Electro-optical Characterisation of InP Nanowire based P-N, P-I-N Infrared Photodetectors

Mohammed Nurul Amin
Halmstad University/IDE, Halmstad, Sweden
Email: amin_m154@yahoo.com

Md. Obaidul Alam
Halmstad University/IDE, Halmstad, Sweden
Email: obai_aust@yahoo.com

***Abstract*—High speed photodetectors are most sophisticated optoelectronic devices, because it has high photo sensitivity, low noise, high conversion efficiency and allow a large wavelength range of detection from 750 nm to 1.3–1.55 µm in the optical communication system. These photodetector is used as an optical receiver which transforms the energy of optical radiation such as infrared, visible or ultraviolet into the electrical signal that is convenient for measurement. Since the last decade, the electro-optical characterisation of photodetectors has been investigated to improve their performance and price. In this paper, we are going to discuss the characterisation of the two different type infrared photodectors based on nanowire that we have worked on our project. One photodetector is p-n nanowire structure, and another is p-i-n structure. Both photodetectors is worked based on internal photoelectric effect and on the theory of p-n junction. We investigated the detector performance at 77K-300K temperature corresponding with wavelength in darkness and under illumination as regarding breakdown voltage, sensitivity, and quantum efficiency. We have also compared the differences between the two photodetectors performance characteristics.**

***Index Terms*—InP, IR Photodetector, NWs, Signal to Noise Ratio (SNR), Bit Error Rate (BER).**

I. Introduction

Photodectors are played an important key role in modern communication system as a receiver interms of their high sensitivity, high conversion efficiency, and low noise. In the past years the demand in the speed and capacity of communication systems has been increasing due to the massive growth in different communication system like optical communicationsystem (OCS), optical wireless communication system (OWCS), and fibre-based microwave links. High speed photodetectors with high opto-electronic conversion efficiency and high Power handling capability are key elements in these systems. NWs based InP infrared photodetectors are new promising and highly researching optoelectronic device

That provides a high capacity of information transmission with different bit rate in optical communication system [13]. An infrared detector is worked based on the absorption of electromagnetic infrared radiation. It has longer wavelength (lower energy) than visible light. The energy of the infrared radiation is expressed by the following equation (1).

$$E(eV) = h\nu = \frac{hc}{\lambda} = \frac{1.24}{\lambda(\mu m)}. \tag{1}$$

The range between 750 nm to 1 mm is known as infrared radiation. All objects emit infrared radiation as a function of temperature in certain wavelength. At absolute zero temperature, the infrared radiation energy is very low and it is increased with respect to increase in temperature. Applications based on infrared radiation detection include surveillance, night vision, remote Infrared sensors can be made by III-V semiconductor elements as extrinsic or intrinsic infrared photodetectors, and these types of detectors have been improved and widely used for many years. Recently a new kind of detector based on nanowires has been proposed [1].

In the last decade, one-dimensional nanostructures (nanowires) have been widely researched as potential building blocks for micro and nano-electronic circuits. One of the most studied phenomena in NWs is their sensitivity to light (photosensitivity), which is emerging as a very promising NW application for photodetectors, photovoltaics, optical switches, optical interconnects, transceivers and biological and chemical sensing. NW photodetectors can yield higher light sensitivity than their bulk counterparts due to the large. surface-to volume ratio and small dimensions. Moreover, the possibility to integrate functionality in NW structures, such as homo-an hetero-junctions, within single NW devices or NW arrays, enables large scale integration (for optical interconnects, transceivers etc.).

NWs infrared photodetectors based on material, optical, and charge transport properties will be Beneficial to

Manuscript received March 5, 2012; revised May 20, 2012; accepted June 13, 2012.Corresponding author

doi:10.4304/jcm.7.11.808-820

push fundamental research toward practical applications. The conventional photodector with NW

Photodetector structures could be facilitated implementing new designs that gain full benefits from the unique photosensitivity properties of NWs [7].

II. Background and RELATED work

The first IR detector actually dates back to 1800 when prisms were used to detect this band. By 1900, objects could be detected as far as a quarter mile in distance. Nowadays, infrared radiation is widely used in many applications such as night vision, thermal cameras, remote temperature sensing, and medical diagnosis. It can be used to detect irregularities in machinery, ice on aircraft wings and faults in circuit boards. As it has a low energy, long wavelength, it is invisible to the human eye [1,12]. Infrared sensors can be classified into two categories;one is thermal detectors that have no wavelength dependence and the other one is photodetectors also called quantum detectors that are wavelength dependence. A generic optical communication system is shown in below [10]:

Fig.1 Generic optical communication system

A. Photon Detector

Photon detectors work due to the photoelectric effect. When a semiconductor material absorbs photons, this causes excitation of charge carrier (electrons and holes) from low energy levels to higher energy levels and thus an electric current can flow under the influence of an electric field. In the internal photoelectric process, all free carriers are produced inside the material which leads to a photoconductivity signal. The simplest representation of the photon detector is shown in figure below:

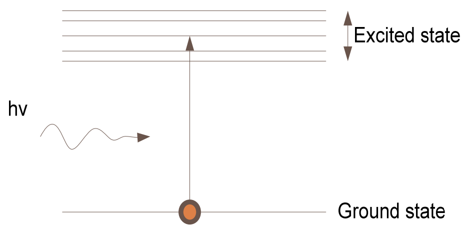

Fig.2 Photo-electron emission

B. Internal Photoelectric Effect

The internal photoelectric effect is based on the fact that electron can be excited from the valance band to the conduction band in the semiconductor material due to the absorption of photons. When the material is illuminated by light and absorbs the photon, an electron is kicked up from the valence band to the conduction Band, leaving behind a free hole in the valence band. In the presence of an external electric field, the photocurrent flows through the circuit. Such kinds of devices are, for example p-n photodiodes, p-i-n Photodiodes, heterostructure

Photodiodes, Schottky-Barrier photodiodes. Nowadays, many photodetectors operate based on nanowire internal photoelectric effect because it has high responsivity and sensitivity. However, these kinds of photodetectors produce the dark current due to thermal excitation. To reduce the dark current it can be necessary to cool the detector by using thermo-electric cooling or cryogenic liquids [1,2].

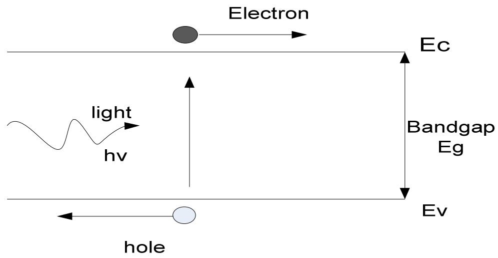

Fig.3 Interband transition in a semiconductor

C. P-N Infrared Photodetector

The p-n photodiodes are semiconductor light sensors with reversed bias. When the p-n junction in the semiconductor is illuminated by light with photon energy larger than the photon energy in reverse bias condition, it excites an electron, and thereby a free electron and a free hole is created. In the presence of a high electric field, charge carriers will drift quickly in opposite directions in the depletion region. That means holes move to the left in the p-doped region and electrons to the right in the n-doped region until they are collected at the electrode, and hence generate a flow of current in an external circuit proportional to the incident power (see fig.4 below). Photodiodes are often used for accurate measurement of light intensity in science and industry. They generally have a better, more linear response than photoconductors [2].The figure below shows the basic construction and energy band diagram;

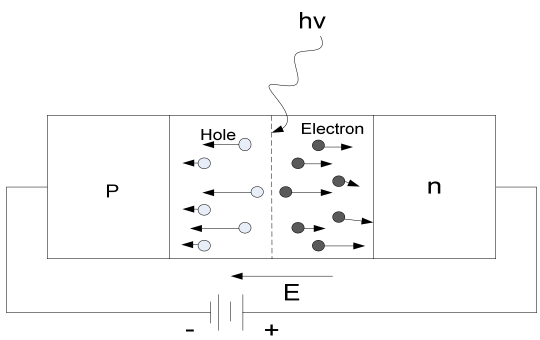

Fig.4 p-n photodiode under illumination with reverse bias

D. P-I-N Infrared Photodetector

We know that the most important part of the photodiode is the active region or depletion region, where the light is absorbed and the photon energy

Excites the electron and, hence, generates the external circuit current called photocurrent. For this reason, if we want to have a high photocurrent, we should make a photodiode with a wider depletion or active region. As a result we can trap more photons and get a higher photocurrent.

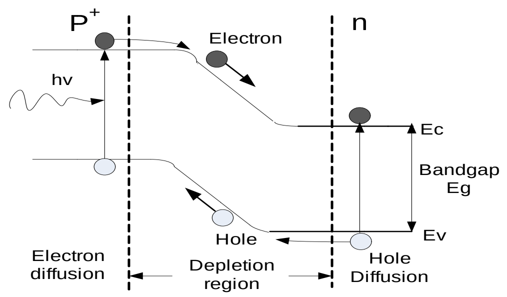

Fig.5 Energy band diagram of the p-n photodiode

In order to have a wider depletion region, we add an intrinsic layer (i layer) between the p and the n doped regions which in turn provide more efficient conversion of photons to excited charge carriers [3].

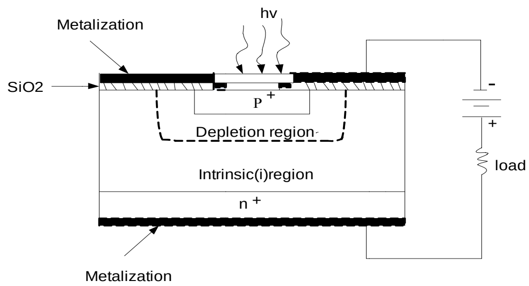

Fig.6 Cross-section view of p-i-n photodiode under reverse biased

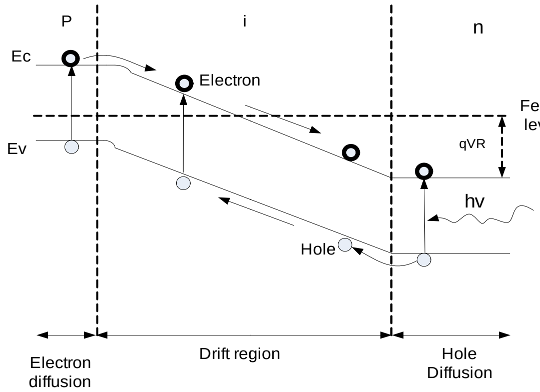

Fig.7 Energy band diagram of p-i-n photodiode under reverse biased

E. Performance Characteristics of Photodetector

In order to have an indication of the performance of IR photodetectors, a number of important characteristics

Are commonly used. These performance characteristics indicate how a detector responds to an input of light energy. The responsivity, dark current and detectivity (D*) are commonly used for a single pixel device. On the

Other hand, the noise equivalent temperature difference (NETD) is more commonly used for detector arrays [4,5].

E1. Responstiivity

The photodetector responsivity is to determine the detector response, when it is irradiated with a certain power of radiation. Therefore, responsivity is the output voltage or output current per watt (measure in V/W or A/W) of incident energy without noise consideration. For detectors that generate an electrical current, the responsitivity is

$$R = \frac{I}{\Phi_e} = \frac{I}{E_e.A} \qquad (2)$$

Where, I =rms signal current output of the detector, measured in amperes. F*e*=Incident radiation power, measured in watts.*Ee*=Incident irradiance, inwatts/ cm^2 A = Irradiated area of the detector, in cm^2 .For detectors that are generator of voltage, the responsitivity is,

$$R = \frac{V}{\Phi_e} = \frac{V}{E_e.A} \qquad (3)$$

Where, V=rms signal voltage output of the detector in volts.

Responsivity will vary with changes in wavelength, bias voltage, and temperature. Responsivity changes with wavelength since the reflection and absorption characteristics of the detector's sensitive material change with wavelength.

The detector responsivity also can be measured in terms of two important parameters, quantum efficiency and photoconductive or internal gain, which are explained in the following section.

E2. Quantum efficiency

For the photodetector, quantum efficiency is defined as the ratio of the number of photoelectrons transferred from the detector to the number of incident photons on to the detector, i.e. the quantum efficiency is defined by:

η =Number of photoelectrons transferred /Number of incident photons

The value of η for a detector is also determined by the conduction and light absorption properties of the material and is related to the absorption quantum efficiency. A good photodetector should have large values for η , approximately 1. For this reason, all excited electrons are liberated with high energy due to the photon absorption in the material. If η is low, that Means that the incident photons are not absorbed sufficiently in the detector material.

E3. Internal gain

Generally, gain is defined by the ratio between the number of free excited electrons and the number of absorbed photons in the detector, when the detector is under illumination. However, internal or photoconductive gain is given by the ratio of the free carrier lifetime τ to the transit time τ_T between the electrodes. Therefore, in the interband transition like p-n photodiode, the gain is almost one. This value shows how well the generated electron-hole pairs are used to generate a current response in a photodetector. An infrared photodetector with internal gain higher than one is the avalanche photodiode other example are photomultiplier tubes and the phototransistors.

E4. Relation among infrared photodetector parameters

The photocurrent is the part of the current that is caused by the light. When light enters into the detector at a certain wavelength, the photocurrent (I_{Ph}) is expressed by the following equation (4)

$$I_{ph} = \eta q \frac{PA}{hc/\lambda} M = \frac{\eta q P A \lambda}{hc} M \,. \qquad (4)$$

Where, η is the quantum efficiency, P is the incident energy, A is the effective area of detector, λ is the light wavelength, M is the internal gain,c is the light velocity and h is the planck constant. However, photocurrent measurement is not the only way to classify the detector. To get better classification, you can consider the responsivity of the detector. The responsivity R is given by:

$$R = \frac{I_{ph}}{PA} M = \frac{I_{ph}}{N^* \frac{hc}{\lambda}} M = \eta \frac{q\lambda M}{hc} (A/W). \qquad (5)$$

Instead of incident energy, we use power density P [W/cm^2]. The magnitude of the responsivity depends on the gain and the quantum efficiency, that means detector performance, depends on both high absorption and a long lifetime of the excited charge carriers.

E5. Dark current

Dark current is the relatively small electric current that flows through a reverse biased phpotodetector due to a high electric field even if no photo-excitation occurs. It is also called the "reverse bias leakage current". Higher reverse bias voltages result in higher dark currents. The dark current is raised with increasing temperature. In zero bias, dark current is not present in the detector. In general, dark current denoted by i_0 , it can be modelled by a Poisson distribution with noise due to dark current,

$$¶_{io} = 2e\bar{i_0}\Diamond v \qquad (6)$$

Where, $\Diamond v$ is the bandwidth of the photodetector. Usually, the dark current is varies several to hundreds of Nanometers. It´s depends on the design of photodetector by manufacturer.

E6. Noise

In order to achieve good performance of the photodetectors, we have to make sure that it has present high bandwidth, high responsivity, low noise and high saturation power. Most objects which are capable of allowing the flow of electrical current will exhibit noise. This occurs as some electrons will have a random motion, causing fluctuating voltage and currents. Noise is the most important factor for the photodetector. Usually various kind of noises are thermal noise, shot noise, generation-recombination noise, flicker noises are exhibited when either flowing charge carriers or temperature rises in the photodetector.

E7. Noise equivalent power (NEP)

This is defined as the signal power or incident light power required to obtain signal to noise ratio to be unity. It can be expressed by the following equation (7)

$$NEP = \frac{p_{opt} / \left(S/N\right)^{-1}}{\sqrt{\Diamond v}} = \frac{hc}{\lambda \eta q}\left[2q(i_s + i_0)\frac{4K_B T}{R}\right] \qquad (7)$$

Where, $\Diamond v$ is the bandwidth, i_S and i_0 are signal and dark current respectively. The smallest value of the NEP,the better is the detector.

E8. Detectivity

When the consideration of detector performance interms of their detecting ability, we can define the new term is called the detectivity. This is one of the most important performance parameter for the photodetector. that is used to characterize NEP and it can be defined as;

$$D^* = \frac{\sqrt{A_d B}}{NEP} \qquad (8)$$

Where, D^*= Spectral detectivity, cm (Hz)½/W, Ad= Area of the detector, cm2, B= Band with of measuring system in Hz, NEP= Noise Equivalent Power.

E9. Signal to Noise Ratio (SNR)

The signal to noise ratio term is used to evaluate and characterize the performance of the photodetector. It´s compare the level of a average signal power to the level of a noise power [11]. The SNR is defined by:

$$SNR = \frac{I_P{}^2}{¶^2} = \frac{\eta P_{in}}{2hv\Diamond f} \qquad (9)$$

Where, Ip= average signal power, ¶= noise power,

η = quantum efficiency, Pin= optical input power, $\Diamond f$=bandwidth, $h\nu$=photon energy.

E10. Bit Error Rate(BER)

Bit error rate is used in optical communication system as a figure of merit for how effectively the Receiver is able to decode transmitted data. It is the percentage of bits that have errors relative to the total number of bits received in a transmission [8].

The BER is the likelihood of a bit misinterpretation due to electrical noise $w(f)$. Considering a bipolar NRZ transmission, we have for a 1

$$x_1(f) = A + w(t) \quad (10)$$

And for a 0

$$x_0(f) = -A + w(t) \quad (11)$$

Each of $x_1(f)$ and $x_0(f)$ has a period of *T*, and $\frac{N_0}{2}$ is the bilateral spectral density, so

$$x_1(f) = \mathrm{N}(A, \frac{N_0}{2T}) \quad (12)$$

$$x_0(f) = \mathrm{N}(-A, \frac{N_0}{2T}) \quad (13)$$

Returning to BER, we have the likelihood of a bit misinterpretation $p_e = p(0 \mid 1)p_1 + p(1 \mid 0)p_0$.

$$\mathrm{P}(1/0) = \frac{1}{2} erfc(\frac{A+\lambda}{\sqrt{N_0/T}}) \quad (14)$$

$$\mathrm{P}(0/1) = \frac{1}{2} erfc(\frac{A-\lambda}{\sqrt{N_0/T}}) \quad (15)$$

where λ is the threshold of decision, set to 0 when $p_1 = p_0 = 0.5$.

We can use the average energy of the signal $E= A^2T$ and adding the p_1, p_0 to find the final expression :

$$BER = P(1/0) + P(0/1) \quad (16)$$

$$\text{or, } BER = \frac{1}{2} erfc(\sqrt{E/N_0}) \quad (17)$$

In the optical communication system a BER of 10^{-6} corresponds to on average one error per million bits.

E11. Response time

When the photodetector is under ray radiation, time lag exists before generated signal reaches its steady-state. The phenomenon of time lag is called inertia which is expressed by response time [9]. Response time is influenced by the time constant τ and it is expressed by:

$$\tau = RC = (R_S + R_L)C_D \quad (18)$$

Where, *Rs* is series resistance of photodetector, R_L is the load resistance and C_D is junction capacitance.

F. Nanowires (NWs)

A nanowire is a very thin wire in which constrained diameter is a few tens of nanometers (10^{-9} m) or less and the length in unconstrained. This shows length to width ratio of 100 or more, which makes it a one dimensional material that has different and interesting properties compared to the bulk and 2-D materials. It is basically either a single quantum wire or array of quantum wire where quantum mechanical effects are exhibited. The final nanowire is likely to be a chain of single atoms. Nanowire technology is being investigated for faster and smaller electronic devices. There are many types of nanowires, semiconducting (InP, Si), Metallic (Pt, Au), and insulating (SiO_2) etc. The material of nanowires is varied with respect to their application, for example, InP nanowires are used in photoconductors and LED's and, SnO_2 nanowires are used in Lithium Ion batteries [11,12].

F1. Growth technique of NWs

There are different methods for the fabrication of NWs and all can be divided into two groups.

(i) Top-down: Lithography is the main strategy for the top-down method. To achieve better quality, as well as higher density of NWs on the substrate, we need to use the bottom-up strategy.

*(ii) Bottom-up: V*apour-phase growth and solution-based growth are the two common techniques to get high density along with high quality [5, 2].

F11) Vapour Phase Growth (VPG)

This approach is widely used today. In this method the material is in vapour phase. Usually, there is some catalyst at the top of the substrate where the material of the substrate and NWs can be either the same or different. The investigated samples during this project work are fabricated using MOVPE (metal organic vapor phase epitaxy).

F12) Solution based growth

This method is basically more common for the inorganic materials. In this approach, some templates of porous alumina are used. During this method, due to the electrodeposition, the NWs are guided inside the templates. The templates are removed when the process of electro deposition is completed for growth of NWs.

Metal organic vapour phase epitaxy (MOVPE) is mainly a chemical vapour deposition method, which was first demonstrated in the 1970s for GaAs thin film formation. Since then, the fundamentals have not changed, although the complexity of layer compositions and combination has increased dramatically. The technique involves passing vapors containing the individual components required for the target film into a deposition chamber containing a heated substrate. The vapors flow over the substrate and are thermally

Decomposed to deposit a coating, with the by-products swept away from the surface by the carrier gas.

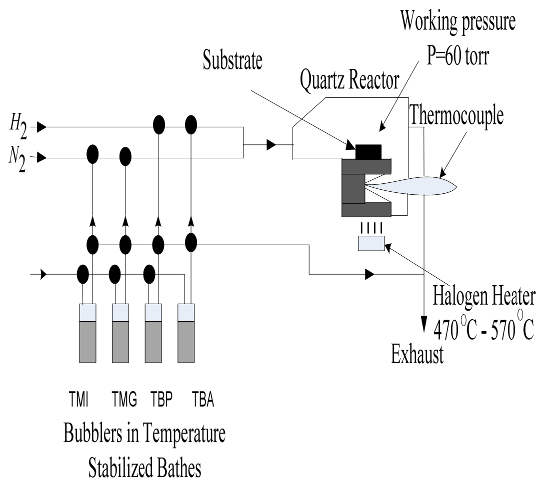

Fig.8 Schematic diagram of the MOVPE system

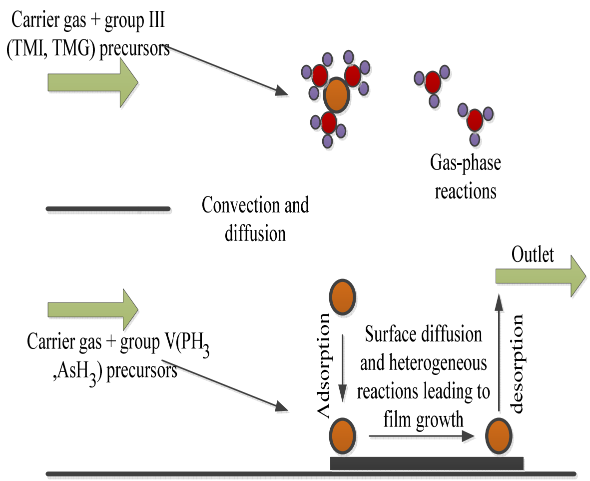

Fig.9 Flow diagram of MOVPE process

Figure 8 shows the MOVPE system consists of a quartz glass reactor and some gas lines. Hydrogen is injected through bubblers containing the metal organic precursors. Nitrogen or Hydrogen carrier gas (Shown in figure 9) is used to bring the precursor vapor's to the reactor. A computer (having mass flow controller) is used to control the flow of vapors. The temperature of precursor container is stabilized with a bath that also helps to control the pressure of the bubblers. The substrate (wafer) is inside the reactor, at the top of a graphite plate that can be heated up by a halogen or RF heater at 470 ^0c -570 ^0c and 50 mbar pressures. A thermocouple is used to control the temperature of the graphite and substrate.

For our samples, Au colloidal nanoparticles with average diameter of 40 nm were used as the seeds for controlling the nanowire growth in a vertical MOVPE reactor operating at low pressure. The total pressure in

The reactor during growth was 60 Torr. Trimethylindium (TMI) and tertiarybutyl phosphine (TBP) were used as the precursors with hydrogen as the carrier gas. The V/III ratio during the growth was kept constant at 120 and the growth duration was varied from 5 to 60 s. Prior to the growth, the samples were annealed at high temperature for 10 min under a constant TBP flow, followed by growth at a relatively lower temperature [17]. The high-temperature anneal was carried out to remove the initial native oxide on the surface as well as for forming an initial Au–In eutectic liquid by consuming In from the substrate by the molten Au particle at high temperature. For obtaining a proper condition for stable nanowire growth, the pre-growth anneal and the growth temperatures were varied systematically in the ranges of 440–540 and 370–440°C, respectively. The growth of InP nanowires was terminated by switching off the indium supply while maintaining the TBP supply until the samples had been cooled down to room temperature [15,16].

Figure 10 shows the Scanning Electron Microscopy (SEM) images where NWs lengths and diameters were measured by investigating 30 nanowires per array. The samples were studied with a Tecnai 10 keV TEM in both brightfield as well as in high-angle annular dark field (HAADF) mode.

Fig.10 SEM image of InP NWs that has grown during MOVPE process

F2. P-I-N Nanowire photodetector

This was a first sample that we measured and investigated in the laboratory. It was made by InP which is III-V group semiconductor material. The substrate and the nanowires in this sample are made of the same material to obtain a greater lattice match.

The investigated photodetectors in this thesis project are based on an ensemble of InP NWs grown on an InP substrate, some general information and important characteristics of the samples are described here for the better understanding of the sample. But due to some marketing trends and policies, the detailed production technology is not allowed to be discussed here. NWs are directly grown on the substrate from 40 nm gold seed particles. The InP substrate is p-type and the NWs are n-

Type with an initial nominally undoped (intrinsic) region. The general design of the sample is shown in figure 11.

When the NWs are grown, firstly an intrinsic layer with the length around 1μm is formed. After the intrinsic layer the growth of the NWs starts with high n-type doping. The nanowires are grown on the epi layer with the density of 0.28 NWs/μm ^{2} in 3μm length with a 40 nm diameter.

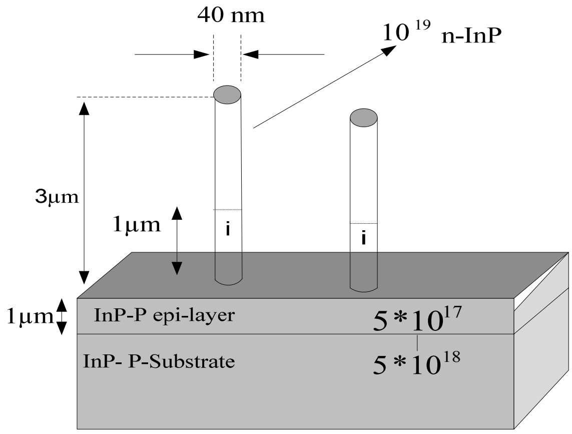

Fig.11 Schematic diagram of p-i-n nanostructure

These types of photodetectors are supposed to have good photoresponse due to the carrier confinement. The upper part of the substrate layer, which has grown by homoepitaxy process is called epi-layer. The epi-layer is to more lightly doped ($5*10^{17}$) than the substrate layer ($5*10^{18}$) to maintaining the low collector resistance and to get a higher breakdown voltage across the collector-substrate junction. Meanwhile, the Lower collector resistance allows a higher operating speed with the same current.

Figure 12 shows the isolation system of NWs. All the nanowires are isolated by SiO_2 which is a very good insulator. This prevents contacts between the nanowires. Below, we can see the insulation system of the nanowires. When the insulation process is completed, all spaces between the nanowires are filled by indium tin oxide (ITO) in order to make a metal contact. The ITO has good metallic properties to provide an ohmic contact to increase the carrier Collection efficiency as well as showing good transparency [9].

This is necessary in the many optical devices. The circuit connection of the complete cross-section sample at a reverse bias is shown in figure 13. The energy band diagram is also shown in figure 14. This energy band Diagram is similar to the energy band diagram of conventional p-i-n photodetectors. In our case, most of the light will probably be absorbed by the substrate and generate electron-hole pairs that diffuse to the depletion region at the NW/substrate interface.

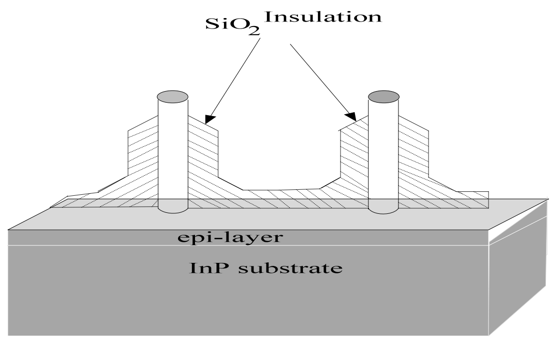

Fig.12 Schematic diagram of Sio_2 isolation between two NWs

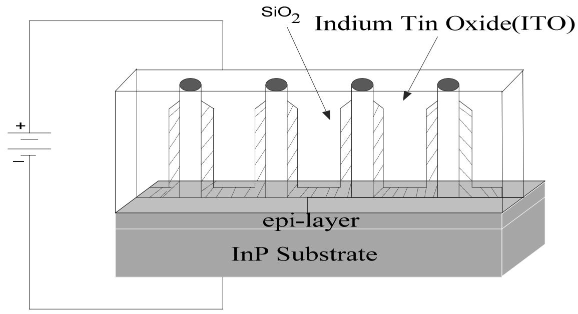

Fig.13 A nanowire photodiode cross-section with reverse bias

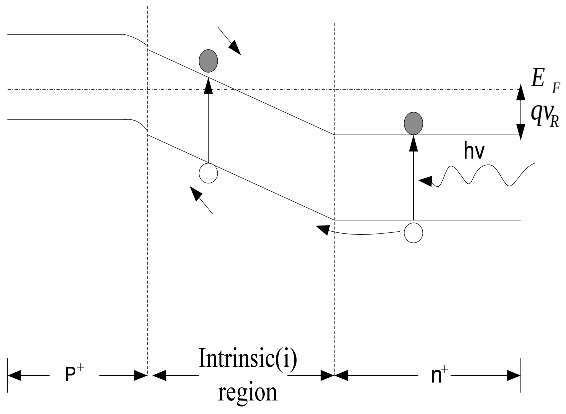

Figure.14 Energy band diagram of the sample under reverse bias

A fraction of the light will be absorbed directly in the depletion region of the NWs, where the electric field will separate the electron hole pairs and cause the current to flow in the external circuit [18].

F3. P-N Nanowire structure

This was fabricated in the same way as sample 6080, but there was no intrinsic layer. It is simply a p-n photodiode which had schematic diagram shown below:

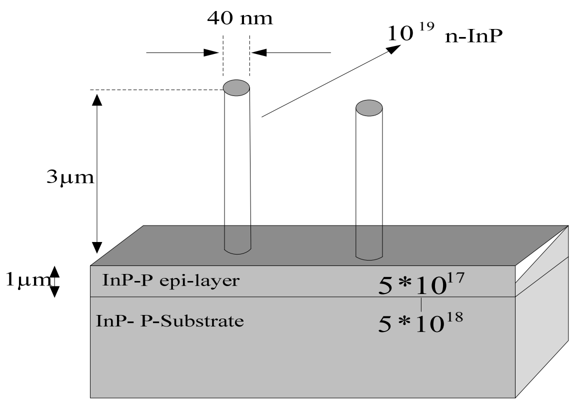

Fig.15 Schematic diagram of p-n nanowire structure

III. EXPERMENTAL PROCEDURE

In our experiments, we investigated how much photocurrent was generated as a function of wavelength at different temperatures, when the infrared light is passed through the sample. In this experiment, we have used Fourier Transform Infrared Spectroscopy (FTIR) to test the optical properties of the photodetectors. These properties are investigated to check the quality and response of the sample. Actually, infrared spectroscopy is an experimental technique used to:

- check the quality of the sample and to see if there are any defects
- find out the kind of materials used in a sample
- determine the spectral sensitivity of a sample

For infrared spectral analysis, FTIR is more advantageous modern technique than the conventional or dispersive technique because it has more reliable and precise measurement technique [5,6].

A The Measurement Process

Figure 16 shows the flow diagram of experimental setup, where we have done our measurement according to this. Now we are going to discuss the main parts that we have used in this experiment.

A1) Light sources

The basic instrument is equipped with a MIR source. The MIR light source is a globar that emits mid-infrared light (i.e. a U-shaped silicon carbide piece). Besides the standard MIR source (aircooled), We used the NIR source for all our experiments. The spectral range of the IR can be switched from Near Infrared (NIR) to Medium Infrared (MIR) using the computer interface. The source can be switched OFF if someone wants to analyse the electrical signal without illumination. Theaperture (which Controls the amount of light) is also controlled from the computer.

A2) Laser

The FT-IR is equipped with HeNe laser which has

Wavelength of emitted red light 632.8nm and rated output power 5mW. The laser measures the position of the moving interferometer mirror (also called scanner) and is used to determine the data sampling positions

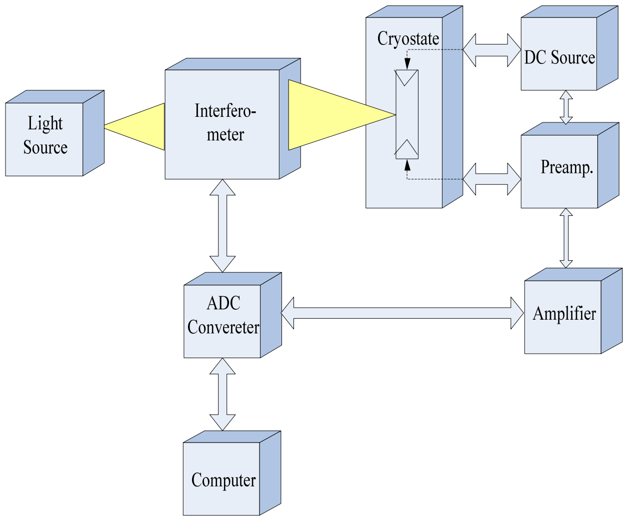

Fig.16 Flow diagram of experimental set up.

A3) Interferometer

The FT-IR is equipped with an actively aligned ultra-scan interferometer based on a linear scanner which ensures a spectral resolution better than 0.07cm-1). The linear scanner is supported by an air bearing which requires the connection to a nitrogen line.

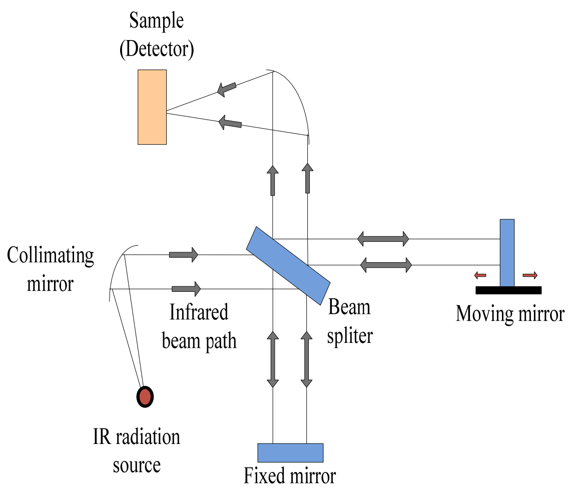

Fig.17 Schematic of Interferometer

The optical pathway of the spectrometer is shown in figure 16. An infrared radiation light source produces a highly coherent beam of light by using collimating mirror. This beam is divided into two beams when it comes to the beam splitter. Each beam will reflect off from their respective mirrors to recombine again at the output of the interferometer. The position of one mirror is constant while the position of the other changes constantly, so due to this reason the different frequencies of the signal are modulated in a unique way and the interferometer output is a signal containing all frequencies of IR coming from the source. The interferometer output signal versus position of the moving mirror is called an ''*interferogram*''.The

Interferogram is converted to a spectrum using the Fourier transform by computer.

A4) Cryostat

The cryostat is one of the main parts of the FT-IR system. The FT-IR installed at Halmstad University has a cryostat name is *Optistat DN*. It is a top loading and static exchange gas cryostat with optical access provided via four sets of radial and one set of axial windows [20].

A5) Detectors

The basic configuration of the spectrometer includes a DigiTect™ DLaTGS detector. The detector contains an analogue-to-digital-converter that converts the analogue signal from the detector directly into a digital signal. This digital signal is transmitted to the data processing electronics unit of the spectrometer. The standard detector is a pyroelectric DLaTGS detector which covers a spectral range from 12,000 to 250cm-1, operates at room temperature and has a sensitivity of D*>4x108 cm Hz1/2 W-1. Apart from the standard detector , there are a large number of optional detectors. All detectors are mounted on dovetail slides which allow an easy exchange. In our experiments, the NW-based photodetectors under investigation act as detectors themselves. The integrated DLaTGS detector is only used to record the spectral content of the NIR source [21].

A6) DC Source

For this reason, we have used KEITHLEY 2602A SourceMeter® Instrument made by USA. This is a dual-channel system SourceMeter instrument with current (±DC, 1pA to 3A) and voltage (±DC, 1μV to 40V). It is also high power and simplicity for R&D applications. The instrument comes with the software LabTracer 2.0 which allows users to configure and control up to eight model 2602 SourceMeter channels quickly and easily for curve tracing or device characterization [19].

A7) Amplifier

KEITHLEY 428 instrument was used as an amplifier. This instrument is installed with the FT-IR system to amplify and convert the small photocurrent generated in the samples to an output voltage to be Fourier transformed. Usually, we amplified the signal by 105 and 106 using this instrument [19].

Figure 16 shows the whole measurement setup. We have used a Halogen tungsten lamp as a NIR light source. This light was emitted to go through a interferometer as it was described before (*A3)*. After that it is focused on a biased sample inside cryostat that acts as a light detector. The generated photocurrent is converted to voltage by a low-noise current preamplifier. Then the amplified signal is sent to an analog-to-digital converter (ADC). A digital interferogram is read and transformed using the Fourier transformation algorithm by a computer.

IV RESULT AND DISCUSSION

In our project, we have characterized p-n and p-i-n Photodetector electrically and optically using Fourier Transform Infrared Spectroscopy. Basically optical characterisation is the spectral or photoresponse at different biases and temperatures by using and the electrical characterization, or I-V characteristics which were carried out at different temperatures in darkness as well as under illumination.

A. Electrical Characterization (I-V curves)

The I-V curves can be divided in:
Forward bias state, in which the current increases exponentially. This state is also known as forward bias mode. Reverse bias state, in which the reverse saturation current appears, can be related to the dark current as:

$$I_D = I_S(e^{qv/kT} - 1) \qquad (20)$$

Under the illumination, I-V curve is shifted by the amount of photocurrent which is called solar cell curves Due to the photovoltaic action. Thus, this relation stand by the equation (21) is

$$I_D = I_S(e^{qv/kT} - 1) - I_L \qquad (21)$$

When the applied reverse bias increases, we reach a point where the reversed current start to increase rapidly, this point is referred to as the breakdown voltage. Figure 18, 19, 20 and 21 show the IV curves from 78K to 300K without and with illumination, respectively.

A1.P-I-NPhotodetector

Here we can see the sample 1(fig.18) in darkness, the breakdown voltage is almost -3V at 78K. However, for the 300K, the breakdown voltage is approximately -0.5V. For the sample 2(fig.19) under illumination, the breakdown voltage is -4V at 300K. In contrast, the breakdown voltage is different for the both samples due to the sample defect. It can be also seen from the figure 18 and 19 that the current increases with increasing temperature. Since, it is a high density sample, its resistance is low.

It is quite clear that the breakdown voltage is also decreased due to a rise in the temperature. Before the breakdown voltage, we get the straight line which shows the photodetector stability.

A2. P-N Photodetector

Figure 20 and 21 shows the IV curves for two samples in darkness as well as under illumination respectively. The sample 2 (fig.21) has more stable properties than the sample 1(fig20). The breakdown voltage is almost -0.5V of sample 2, while sample 1 has shown -0.25V. However, the curve is shifted downwards by the photocurrent under illumination.

B. Optical Characteizations

This basically defines the spectral response or sensitivity of the photodetector in terms of conversion of light to electrical current. Figures (22-25) for both photodetectors (p-n, p-i-n) have been revealed that there are two clear peaks for each photocurrent spectra.

The first peak corresponds to the band gap energy and there is still no reported confident comment about the 2nd peak. But, after careful consideration, we think that it is actually related to the band structure of InP.

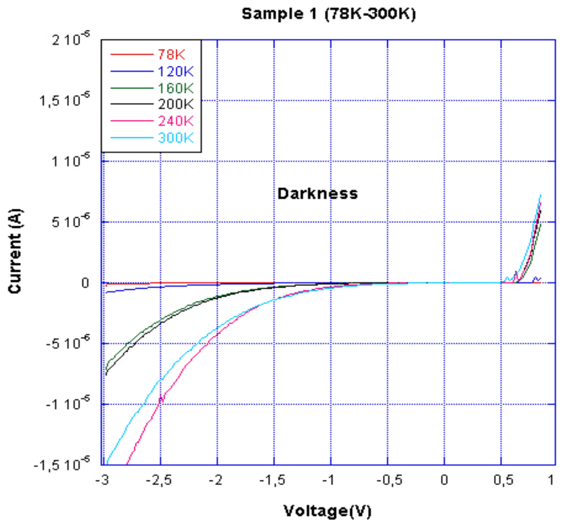

Fig.18 I-V characteristics of sample 1 in darkness

B1. P-I-N Photodetector

Figure 22 shows the sample 1 at 78 K, one peak appears at about 1.4eV and 2nd peak appears at 1.6 eV, which are corresponding to the 885 nm and 800 nm of wavelength respectively. However, these results are quite different at 300 K, there is only one peak reveals at 1.35eV (918 nm). However, the photocurrent response varies with respective samples. At 300k, it can be seen that the photocurrents amplitude are 7800 a.u. and 5400 a.u. for sample 1(fig.22) and sample 4(fig.23) respectively. Nevertheless, the photoresponse shows the same amplitude at the same temperature for different biases.

The photocurrent will increase or decrease depending on an increase or decrease in temperature. It is also clear that the photoresponse depends on temperature, but not on the applied biases. Clearly, the shift of band gap towards lower energy at high temperatures can be seen. The band gap is almost 1.40eV and 1.35eV at 78K and 300K temperature respectively. These values are very close to the reported values of InP band energy.

B2. P-N Photodetector

Figure 25 shows the same peak value corresponding the same wavelength as like figure 22. Figure 24 shows the photocurrent for sample1 at 300K for different biases, all curves look the same with amplitude of 11500 a.u. However, the amplitude is fallen by 10700 a.u. at 300K Due to the applied bias effect. There is only one peak appears at about 1.4 eV with respect to 885 nm.

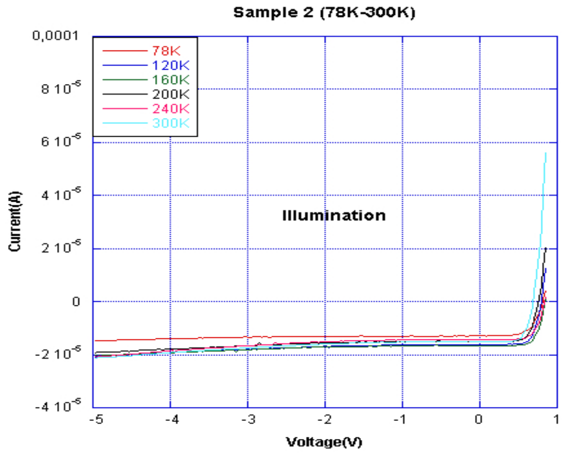

Fig.19 I-V characteristics of sample 2 under illumination

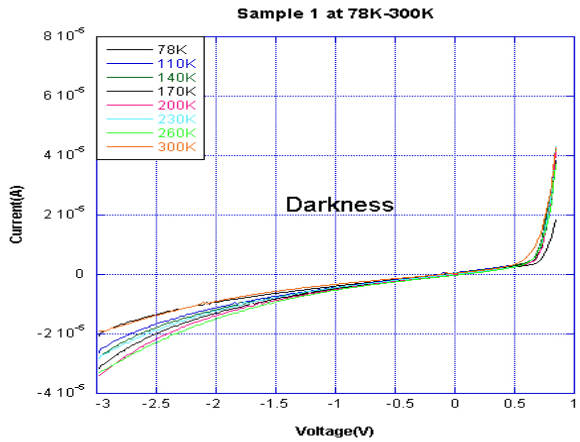

Fig.20 I-V characteristics of sample 1 in darkness

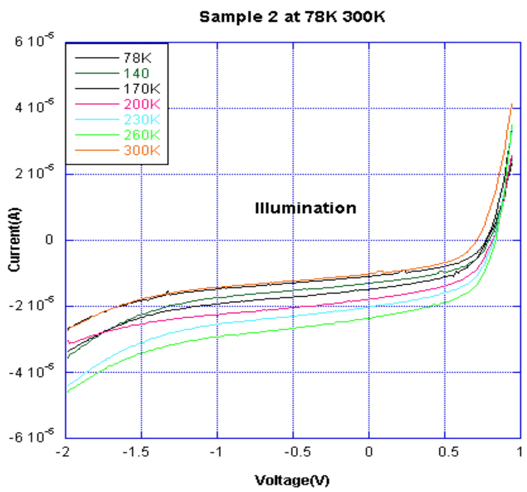

Fig.21 I-V characteristics of sample 2 under illumination

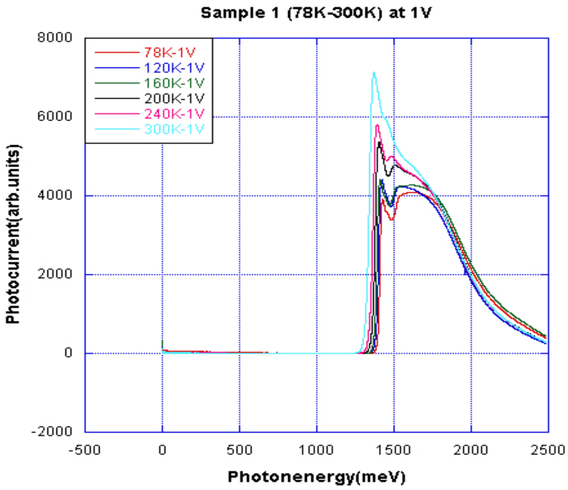

Fig.22 Photo characteristics of sample 1 at different temperature

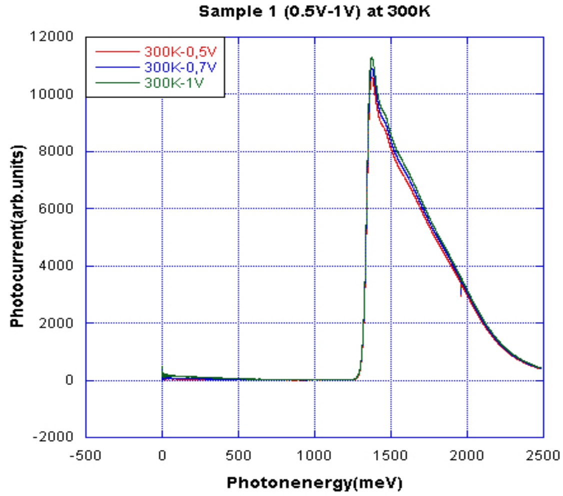

Fig.24 Photo characteristics of sample 1 at different temperature

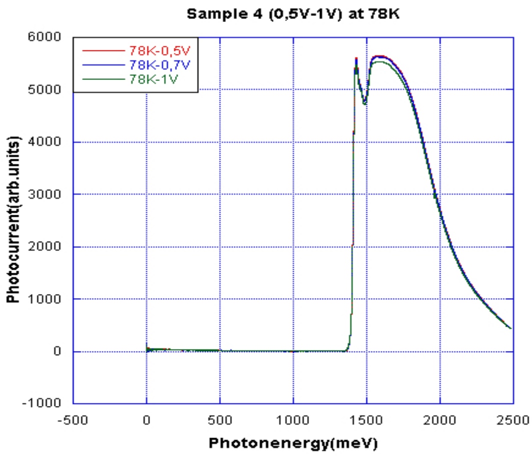

Fig.23 Photo characteristics of sample 4 at different temperature

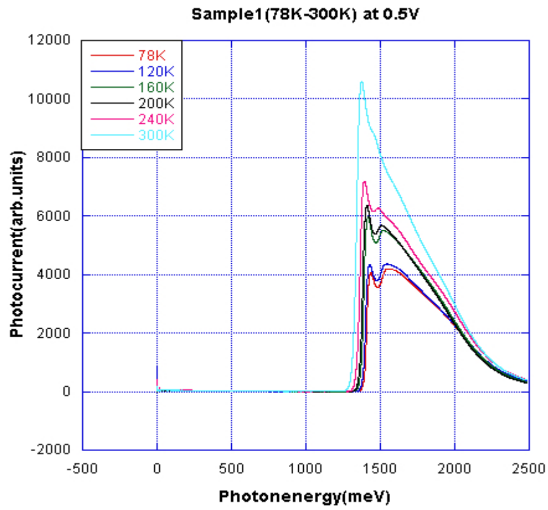

Fig.25 Photo characteristics of sample 1 at different temperature

The temperature is raised due to applied bias into the photodetector and created the noise level during their operation. As a result, photodectors have been merged draw back regarding speed and efficiency and need to improve their performance characteristics. Now we are going to discuss the noise which produces in the photodetctor.

Figure 26 shows the natural logarithmic plots of the IV curves that have been taken with and without illumination at different temperatures from 78K to 300K temperature.

As these values are logarithmic, it is easy to see minimum current and its corresponding voltage with noise contribution. It can be seen that there is almost no current at 0V applied bias for the IV curves without illumination, especially at high temperatures. There is a small laser generated signal, that's why the logarithmic curves without illumination are shifted towards positive voltage, especially at low temperatures.

Usually real diodes do not behave like ideal diodes (Eq. 21). So the equation for the device has to be modified by using a parameter to show whether the diode behaves closely or apart from the ideal case. This Parameter is known as the ideal factor or slope parameter (η). We can easily conclude the detector performance by using this slope parameter. This slope factor is affected by many physical processes, such as carrier generation-recombination, tunnelling, presence of interface states etc. Usually, it is a function of temperature and the applied bias. For a real diode, the current flow under forward bias in dark, is represented by the equation

$$I = I_0 e^{qv/\eta KT} \tag{22}$$

To find the ideality factor we can rewrite this as:

$$\eta = \frac{q}{T} \Diamond v \log(e) \qquad (23)$$

Where $\Diamond v$ is the change in voltage with respect to per decade of the current. So, we can select randomly one of the above curves, and the ideality factor can be calculated by using the equation (23).

For a non-ideal case, the current and voltage are affected by the shunt and series resistance; hence the relation is given by

$$I = I_0\left[\frac{q(V - IR_S)}{\eta KT} - 1\right] + \frac{V - IR_S}{R_{Sh}} \qquad (24)$$

As we can see in ln(I)-V figure regarding Equation (24) the curves are more linear in low bias level than in the high voltage level. This is because the current is increased with respect to the increase voltage and hence, this leads to a voltage drop across the series resistance. At low voltages, the device's performances are dominated due to the shunt resistance (R_{shunt}) effects, wherease series resistance is dominated at high voltage.

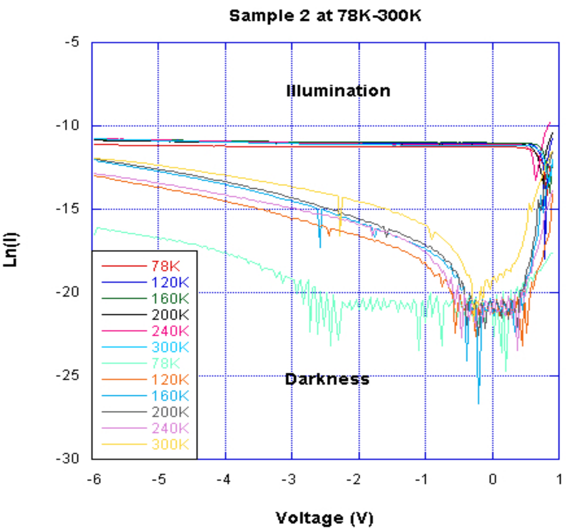

Fig. 26 ln(I) vs V curves for sample 2 in darkness and under illumination

V. Conclusion

The purpose of the study was to investigate and analyze the electro-optical characterization for the NW based p-n and p-i-n structure photodetectors. The intrinsic layer of the p-i-n photodector is the main crucial factor that has made the electro-optical characterization more promising than the p-n photodector. However, p-i-n structure has shown more noise with increasing temperature.

Acknowledgment

This project work is based upon research on NW based Infrared Photodetectors by using InP NWs instead of Silicon which is granted for master´s thesis of the electrical Engineering and performed at Mathematics, Physics and Electrical Engineering (MPE) laboratory, Halmstad University, Sweden.

References

[1] Nave, R., "Wave-Particle Duality". HyperPhysics. Fowler, Michael,"The Photoelectric Effect". Physics 252, University of Virginia.

[2] International Union of Pure and Applied Chemistry. "Photodiode".Compendium of Chemical Terminology Internet edition.

[3] G. Giuliani and D. D'Alessandro, "Noise Analysis of Conventional and Gain-Clam Semiconductor Optical Amplifiers,"*J. Lightwave Tech.*, vol. 18, 2000, pp.1256-63.

[4] R.C. Jones,"Proposal of the detectivity D*for detectors limited by radiation noise," J.Opt.

[5] Brian C. Smith, Fundamentals of Fourier Transform Infrared spectroscopy, CRC press, Boca Raton, 1996

[6] CesareSoci,ArthurZhang,Xin-YuBao†,Hongkwon, Kim Yuhwa Lo, and Deli Wang Department of Electrical and Computer Engineering, Jacobs School of Engineering, University of California, sandiego,9500 Gilman Drive, La Lola, California 92093-0407, USA

[7] http://en.wikipedia.org/wiki/Bit_error_rate

[8] Xiang Son FU, Su Ying Yao, Jlang Tao Xu, Yao Lu, Yun Guang Zheng, Optical application, vol XXXVI no. 2-3, 2006.

[9] hh.divaportal.org/smash/get/diva2:359979/FULLTEXT01, MN Amin. Mo Alam, technical report, IDE 1056, October 2010.

[10] "Fiber-optic communication systems", Govind P Agrawal, 3rd edition (2008).

[11] Magnus Borgström, Epitaxial Growth, Processing, and Characterization of Semiconductor Nanostructures. Lund University, Sweden 2003.

[12] R. George, Detection of Light From the Ultraviolet to the Submillimeter, 2nd Edition (2003).

[13] "Super conducting nanowire photodetectors array",Tech note, Linconl Labrotary, Massachusetts Institute of Technology..

[14] High Purity Metalorganic Precursors for CPV Device Fabrication,Simon Rushworth, Material Matters Volume 5 Article 4.

[15] "Generic nano-imprint process for fabrication of nanowire arrays" Aurelie Pierret1, Moïra Hocevar, Silke L. Diedenhofen, Rienk E. Algra1, E. Vlieg, Eugene C. Timmering, Marc A. Verschuuren, George W.G. Immink, Marcel A. Verheijen, Erik P.A.M. Bakkers , Philips Research Laboratories Eindhoven, High Tech Campus 11, 5656AE Eindhoven, The Netherlands.

[16] Self-Catalyzed Epitaxial Growth of Vertical Indium Phosphide Nanowires on Silicon Li Gao,† Robyn L. Woo,† Baolai Liang,‡ Marta Pozuelo,§ Sergey Prikhodko,§ Mike Jackson,§ Niti Goel,| Mantu K. Hudait,⊥ Diana L. Huffaker,‡ Mark S. Goorsky,§ Suneel Kodambaka,§ and Robert F. Hicks*,†,§ Department of Chemical and Biomolecular Engineering, Department of Electrical Engineering, Department of Materials Science and Engineering, UniVersity of California, Los Angeles, CA 90095, Intel Corporation, Santa Clara, CA 95052, and Intel Corporation, Hillsboro, OR 97124

[17] S. Bhunia, T. Kawamura, S. Fujikawa, K. Tokushima, Y. Watanabe Physica E, 21 (2004), p. 583
[18] Electrical and Optical Characteristics of InP Nanowire based p-i-n Photodetectors Master's Thesis in Electrical Engineering. Rizwan Ahmed, Shahid Abbas, Technical report, IDE1059, November 2010
[19] Keithley, Test and measurement Product catalog, 2007.
[20] Oxford Instruments, OptistatDN Variable Temperature Liquide Nitrogen Cryostat Operato's Handbook, 2006.
[21] Bruker Optik GmbH, *Vertex 80V Operator's user manual*,German2006.

Mohammed Nurul Amin has born in Feni, Bangladesh, in 1979. He received the B.Sc in Electrical & Electronic Engineering degree from Dhaka University of Engineering & Technology (DUET), Gazipur, Bangladesh, in 2003, the M.Sc in Electrical Engineering degree with specialization Microelectronics and Photonics in 2010 from Halmstad University, Halmstad Sweden. His research focuses on Infrared Photodetector characterization based on nanowires and his research interests are optoelectronic devices, optical sensor design, fabrication of nanowire structure, photovoltaics, microelectromechanical system (MEMS) and nanoelectromechanical (NEMS).

He was worked at Dhaka Electric Supply Authority (DESA) from 2001 to 2006 and Power grid Company of Bangladesh Ltd (PGCB) as an assistant manager (Technical) in 2007.

Md. Obaidul Alam was born in Naoga, Bangladesh, 1984. He has finished BS.c in Electrical & Electronic Engineerig degree from Ahsanullah Science & Technology (AUST) in 2008, and the MS.c in Electrical Engineering degree with specialization Microelectronics & Photonics in 2010 from Halmstad University, Halmstad, Sweden. His research focuses on photodetector characterization, solar cells, nanostructure fabrication, MEMS,

After complition his BS.c degree, he has worked in Energypac Bangladesh Ltd.