Electrical and Optical Characteristics of InP Nanowire Photodetectors

Master's Thesis in Electrical Engineering

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Description of cover page picture/figure: Test Sample: InP Nanowire
Preface

I would like to thank my supervisor and mentor Lars Landin who helped me in all parts of the project. I mention without his precious help, it would have been impossible for me to do this project alone. I am grateful to Professor Håkan Pettersson who helped me every time that was needed. His thoughtful ideas helped me many times. I am glad that he gave the chance to work on this project that is a new technology of photo detectors. I learned so much from these two great teachers.

Finally, I like to dedicate this project to my parents Manouchehr and Mary that without their unsparing support, I would not have been able to do this project. I want to say them I love you forever.

Mehdi Malekrah,
Halmstad University,
June 2010.
Abstract

In this project Fourier Transform Infrared Spectroscopy is used to investigate a new kind of photodiode that is based on nanowires. The photo current and I-V curves for different temperatures, different applied biases, in darkness and illumination condition have been studied. The experiment was conducted in the temperature range from 78 K (-195ºC) to 300 K (27ºC). These photo diodes are designed to work on NIR wavelengths. The results show some excellent properties, such as high break down voltage, and that is an important advantage for photo detectors, low and constant reverse saturation current ($I_s$). The results show some defects, most of them come from fabrication. The design of the sample is also discussed.
**Abbreviations**

NWs: Nanowires  
VLS: Vapor Liquid Solid  
CVD: Chemical Vapor Deposition  
MOVPE: Metal Organic Vapor Phase Epitaxy  
TMI: trimethylindium  
TMG: trimethylgallium  
TBP: triarylbuthylphosphine  
TBA: teriarybutylarsine  
Epi-layer: Epitaxial Layer  
ITO: Indium Tin Oxide  
FTIR: Fourier Transform Infrared  
W: Wavenumber  
E_a: Activation Energy  
NIR: Near Infrared  
MIR: Mid Infrared  
LIR: Long Infrared  
D: Darkness  
L: Light  
ITO: Intelligent Temperature Controller
1 INTRODUCTION

Solid state materials can be classified into three groups; insulators, semiconductors and conductors. The study of semiconductor materials began seriously the twentieth century. Recently scientists studied many semiconductor materials but silicon was more interesting than the others, because of the high quality of silicon dioxide (SiO$_2$) that is a very good insulator. Also, the great supply of silicon on the earth’s crust makes this element very cheap [6]. Unfortunately silicon has an indirect band gap (Fig.1);

![Energy band Structure of Si and GaAs](image)

(a) Si

(b) GaAs

**Fig. 1 Energy band Structure of Si and GaAs**

(a) indirect band gap

(b) direct band gap

For this reason it is not useful for optoelectronics, as direct bandgap materials, and usually a combination of groups III-V elements are used for optoelectronic devices (i.e. InP, InAs, GaAs...). Optics devices have improved very fast in recent years, and have a major role in high technology devices these days. One of the most interesting photonic devices is the photodetector. Depending on which level of wavelength we are interested in (from ultraviolet to infrared), there are specific photodetectors. Infrared wavelengths that are invisible for human eyes are used so much in electronic devices in recent years. For example, night vision,
communication, spectroscopy, astronomy etc are some application of IR wavelengths. Depending on the application, there are also different types of infrared photodetectors.

Because of infrared electromagnetic waves have a big range of wavelengths (from 700nm to 1mm), in each field, the infrared region is divided into different levels, up to 5 levels, but 3 levels division is more common.

- NIR (Near Infrared): from 700nm to 1400 nm
- MIR(Mid Infrared): from 1.4µm to 3µm
- LWIR(Long Wave Infrared): from 3 µm to 1000µm

NIR is the wavelength that is commonly used in fiberoptic communications because of low loss in glass of these wavelengths. The photodetector that is investigated in this thesis also is designed to work in NIR wavelengths.
1 INTRODUCTION

1.1 Goal of the project:

The purpose of this project is to analyse the new generation of photodetector that is based on nanowire. This photodetector is designed for communication applications and Fourier Transform Infrared Spectroscopy (FTIR) will use to analyse the optical properties. The photocurrent will study for various applied biases also at various temperatures (78 K to 300K). I-V curves in forward and reverse biases in different temperatures will be analysed. Arrhenius plots also will be investigated.
1 INTRODUCTION
2 BACKGROUND:

Photodetectors are a kind of semiconductor devices that convert incoming light to an electrical signal. There are different types of photodetectors with different applications, structures, technologies and different sensitivities to wavelengths, but some basic operations are common between all photodetectors that can be classified to three steps like:

1) Carrier generation by incoming light.
2) Carrier transport (multiplication if there is any current gain).
3) Interaction of generated current with external circuit to provide output signal.

All detectors have material inside that is sensitive to incoming light. It will absorb the photons and, if the incoming photons have enough energy, electrons will be excited to higher energy levels and if these electrons are free to move, under the effects of an external electric field, they will produce an electric current. There are two systems to detect the incoming photons and generate the carriers, external and internal [1].

2.1 The External Photoeffect:

If a collision between an incoming photon and a material’s surface in vacuum leads to the escape of an electron from the potential barrier into the vacuum as a free electron, this process is called photoeffect emission. This process will happen if the incoming photon has enough energy [1].

In Fig.1 is shown the energy level of; (a) metal (b) semiconductor for external photoeffect. The lowest work function for a metal (e.g. CS) is about 2 eV, therefore, it will be useful for visible and ultraviolet regions (Fig.1 (a)). The lowest work function for a semiconductor (e.g. NaKCsSb) is about 1.4 ev. Therefore, it will be useful for the near infrared region, as well as visible and ultra violet regions.
Photodetectors based on external photoelectric emission need a vacuum surrounding them, because of this, they are usually used in vacuum tubes, Fig. 2 (a). In order to have a good signal to measure, some metal or semiconductor plates can be add to the inside the tube as an amplifier (dynodes). In this system, the amplification rate can reach to $10^7$, Fig. 2 (b).
2.2 The Internal Photoeffect:

Most of the modern photodetectors are based on the internal photoeffect system. In this method, the generated carrier pairs (electrons and holes) will stay inside the semiconductor and there is no need a vacuum for the excited electrons. In the building of these photodetectors, there is a material with photoconductivity properties. Photoconductor materials will generate electron-hole pairs as a result of absorption induced light, and then the generated electron will excite from valence band to conduction band, Fig.3 [1].

Fig.2 (a). Photo tube (b). Photomultiplier tube

Fig.3 Electron-hole photo generation in a semiconductor
By applying an electric field to the material, the electron-hole pairs will be transported through it and photocurrent in the external circuit of detector will produce. The famous models for photodetectors that are based on the internal photoeffect are p-n photodiodes, p-i-n photodiodes, heterostructure photodiodes, Schottky-barrier photodiodes and array detectors. Each of these detectors has special manufacturing technology, properties, advantages and disadvantages and, according to the application, one of them can be selected. Since the investigated sample in this project is a p-i-n photodetector, p-n and p-i-n photodetectors will briefly introduce [2, 3].

2.2.1 The p-n Photodiode:

The p-n photodiode is a semiconductor with a reverse current that will increase under illumination. A p-n photodiode under illumination and reverse bias is shown in Fig.4

![Fig.4 An idealized p-n photodiode that illuminates with photons. The drift and diffusion currents are indicated in 1 and 2 regions, respectively.](image_url)
The illuminated semiconductor with reversed bias can be classified into three different regions:

(1) In the middle, where the depletion region is formed, electron and hole pairs will be generated, and will drift quickly in opposite directions, electrons to n and holes to p side. Because of this, the generated current in the external circuit is always reversed.

(2) Near to the depletion region, the electron and holes have the chance to enter the depletion region due to diffusion and contribute to the current.

(3) In the region that is placed far from the middle (the depletion region), the generated pairs will recombine randomly and do not have any effect on the photocurrent.

Therefore, most of the photocurrent is generated in the depletion region; this means if we have wider depletion region, we can trap more photons and get a higher photocurrent as a result. In order to have wider depletion region, we can add an intrinsic layer between the n and p doped regions [1, 3].
2.2.2 The p-i-n Photodiode:

P-i-n photodiode is a detector with an intrinsic (lightly doped) in the middle of p-n junction. Fig.5

![p-i-n photodiode structure](image)

This intrinsic layer leads to an extended depletion region compared with the p-n photodiode [1]. The advantages of p-i-n photodiode are:

- Increasing the width of the depletion layer of the device and the area available for capturing light.
- Increasing the width of the depletion layer reduces the capacitance of junction and thereby the RC delay reduces. But, the transit time increase with the width of the depletion region.
- Reducing the ratio between the diffusion length and the drift length of the device results in a greater proportion of the generated current being carried by the faster drift process.

The reasons that photodiodes usually are used in the strong reverse biased are:

1. With stronger reverse bias, the depletion region increases (more important for p-n junctions), therefore more light will be captured
2. With strong reverse bias, the electric field in the junction increases and this will increase the drift velocity of carriers in the depletion region
3. With strong reverse bias, the width of the depletion region increases and that leads to a decreases of the capacitance of the region. Therefore, the RC constant decreases and we will have better response time.
In Fig. 6 the cross-section of a p-i-n photodiode under reverse bias is shown:

![Fig.6 Cross-section of a p-i-n photodiode.](image)

In Fig. 7, energy band diagram of a p-i-n photodiode under reverse bias is shown:

![Fig.7 Energy band diagram of p-i-n photodiode with reverse bias.](image)
2.3 Fourier Transform Infrared Spectroscopy (FTIR):

Infrared spectroscopy is an experimental technique that is used for these reasons:

- To find out the kind of materials that are used in a sample
- To check the quality of the sample
- To determine how much of each material is used in a compound

In this project, FTIR is used to test the optical properties of the sample that is related to check the quality of the sample according to above grouping. In the next section the main parts of FTIR and, the technique that is used in this instrument will introduce briefly.

In the main cryostat, the part in which sample placed (Fig.1), there is very good isolation. The pressure in the lower part is down to $10^{-4}$ mbar and, with liquid nitrogen, the temperature can reach 77 K. There is a digital temperature controller that makes it easy to decide the temperature. The outputs of the instrument are some plots of intensity versus wavenumber.

\[
Wavenumber = W = \frac{1}{\lambda} \text{ cm}^{-1}
\]  

Eq.1

\[
E = \frac{hc}{\lambda} = hcW
\]  

Eq.2

It is clear in the equation Eq.2 that wavelength has a reverse proportion to the energy, but wavenumber is proportional to energy. ($h$ and $c$ are plank’s and light speed constants respectively)

2.3.1 Basic parts of FTIR:

In this section, the basic parts of FTIR and the mechanism that is used on it will introduce.

- **Light source**: This is the component from which the infrared light comes. The range of IR (NIR or MIR); also, the aperture of emitted light can be selected in this part. Aperture is related to the power of the light that will illuminate on the sample.
Fig.1 Schematic diagram of Optistat DN cryostat
**Interferometer:** The output of an interferometer is a signal that contains all frequencies of infrared light. The main parts of an interferometer are a beamsplitter and two mirrors; one mirror is fixed and the other will move (fig.2). Incoming light, after passing the beamsplitter, is divided into two beams that each will reflect off to their respective mirrors and they will recombine in the splitter when reflected from mirrors. Because the distance of one beam is constant and another one constantly changing, the different frequencies of the signal are modulated in a unique way, and the output signal from the interferometer contains all frequencies of infrared coming from the source. This signal is also called ‘interferogram’.

If the distance displacement consider as $\Delta \kappa$, from Fig.2, it is clear that the output signal of the interferometer is a function of $\Delta \kappa$. When the input signal is monochromatic with wavenumber $\delta_0$, the output signal will be like this:

$$I(\Delta \kappa) = 2I_0(1 + \cos(4\pi \Delta \kappa \delta_0))$$  \hspace{1cm} \text{Eq.3}$$

when $I_0$ is the intensity of the partial beams. If a broad-band source be used instead of monochromatic source, the output signal from the interferometer is given by:

$$I(\Delta \kappa) = 2 \int_0^{\infty} (I(\delta) + I(\delta) \cos(4\pi \Delta \kappa \delta))d\delta$$  \hspace{1cm} \text{Eq.4}$$

The second part of Eq.4 is recognized as the cosine Fourier transform of the total spectrum. Therefore, the sample that is placed in the beam path will react with each element of total spectrum and, if inverse Fourier transform be used, the photocurrent of the sample as a function of wavenumber will obtain. These calculations will be done by computer. The use of a Michelson interferometer gives a possibility to transmit all frequencies at the same time and get answer of all frequencies, as compared to a grating monochromator with narrow entrance and exit slits, which transmits only one frequency at a time [5, 8].

**Sample:** The beam will illuminate on the sample; it will transmit through it, reflect it or be absorbed by it, depending on the sample that is used and the wavelength that is selected for the experiment.

**Detector:** The beam that is transmitted through the sample reaches the detector. This detector usually has a special design for measuring the interferogram signal. (the sample is used as a detector in this project)

**Computer:** The output of detector will send to the computer for Fourier transform calculations and then plot the final spectrum.
Fig. 2 Schematic of interferometer.
3 NANOWIRES:

Nanowires (NWs) are known as one-dimensional (1-D) materials because of their length-to-width ratio are of 100 or more. Being one-dimensional makes them special with unique properties that are different from bulk or 3-D materials. This is because of electrons in NWs which, according to quantum rules, occupy some energy levels that are different with energy levels or bands in bulk or 3-D materials [7]. The applications of NWs are extending, for example, the effect of NWs can be seen on electrical, optical, thermo electrical, chemical, and bio-medical devices. According to the application, the materials of NWs will change, for example, the photodetector that is investigated in this thesis, have InP NWs and SnO$_2$ NWs are used in new generation of lithium-Ion batteries [11].

3.1 Growth of Nanowires:

There are different methods to fabricate the NWs, but all methods can be arranged into two groups, ‘‘top-down’’ or ‘‘bottom-up’’. The two known methods for top-down growing are lithography and electrophoresis, but these methods are not common nowadays for growing semiconductor NWs. With the bottom-up mechanism, better quality and also higher density of NWs on the substrate can be achieved. The two main strategies for the bottom-up mechanism are vapour-phase growth and solution based growth [4, 2].

- **Vapour Phase Growth:** As is clear from the name, the materials are in vapour phase. In this approach, there are usually some catalysts at the top of the substrate. The substrate material can be the same as, or not the same as, the materials of NWs. Some famous methods in vapour-phase mechanism are: VLS, CVD, and MOVPE. The sample that is investigated in this thesis is fabricated by the MOVPE strategy.

- **Solution based growth:** In this method, some templates are used that ordinarily are porous Alumina. Electro deposition will guide the wires inside the template. After deposition is completed, the template will be removed. This method is more common for inorganic materials.

3.1.1 Metal Organic Vapor Phase Epitaxy (MOVPE):

In the metal organic vapour phase epitaxy (MOVPE), the fundamental atoms of the growing layer come from metalorganic precursor vapours. For example, to fabricate a GaInAsP semiconductor that is a III-V combination, trimethylindium (TMI), trimethylgallium (TMG), teriarybuthylphosphine (TBP) and teriarybutylarsine (TBA) are used. A schematic of MOVPE system is shown in Fig.1 [10].
As can be seen, the system has some gas lines and one quartz glass reactor. Hydrogen will be injected through bubblers container of metalorganic precursors, and the precursor vapours are brought to the reactor by hydrogen or nitrogen carrier gas. The flow of vapours is controlled by a computer that uses a mass flow controller. As shown in Fig.1, the precursor container’s temperature is stabilized with a bath that also helps to control the pressure of the bubblers. The substrate is inside the reactor and at the top of a graphite plate that will be heated up by a halogen heater. The temperature of graphite and substrate is controlled by a thermocouple. The main processes in MOVPE growth are mass transport from the vapour phase to the substrate surface, precursor molecule decomposition and atom adsorption, atom diffusion on the substrate surface, and atom desorption from the substrate surface. Invariably, one or more of these processes makes some limitation for growth. Ordinarily, the limitation is about temperature, for example, the decomposition temperature respectively for TMI and TBP are 325ºC and 475ºC, whereas the typical temperature for InP NWs without catalyst is 350ºC. This means that all TMI molecules will decompose, but decomposition of TBP not occur at all. One solution to this problem is to add some metal nano particles catalyst that leads to growing of NWs taking place at the higher temperature.

For growing InP NWs, the diameter of gold nano particles, depends on which diameter is of interest for the NWs. In this case gold nano particles with diameters of 40nm are used and the growing temperature is increased by 100ºC. The growing rate in this method on average is around 24 nm/s and density about 7×10^8 cm^-2 if, we consider the diameter of wires of around 50nm. For this diameter and 430ºC, the average length of 2.5µm is reported. The diameter of NWs is dramatically dependent upon the growing temperature [10].

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**Fig.1 Schematic of MOVPE system**

As shown in Fig.1, the precursor container’s temperature is stabilized with a bath that also helps to control the pressure of the bubblers. The substrate is inside the reactor and at the top of a graphite plate that will be heated up by a halogen heater. The temperature of graphite and substrate is controlled by a thermocouple. The main processes in MOVPE growth are mass transport from the vapour phase to the substrate surface, precursor molecule decomposition and atom adsorption, atom diffusion on the substrate surface, and atom desorption from the substrate surface. Invariably, one or more of these processes makes some limitation for growth. Ordinarily, the limitation is about temperature, for example, the decomposition temperature respectively for TMI and TBP are 325ºC and 475ºC, whereas the typical temperature for InP NWs without catalyst is 350ºC. This means that all TMI molecules will decompose, but decomposition of TBP not occur at all. One solution to this problem is to add some metal nano particles catalyst that leads to growing of NWs taking place at the higher temperature.

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3.2 Design of the Sample:
The nanowire photodetector that is investigated in this project is a compound of III-V materials (InP). Unfortunately it is not allowed to discuss the production technology of the sample because of marketing policy but some general information about the design and characteristics are allowed.

The substrate and NWs in this sample are InP material. Ordinarily, when the substrate and wires have the same material, there is better lattice match between the wires and substrate. The detector is a p-i-n photodetector that substrate is p-type with concentration of $5 \times 10^{18}$ cm$^{-3}$ (Fig.1).

On top of the substrate, there is another p-type InP layer that will grow epitaxial and is called epi-layer. The concentration of this part is $5 \times 10^{17}$ cm$^{-3}$ and has a thickness of around 1μm. Above the epi-layer, NWs are grown. At first, one intrinsic layer with the length around 1μm is expected (In practice, it may have lower doping instead of ideal intrinsic). After that, the growth of NWs continue but with a high doping concentration of around $10^{19}$ cm$^{-3}$ and n-type. The length of NWs will reach to 3μm, with a density of 1NW/μm$^2$. In next step, all the NWs are isolated with SiO$_2$, which is a very good isolator and prevents contact between NWs or short circuit conditions (Fig.2).

Fig.1 Schematic of Nanowires

Fig.2 All nanowires will be isolated with SiO$_2$ to prevent short circuits between each other
In the next step, the SiO$_2$ on top of the NWs will be removed and the space between NWs will be filled with indium tin oxide (ITO). ITO is a good electrical conductor material. In addition, ITO is also good optic conductor. Because of these two excellent properties, ITO has so many applications in optical devices. The role of ITO in this sample is connecting the NWs to each other and is also a cover for NWs (Fig.3). The energy band diagram of the sample in the reverse bias also is shown in Fig.4.

**Fig.3 A cross-section of the sample**

The energy band diagram of the sample under reverse bias is shown in the Fig.4.

**Fig.4 Energy band diagram of the sample under reverse bias**
3.3 Experimental Setup:

Fourier transform infrared spectroscopy instrument actually includes two different parts: *spectrometer* and *cryostat*. In this section, is tried to give some general information about these two parts of FTIR that is used in Halmstad University for this project.

3.3.1 General Information of spectrometer:

The model of spectrometer that is used in Halmstad University is *Vertex 80V* that is made by the BRUKER Company in Germany. It is an evacuable, and fully digital, FTIR spectrometer that uses functions such as AAR (Automatic Accessory Recognition), ACR (Automatic Component Recognition), and Performance Guard [12]. The function AAR recognizes automatically the accessories that are installed in the sample part, performs several tests and loads automatically the corresponding experiment file, including the predefined measurement parameters. ACR will identify automatically the installed optical components, such as source detector and beamsplitter. These data will be sent to the application software, OPUS. The purpose of ACR is to enable the user to select the right optics parameters in OPUS software. In addition, all the spectrometer’s components will be monitored permanently to be sure they are operating in the specification range. This function is called Performance Guard, and its purpose is fault recognition and maintenance. Vertex 80V also needs a computer with operation system Microsoft Windows and that the spectroscopic software, OPUS, is installed on it.

There are two different positions for the light source, also there are detectors in this spectrometer that give a wide range selection of wavelengths in which to work (Fig.5). Removable vacuum-tight, provide access to the detectors and beamsplitter if they need to be changed but, pressure of inside the system must reach to room pressure. Inside the spectrometer it is possible to have a very good vacuum condition to prevent the effect of water vapour (H₂O) or carbon dioxide (CO₂) on the photocurrent answer. This vacuum condition will be provided by a vacuum pump that is oil-free to prevent introducing the oil vapour accidently inside the spectrometer.

3.3.2 General Information of Cryostat:

The model of cryostat that is installed in the FTIR in Halmstad University is *Optistat DN Cryostat*, which is made by Oxford Instrument. A schematic diagram of this cryostat is shown in Fig.1 (chapter 2 page 13). The optistat DN is a top loading, static exchange gas cryostat with optical access provided via four sets of radial, and one set of axial, windows. There is a liquid nitrogen reservoir on the upper part of the central sample tube, and it supplies liquid nitrogen by a capillary tube to a heat-exchanger. The flow of liquid takes place by gravity and it can be controlled by the exhaust valve that is placed top of the sample tube. The reservoir and sample space are thermally isolated from the room temperature surroundings by the outer vacuum chamber (OVC). This space will be pumped to a high vacuum before the cryostat cools down. The inner windows are sealed into the window block by one of two methods. The chosen method depends on the materials of the windows and the operation temperature of the cryostat. In this model that is designed to operate up to 300 K, the windows are sealed by indium wire. In the table.1 the specifications of optistat DN cryostat are shown:
Table 1:

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample space (mm)</td>
<td>20 (diameter)</td>
</tr>
<tr>
<td>Temperature range (K)</td>
<td>77-300</td>
</tr>
<tr>
<td>Temperature stability (K)</td>
<td>±0.1</td>
</tr>
<tr>
<td>Cool down from ambient (min)</td>
<td>~20</td>
</tr>
<tr>
<td>Liquid nitrogen capacity (l)</td>
<td>1.2</td>
</tr>
<tr>
<td>Hold time at 77K (hours)</td>
<td>≥15</td>
</tr>
<tr>
<td>Sample change time (min)</td>
<td>5</td>
</tr>
<tr>
<td>Cryostat weight (Kg)</td>
<td>5</td>
</tr>
<tr>
<td>Optical port</td>
<td>5 (4 radial, 1 axial)</td>
</tr>
<tr>
<td>Radial Optical Access</td>
<td>f/1</td>
</tr>
</tbody>
</table>

Fig. 5: VERTEX 80V- Optical Path
3.3.3 Preparing the System for the Experiment:

In order to use the system at low temperatures, it must be made ready so that it takes some hours, and it is better to start to prepare system the day before experiment.

In order to reactivate the sorption pump, the first step is to heat up the cryostat while pumping the system. For heating up, the voltage of intelligent temperature controller (ITC) must be set on 12V and pumping valve must be open. This process lasts a few hours (at least four hours). Next step is cooling down the cryostat, therefore pumping valve must be closed and heater must be off. Cryostat needs at least two hours to cool down completely. In this level, sample holder that sample is installed on it before, can be put inside the cryostat. Then the pumping valve must be open again and ITC must be adjust at the desired temperature (77 K in this project). Liquid nitrogen will be used to cool down the cryostat. The exhaust valve of cryostat must be open before filling liquid nitrogen in the corresponding valve. When the exhaust valve is open, the liquid nitrogen will flow by the force of gravity. Filling of the reservoir must be continued until the liquid nitrogen comes out from the other vent. In this level, the temperature starts to go down with the rate of around 20 K/min (Table1). When the temperature reached to the desired temperature, the reservoir must refill again and, exhaust valve must be fully closed and then open ¼ to ½ turn in order to reduce the flow of liquid nitrogen. In order to reach the desired temperature ITC will be used [12]. Temperature stability for this system is around ±0.1K (Table1).

Now the system is ready and by a computer that related software (OPUS) be installed on it, experiments can be done. In this project NIR is selected as a light source and CaF$_2$ as a beam splitter that has operational wavelengths ranging from ultra violet to near infrared. There was no need to the internal detectors of the instrument in this project because the sample was a photodetector. If is needed to change the sample, it is better to heat up the sample space to room temperature in order to prevent thermal shock to the sample.

For the I-V measurements, KEITHLEY 2602A source-measure instrument is used; this is made in the U.S.A and has a capability shown table 2:

<table>
<thead>
<tr>
<th>Function</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source ±DC voltage</td>
<td>1μV to 40.4V</td>
</tr>
<tr>
<td>Source ±DC Current</td>
<td>1pA to 3.03A</td>
</tr>
<tr>
<td>Measure ±DC voltage</td>
<td>1μV to 40.8V</td>
</tr>
<tr>
<td>Measure ±DC Current</td>
<td>1pA to 3.06A</td>
</tr>
</tbody>
</table>

In this part of experiment, the source-measure instrument will connect directly to the sample that is inside the cryostat. In fact, for I-V measurements, there is no need to the spectrometer, but preparing the cryostat for the experiment is the same process as photocurrent experiment. The instrument (KEITHLEY 2602A) is connected to a PC that corresponding software is installed on it. This software helps to check the I-V curves and save or load data.
4 Results:

The Fourier transform spectrometer at Halmstad University is used for the optical properties of the sample. The investigated sample is a photodetector that is based on NWs with the code #6080; this sample has been investigated in Lund University also. In this project, electrical and optical characteristics of sample are studied completely.

The sample #6080 has a schematic figure as shown at Fig.1, a plate that there are many photodiodes on it. All the subsamples (photodiodes) are fabricated at the same time, but three of them randomly are tested to establish whether they have same properties or not.

![Schematic of #6080](image)

*Fig.1 Schematic of #6080 with related pin numbers. Tested samples are marked in the picture.*

In all the results, the code of the three samples is changed to be easier to use.

Sample 1= Sample (R01 C03)
Sample 2= Sample (R01 C04)
Sample 3= Sample (R03 C02)
4.1 Photo Current of Sample:

All three samples are tested from 77 K to 300 K and for different apply biases from 0V to 1V to see the effect of temperature and applied biases on the photocurrent.

Fig. 1 (a) photo current for different temperatures and 0V apply bias.

Fig. 1 (b) Logarithmic plot for same photocurrent plot.
In (Fig.1.a) is shown the sample for 0V applied bias on the different temperatures. For 300 K one peak occurs on 1360 meV corresponding to a 911 nm wavelength while the peak for 78 K occurs on 1420 meV corresponding to a 875 nm wavelength. This difference is related to the effect of temperature on the band gap and it is normal, but there is something strange in the plot.

In the (Fig.1.a) as can be seen there are two peaks for 78 K but one peak for 300 K. There is no confident comment for two peaks for 78 K. Another sample that has no nanowire in the structure also investigated but two peaks still exist. There is a low probability comment that is not proven yet: the second peak perhaps comes from the crystal structure difference. It is true that both wire and epi-layer are InP material, but they are different in crystal structure. The crystal structure of wire is Wurtzite (a hexagonal structure) while the epi-layer is normal Zincblende (a cubic structure). It is known that the bandgap of the Wurtzite structure, 100 to 150 meV is larger than a normal cubic structure. If this comment is true, the question is still why are there two peaks in the sample without nanowires? This problem needs more research and investigation in future.

In (Fig.1.b), logarithm is used for the intensity axis just to see the bandgap difference more easily at different temperatures. In (Fig.1.c) is shown the sample at fixed temperature, but different apply biases from 0 to 1V. It is clear that photocurrent is not dependent upon the applied biases and there are approximately the same answers for all applied biases which can be an advantage for the sample.

![Fig.1 (c) Photo current at room temperature with different apply biases](image)
4.2 I-V curves of Sample:
All three samples are checked for different applied biases from -5.5 to 0.7 V at different temperatures for darkness and illumination separately. The results show some differences between the samples that can related to the fabrication process.

Fig. 2 I-V curves of sample 1
(a) In Darkness.
(b) Under Illumination
In the (Fig.2.a) the sample 1 is shown in darkness from -5.5 V reverse bias to 0.7 V forward bias. The breakdown voltage for 300 K is around -2.5V, and there is a constant dark current for reverse bias. Low and constant dark current can be considered as an excellent property for a photodetector.

In (Fig.2.b) the same sample under illumination is shown; the stability of the sample for reverse bias also is clear. We know that the diode equation is:

\[ I = I_s \left( e^{\frac{qv}{KT}} - 1 \right) \]  

Eq.1

With consider the reversed biased photodiode under illumination; the Eq.1 will be:

\[ I = I_s \left( e^{\frac{qv}{KT}} - 1 \right) - I_L \]  

Eq.2

That \( I_L \) constant is the illuminating current and it looks like a current source that is parallel with the diode. These kinds of I-V curves are also known as “solar cell curves”.

In (Fig.3.a) the sample 2 is shown for the same voltage biases. However, it is clear that there is a difference for breakdown voltage of this sample as compared to previous one (Fig.2); the breakdown voltage for 300 K is around -1.5V but, the dark current still is low and constant. In (Fig.3.b) sample 2 is tested with the same apply biases, but under illumination. The curves and breakdown voltages are similar to the darkness condition, but having lower breakdown voltage, can be considered as a defect.
Fig. 3 I-V curves of sample 2
(a) In Darkness
(b) Under Illumination
In Fig. 4 the I-V curves for sample 3 with the same apply biases is shown. As can be seen, this sample has higher breakdown voltage around -4.5V for 300 K.
In the Fig. 5 Ln(I)-V curves in darkness and under illumination condition are shown for three samples. In these curves, because the current values are logarithmic, the constant dark current and breakdown voltages are clearer.
Obviously Sample 3 has more stability in darkness and illumination for reverse bias than the two others, and this stability is more at, or near to, room temperature.

In Fig.6 the Ln(I)-V curves are shown just for forward biases at different temperatures. In practice, diodes do not behave as an ideal diode. In order to be able use an ideal diode equation (Eq.1) in real life, ideality factor ($\eta$) is added to the ideal diode equation (Eq.2). These curves help to calculate the $\eta$.

$$I_F = \exp \left( \frac{qV}{KT} \right)$$  \hspace{1cm} \text{Eq.1}$$

$$I_F = \exp \left( \frac{qV}{\eta KT} \right)$$  \hspace{1cm} \text{Eq.2}$$

The ideality factor has values like this:
• If diffusion current dominate; $\eta = 1$
• If recombination current dominate; $\eta = 2$
• When both, diffusion and recombination are comparable; $1 < \eta < 2$

Fig. 6 (a) lnI-V plots for forward biases and different temperatures, sample 1.

Fig. 6 (b) lnI-V plots for forward biases and different temperatures, sample 2.
The ideality factor can be calculated from EQ.2. Actually, some curves with more linear region was expected, but it is clear from plots that curves are linear only for low voltage biases (at room temperature is worst) and the value of \( \eta \) cannot be calculated. This behaviour can have two reasons: series resistance and high injection.

**Series Resistance:** In Eq.2, an ideal diode with zero internal resistance is considered. However, all diodes have some internal resistance and the diodes equation, by consider the resistance, will look like Eq3:

\[
I = I_s \exp \left[ \frac{q(V-IR)}{KT} \right]
\]

Eq.3

This resistance leads to IR voltage drop but, for lower voltages in which the corresponding current also is low, the IR drop can be ignored. For example, for 1\( \Omega \) resistance and 1mA, the drop is only 1mV while, for 100mA, the IR drop reaches to 100mV that it four times larger that \( kT/q \) and cannot be ignored. This can be one reason that, in Fig.6, the slope of plots decreases dramatically for higher voltages.
**High Injection:** This effect refers to the carrier concentration. If consider a high current density, the injected minority carrier density is comparable with the majority carrier density. For example, in this condition can say that on the n side of a diode, \( p_n \approx n_n \). This effect is known as *high injection*. Carrier concentration equation is:

\[
p_n n_n = n_i^2 e^{(qV/kT)}  \hspace{1cm} \text{Eq.4}
\]

If high injection effect considered:

\[
p_n(x = x_n) = n_i e^{(qV/2kT)}  \hspace{1cm} \text{Eq.5}
\]

Using Eq.5 as a boundary condition, the current will be proportional to \( \exp(qV/2kT) \). It means that the current will increase more slowly under high injection effect conditions.

In Fig.6, the behaviour of samples for 78 K and low biases is strange. There is no confident comment. It seems that the device is frozen and there is no current.

In Fig.7 I-V, curves are plotted again but both axes are in the logarithm scale. The interesting data that can be concluded from these plots are the rate of current change as compared with the voltage in the reverse bias and different temperatures.
Fig. 7 (a) Logarithm of I-V curves in darkness and illumination for 78K and 300K, sample1
Fig. 7 (b) Logarithm of I-V curves in darkness and illumination for 78K and 300K, sample2
Fig. 7 (c) Logarithm of I-V curves in darkness and illumination for 78K and 300K, sample 3.
It is better for a photodiode that current change slower with increasing voltage beyond the breakdown voltage, otherwise a small change in the voltage may destroy the device. The calculated slopes of Fig. 7 are shown in Table 3:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Slope(78K)</th>
<th>Slope(300K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>4.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Sample 2</td>
<td>5.2</td>
<td>3.44</td>
</tr>
<tr>
<td>Sample 3</td>
<td>14.7</td>
<td>15.15</td>
</tr>
</tbody>
</table>

This rate must be as low as possible. For example, the slope value of 4 means that the current will change with the power of 4 toward voltage $I = V^4$. This rate can consume as a defect for photodetector; actually, this rate is around 15 for the sample 3. As can be seen in Fig 4.a, sample 3 has higher breakdown voltage compare to the other samples but, beyond the breakdown voltage the current increases rapidly, which could be as a disadvantage.

In Fig. 8 the *Arrhenius* plots for samples 1 and 2 are shown. These plots show the effect of temperature on the samples and activation energy can be calculated from the plots. Unfortunately, the sample could not be heated up so much because the cryostat is designed for up to 320 K. However curves have linear behaviour for low voltage bias around room temperature that helps to calculate *Activation Energy* Fig. 8.
The calculated activation energy, \( E_a \) from Fig.8 for sample 1 and 2 are 0.38eV and 0.34eV respectively.
5 Conclusion

I have studied electrical and optical characteristics of InP nanowire photodetectors. The investigated chip had eleven nanowire photodiodes (samples), and all of them had the same technology in fabrication. Three of the photodiodes were chosen randomly to check the photocurrent and I-V curves.

The photocurrent measurements clearly show the onset at the bandgap energy. The shift of the bandgap energy due to different temperature is observed. The photocurrent of the diodes show that they are independent of bias voltage. The photocurrent spectrums show two peaks (more clear for low temperatures) with around 105 meV energy separation. Further studies are needed to explain the origin of the second peak.

Achieved I-V curves show that the investigated samples have behaviour as a diode. Study of darkness and illumination curves, prove that they are photodiodes. The analyse of different types of I-V curves for darkness and illumination conditions show that three selected samples that are fabricated at the same time, do not have the same behaviour, and this must be related to fabrication. Some reported experiments from Lund University show that epi-layer has not the same quality for all samples and it can be a reason for difference between I-V curves. The photodiodes have very good reverse bias answers that do not depend on bias voltage, (especially above 150 K). It means that, depletion region is independent of bias voltage, and this is a very important factor for a photo detector. They have high breakdown voltage that can be a big advantage. Also it is observed that the reverse bias conductance $\frac{dI}{dV}$, increases rapidly beyond the breakdown voltage which can be a disadvantage for the sample.
6 REFERENCES


[8] Lars Landin, Optical Studies of InAs Quantum Dots in III-V Semiconductors. Lund University, Sweden 2000


