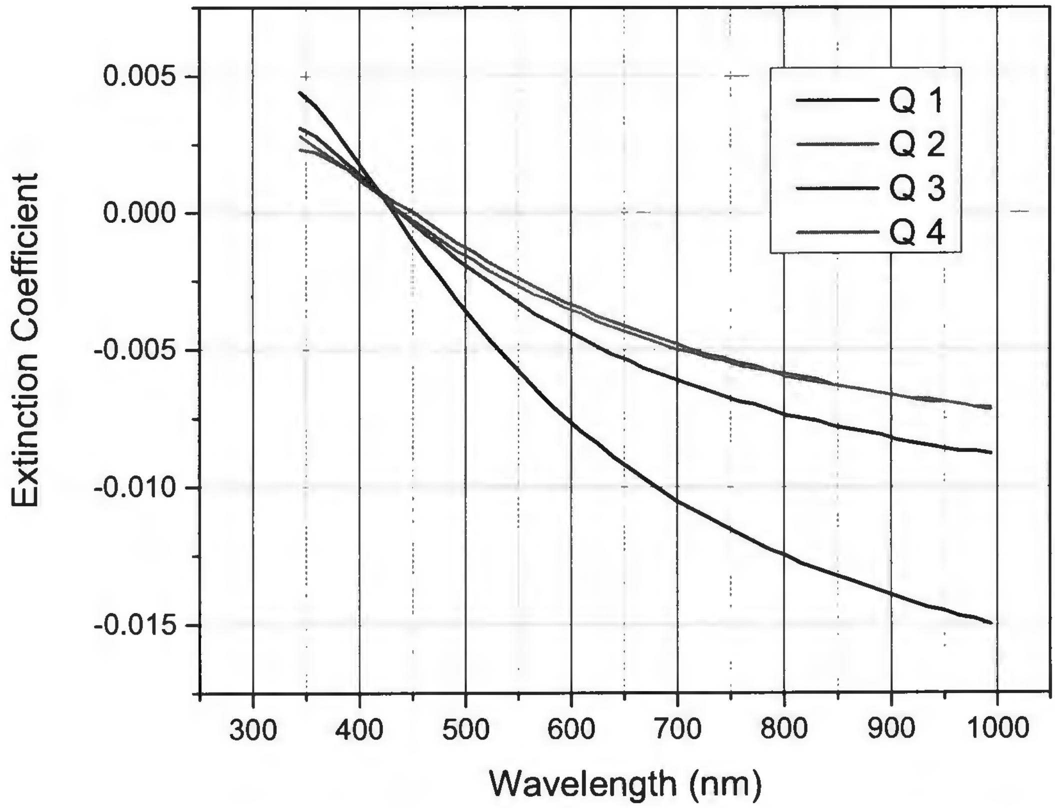

Fig 56. Graph between Extinction Coefficient and Wavelength at each region of Quadrant Detector

Ellipsometry is also used to evaluate the Extinction Coefficient (K) for each point of the silicon based quadrant detector. As this in measured of absorption of the light in the medium, It depends on the material properties of interacting with the light. When a quadrant is illuminated, the extinction coefficient exponentially decays with the increasing wavelength for all cases with a little difference in their magnitudes. A slight-difference for Q_1 may be attributed to the quality of proven definition beneath the region (device Q_1). Nonetheless; the % difference in the values is little to imagine any larger deviation in the efficiency of the certain device quadrant compared with others.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Keeping the abstract of this work in view; this study was focused on design and process development of silicon based quadrant photo detectors. The summary of this work is as follows:

a. A rigorous design approach was maintained throughout this work to provide and industrial driven process recipe in order to effectively design a " planar " structure of quadrant photo detector compatible with concurrent CMOS technology;

b. It was resolved that the trade off designed parameters between the quadrant geometry and PIN photo – diode processing yields in significantly cost effective and efficient solution to manufacture such photo detectors. Less number of processing steps with better uniformity may be seen a advantage of the proposed design strategy.

c. Efficiency of the fabricated device is mapped with a number of simulated and experimental techniques. A close comparison and analysis with prevailing design and processes schemes revealed that the proposed structure is not only compatible but robust in the wake of position sensing mechanism. The ingredients of the desired properties such as Quantum efficiency, Photo-Response, Dark and Illuminated Current-Voltage profiles, Terminal Response (cathode dynamics) material (of the device active region) response in electro-optical terms useful for position mapping, sensing and detection etc. Testified the applicability of the process and device scheme and thus presented a proficient design for consequent fabrication and manufacturing.

6.2 Future Work

We may dwell further in many possible directions based on the experiments and their results highlighted in this work:

a. Vertical geometry of Photo Detector based on PIN diode structure may be investigated in order to evaluate the impact of geometry on the efficiency of the detection and sensing.
b. Detailed analysis and possible tailoring of underlining physical model of the simulation tool may yield a better understanding on the fine tuning of process and device parameters selected tool design the matrix of the quadrant photo detector.
c. One may look for other competing choices of initial material (substrate) for example SiGe or III-V semiconductors in order to design this device in "beyond CMOS" approach for variability of applications.

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APPENDIX

COMMAND FOR SIMULATION OF PIN PHOTODIODE

```
go Athena
#
line x loc=0.00 spac=70
line x loc=500 spac=15
line x loc=1000 spac=15
line x loc=1500 spac=15
line x loc=2000 spac=15
line x loc=2500 spac=70
#
line y loc=0.00 spac=0.1
line y loc=12 spac=1
line y loc=22 spac=1
#
```

```
init silicon phosphor resistivity=1000 orientation=100 two.d

#

deposit oxide thick=0.6

#

etch oxide start x=500 y=-0.6

etch cont x=500 y=0.0

etch cont x=1000 y=0.0

etch done x=1000 y=-0.6

#

deposit nitride thick=1

#

etch nitride start x=500 y=-1.6

etch cont x=500 y=0.0

etch cont x=1000 y=0.0

etch done x=1000 y=-1.6

#

diffus time=120 temp=1200 nitro c.boron=8.09e16
```

```
#

etch nitride all

#

etch oxide start x=1500 y=-0.6

etch cont x=1500 y=0.0

etch cont x=2000 y=0.0

etch done x=2000 y=-0.6

#

deposit nitride thick=1

#

etch nitride start x=1500 y=-1.6

etch cont x=1500 y=0.0

etch cont x=2000 y=0.0

etch done x=2000 y=-1.6

#

diffus time=70 temp=1150 nitro c.phosphor=8.02e18

#
```

```
etch nitride all

#

deposit aluminum thick=0.6

#

etch aluminum left p1.x=501

#

etch aluminum right p1.x=1999

#

etch aluminum start x=999 y=-1.2

etch cont x=999 y=0.0

etch cont x=1501 y=0.0

etch done x=1501 y=-1.2

#

electrode name=Anode x=700

#

electrode name=Cathode x=1800

#
```

```
diffus time=30 temp=500 nitro

struct outfile=pindiode1.str

#

init infile=pindiode1.str

#

go atlas

#
```

For IV Characteristics

```
## 1=anode # 2=cathode

electrode   name=Anode number=1

electrode   name=Cathode number=2

#

#contact     name=Anode neutral

#contact     name=Cathode neutral

#

models conmob fldmob b.electrons=2 b.holes=1 evsatmod=0 hvsatmod=0 boltzman \
print temperature=300
```

```
#

method    newton itlimit=25 trap atrap=0.5 maxtrap=4 autonr nrcriterion=0.1 \
 tol.time=0.005 dt.min=1e-25

solve init

solve vanode=0

log outf=pindiode1_0.log

solve name=cathode vcathode=0 vfinal=-1 vstep=-0.05

##

output    j.electron j.hole j.conduc j.total ex.field ey.field flowlines \ e.mobility h.mobility
e.temp h.temp con.band qfn j.disp photogen impact

save      outf=pindiode2.str

#

tonyplot pindiode1_0.log

tonyplot pindiode2.str

quit
```

For Quantum Efficiency

```
Go atlas

#

## 1=anode # 2=cathode

electrode   name=Anode number=1
```

```
electrode   name=Cathode number=2

#

#contact    name=Anode neutral

#contact    name=Cathode neutral

#

Material material= Aluminum imag.index=700

Material material = Silicon taun0=1e-6 taup0=1e-6

#

Beam=1 x.origin=700.0 y.origin=-2.0 angle=90.0

#

Models conmob fldmob consrh print

#

Solve init

Solve previous

Solve previous b1=0

Logoutf=pindiode1_2.log

Solve b1=1 beam=1 lambda=0.3 wstep=0.025 wfinal=1.0
```

Tonyplot pindiode1_2.log –set pindiode1_3.log

Extract init inf=pindiode1_2.log

Extract name= "IQE" curve(elect. "optical wavelength", \

-(i. "anode")/ elect. "available photo current") outf= "IQE.dat"

Extract name= "EQE" curve(elect. "optical wavelength", \

-(i. "anode")/ elect. "available photo current") outf= "EQE.dat"

Extract name= "EQE2" curve(elect. "optical wavelength", \

-(i. "anode")/ elect. "available photo current" *elect. "absorption") outf= " EQE2.dat"

Tonyplot IQE.dat –overlay EQE2.dat –sat pindiode1_1.set

For DC characterizations

Go atlas

#

1=anode # 2=cathode

electrode   name=Anode number=1

electrode   name=Cathode number=2

#

#contact   name=Anode neutral

```
#contact     name=Cathode neutral

#

Material material= Aluminum imag.index=700

Material material = Silicon taun0=1e-6 taup0=1e-6

#

Beam num=1 x.origin=700.0 y.origin= -2.0 angle= 90.0 power.file=pindiode1.spec
wavel.start=0.5 wavel.end= 0.8 wavel.num=5

#

Models srh auger conmob fldmob

#

Method newton trap

Solve init

Solve vcathode=0.5

Solve vcathode=1

Solve vcathode=1.5

Solve vcathode=2.0

#
```

```
Logoutf= pindiode1.log master

Solve b1=0.1 lit.step=0.1 nstep=9 outf=pindiode1_1.str master

Tonyplot pindiode1.log –set pindiode1_1.set

quit
```