Growth and Characterization of Polycrystalline Indium Phosphide on Silicon

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Abstract

III-V thin film solar cells attract large interest among the scientific community as a highly efficient solar energy source. High cost of the III-V materials, however, is the fundamental limitation for using these materials as a household energy source. Integrating these materials on low cost and large area Si wafer both for photovoltaic and photonics application is a field of research that draw intense attention of the scientific community. The fundamental challenge to fabricate III-V materials directly on silicon wafers arises from the disparity in polarity, large lattice and thermal mismatch between the III-V semiconductors and Si.

In this work, we introduce a method to synthesize polycrystalline InP directly on silicon wafer by using In$_2$O$_3$ or In as intermediate material. The crystal quality and conversion degree of the intermediate material and the final poly-InP were analyzed by Powder X-ray Diffraction. Depending on the type of the intermediate material and substrate orientation (Si (100) or Si (111)), the crystallite size was found to be varying from 739 to 887 nm. The surface morphology of poly-InP was studied by using Atomic Force Microscopy. The root mean square surface roughness of the InP thin film was found to be varying from 314 to 1944 nm. Structural and optical qualities of intrinsic and sulfur doped InP layers were compared at different growth conditions (growth time, growth temperature, PH$_3$ source flow), intermediate material type (In$_2$O$_3$ and In) and substrate type (Si (100) and Si (111)). Within the investigated experimental parameter range, the higher PH$_3$ source flow at longer growth time improved the structural quality of InP layer grown on In$_2$O$_3$ coated on silicon substrate,
which also result in good optical quality.

Comparison of structural and optical qualities of InP grown from In and indium oxide precoated substrates show that the former gave better quality InP. These achievements will be helpful in the realization of the high efficiency III-V solar cell on silicon substrate as a low cost option.
List of the Acronyms

InP- Indium Phosphide

PH3- Phosphine

In2O3- Indium oxide

In- Indium

In (OH)3- Indium hydroxide

InCl3- Indium trichloride

CH3COOH- Acetic acid

H2O- Water

CO2- Carbon dioxide

Si- Silicon

HCl- Hydrochloric acid

In (CH3COO)3- Indium Acetate

H2- Hydrogen

XRD- X-Ray Diffraction

AFM- Atomic Force Microscopy

PL- Photoluminescence

nm- Nanometer

a.u- Arbitrary unit

HVPE- Hydride Vapor Phase Epitaxy

sccm- Standard Cubic Centimeters per Minute

min- Minute
FWHM- Full Width at Half Maximum

TC- Texture Coefficient

°C- Centigrade

WH- William and Hall linear plot

$R_q$- Root means Square

SEM- Scanning Electron Microscopy

Transverse Optical phonon - ΓTO

Longitude Optical phonon - ΓLO
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Chapter 1

Introduction

1.1 Why Polycrystalline InP on Silicon Substrate?

III-V semiconductor solar cells have demonstrated the highest power conversion efficiencies to date [1]. Specifically, InP and GaAs have the most ideal band gaps and highest theoretical efficiencies for single-junction cells. InP solar cells have shown superior radiation resistance when compared to GaAs and silicon solar cells, which makes them ideal for space applications.

However, the cost of III-V semiconductor solar cells is too high for household or to use as a common energy source. This is mainly due to the insufficient availability of the elements that make up the III-V compound semiconductors in nature. In addition, the III-V semiconductors are very fragile and the size of the wafers is limited. On the other hand, silicon is mechanically strong, largely abundant and large wafers can be produced.

Integrating the III-V materials with silicon can give the combined advantages of large size and low-cost III-V solar cells. Therefore, this thesis mainly focuses on a method of synthesizing polycrystalline InP on Si by combining both chemical and epitaxial techniques, a generic approach to achieve low cost and high efficiency solar cells.
1.2 The Requirement of Thin Film Solar Cell

A thin film solar cell (TFSC), also called a thin film photovoltaic cell (TFPV), is a solar cell that is made by depositing one or several thin films of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers [2]. Fig 1.1 shows the global photovoltaic cumulative installation of solar cells from 2007 to 2020 [3].

![Fig 1.1 World solar photovoltaic cumulative installations (in Giga-watts)](image)

This figure clearly presents the increase in demand of thin-film solar cell from 2007 to 2020. To this end, this thesis work addresses how to achieve crystalline III-V solar cell material, InP, on cheap and large area substrate of silicon.

1.3 Selection of Epitaxial Technique

Several reports discuss different techniques to grow polycrystalline InP thin film. The earliest work about fabricating polycrystalline InP was reported in 1987[4], by the use of Liquid Encapsulated Czochralski (LEC) technique. Recently, polycrystalline InP was deposited by Metal Organic Chemical Vapor Deposition (MOCVD) [5], Pulsed
Laser Deposition (PLD) [6], Radio Frequency Sputtering (RF) [7] and Molecular Beam Epitaxy (MBE) [8].

Each deposition technique has its own merits and demerits. In this work we use a relatively simple and cheaper approach to deposit InP on Silicon. The process involves the deposition of indium oxide or In metal on silicon substrate as a starting material for the InP growth in hydride vapor phase epitaxy.

1.4 Objective and Importance of the Present Work

In this thesis we present, the deposition of high quality seed materials, In$_2$O$_3$ and In metal on silicon substrate and the growth of polycrystalline InP in hydride vapor phase epitaxy reactor. The thesis is divided into 5 chapters. We start with the presentation of the motivation for this work in chapter 1, then we present the detailed process of deposition of the In$_2$O$_3$ and In metal on silicon in chapter 2 and, subsequently, we provide description of the InP growth method as well as a brief introduction of the characterization techniques used during this study in chapter 3. In chapter 4 we discuss and summarize the results of our study, providing the conclusions and future outlook in chapter 5.
References


Chapter 2

Deposition of In$_2$O$_3$ and In on Silicon Substrate

2.1 Introduction

In this chapter, the deposition techniques of In$_2$O$_3$ and In on Si substrate will be addressed in detail. From a previous work in our group, growth of polycrystalline InP on Si was achieved employing In$_2$O$_3$ as an intermediate material, and by conversion/phosphidisation of In$_2$O$_3$ to InP using HVPE [1]. The In$_2$O$_3$ film was prepared by spin coating method. In this work we will study the growth of InP on In$_2$O$_3$ instead of conversion and on In by using HVPE.

2.2 Preparation of In$_2$O$_3$ on P-Type Silicon Substrate

2.2.1 Spin Coating Technique

Spin coating is a procedure used to achieve uniform thin films on flat substrates. An adequate amount of solution is placed on the substrate, while it is set to rotate at high speed in order to spread the fluid by centrifugal force. Rotation of the spin coater continues while the fluid spins off the edges of the substrate, until the desired thickness of the film is achieved. The applied solvent is usually volatile, so that it simultaneously evaporates during the spin coating. The higher the angular speed of spin coater, the thinner the film deposited. The thickness of the film depends also on the concentration of the solution and the solvent. The general working principle of
spin coating technique is shown in Fig 2.1 [2].

![Diagram of spin coating process](image1)

Fig 2.1 Working principle of spin coating technique [2].

It is difficult to produce a perfect thin film by spin coating due to the substrate surface roughness, defects and non-uniformities in spin coated films (Fig. 2.2) ultimately arise from neglected effects that become important in individual cases [2].

![Diagram of spin coating defects](image2)

Fig 2.2 Deviations from the ideal spin coated film. a) Streaks in the film. b) Non-uniform liquid expansion during spinning. c) Areas of the substrate remain uncoated [2].

The first type of spin coating defects is streaks presented in the final thin film, which
is probably generated by particulate matter on the substrate. The non-uniform liquid expansion during spinning is originated mainly due to imperfect substrate wetting. Areas of the substrate remain uncoated, which occurs often if the initial liquid volume is too small. In our experiment, since the In₂O₃ is used as a seed for polycrystalline InP growth, the above-mentioned effects will also affect the quality of the InP, hence careful optimization of the process is required.

2.2.2 Spin Coating solution Preparation Process

The spin coating solution for preparing the In₂O₃ films was prepared from indium chloride [1]. A solution of InCl₃.xH₂O (~0.25 M, x=3-4) in deionized water was treated with 28% ammonia solution. The obtained In (OH)₃ precipitate was rinsed multiple times with deionized water and re-dissolved in acetic acid until a clear solution was obtained. The pH value of the solution was measured to be around 2. An aqueous solution of ammonium carboxymethyl cellulose (CMC, 1%) was added as binder to the prepared In³⁺ solution by 20 vol. %. The binder solution helped increase the viscosity of the In³⁺ solution in order to uniformly coat the substrate during spin coating. A p type Si (001) substrate was cleaned and attached to OPTI SPIN SST20 spin coater with vacuum suction. ~0.2 cm³ spin coating solution was dropped on the substrate using a syringe. Spin coating was carried out at 2000 rpm for 30 s. After being air dried at 110°C for 15 min, the coated layer was heated to 400°C and kept at that temperature for 30 min in the ambient atmosphere.

The overall reaction can be written as:
[Precipitation of In(OH)$_3$]

**Equation 2.1** \[ \text{InCl}_3 + 3\text{OH}^- \rightarrow \text{In(OH)}_3 + 3\text{Cl}^- \]

[Dissolution of precipitated In(OH)$_3$]

**Equation 2.2** \[ \text{In(OH)}_3 + 3\text{CH}_3\text{COOH} \rightarrow \text{In(CH}_3\text{COO)}_3 + 3\text{H}_2\text{O} \]

[Annealing of spin coated films]

**Equation 2.3** \[ 2\text{In(CH}_3\text{COO)}_3 + 6\text{O}_2 \rightarrow \text{In}_2\text{O}_3 + 6\text{CO}_2 + 9\text{H}_2\text{O} \]

The spin coating procedure consists four cycles, and each cycle can deposit approximately 20 nanometers thick In$_2$O$_3$.

**2.3 Preparation of In on Silicon Substrate**

**2.3.1 Thermal Evaporation Technique**

Thermal evaporation is a common method of thin film deposition technique; the radiative from hot filament can evaporate the target material into metal vapor. The vacuum allows vapor to travel directly to the substrate where they condense back to a solid state, without colliding with the background gas. The evaporation type is filament evaporation. Schematic of thermal evaporator is shown in Fig 2.5 [3].
The advantages of thermal evaporation:

1) The equipment is relatively simple and cheap.

2) The target (source material) could be made to different shape depending on the requirement.

The disadvantages of thermal evaporation:

1) High electricity consumption.

2) The speed of deposition is very slow.

3) Compound target may get decomposed at high temperature. In which case only part of the compound reaches the substrates.

4) The hardness of the film is not good. The density is poor.

2.3.2 Preparation Process of In on Silicon Substrate

A p-type Si substrate was cleaned and attached on sample holder of Indira thermal
evaporator, and then the temperature of the resistor dramatically increased. The indium was heated to indium vapor. Due to the difference in temperature between substrate and indium vapor, the indium can turn back into the solid state when it reaches the silicon surface. In our experiment the deposition time was 25 seconds for all the samples. The specification of thermal evaporator in our lab is given in table 2.2.

<table>
<thead>
<tr>
<th>Experimental conditions of the thermal evaporator in electrum lab.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporation of thick layers of indium</td>
</tr>
<tr>
<td>Wafer holders</td>
</tr>
<tr>
<td>Uniformity</td>
</tr>
<tr>
<td>Substrate temperature</td>
</tr>
</tbody>
</table>
References


http://www.icmm.csic.es/fis/english/evaporacion_resistencia.html
3.1 Polycrystalline InP Growth from In$_2$O$_3$ and In Thin Film

3.1.1 HVPE Growth Technique

Hydride Vapor Phase Epitaxy (HVPE) is an epitaxial growth technique often employed to produce III-V semiconductors such as GaN, GaAs, InP and their related compounds. Carrier gases commonly used include, hydrogen and nitrogen. The fabrication of InP by this technique uses PH$_3$ as V-species precursor and InCl$_3$ as III-species precursor. The chemical reaction for depositing e.g. InP is described by

**Equation 3.1** \[ \text{InCl}_3 + \text{PH}_3 \rightarrow \text{InP} + 3\text{HCl} \]

The working principle of HVPE at KTH is shown in Fig 3.1.

InCl$_3$ is formed by flowing HCl through the molten In metal. Then the InCl$_3$ will react with PH$_3$ source on substrate surface. In our case, the substrate is silicon precoated with In metal or In$_2$O$_3$. The InP will grow from the In$_2$O$_3$ or In surface. The fabrication of polycrystalline InP on In$_2$O$_3$ film is given by:
Equation 3.2 \[ \text{In}_2\text{O}_3 + \text{InCl}_3 + 3\text{PH}_3 \rightarrow 3\text{InP} + 3\text{H}_2\text{O} + 3\text{HCl} \]

Whereas the growth of InP on the In pre-coated silicon substrate is given by the following chemical equation,

Equation 3.3 \[ 2\text{In} + \text{InCl}_3 + 2\text{PH}_3 \rightarrow 2\text{InP} + \text{H}_2 + 3\text{HCl} \]

Fig 3.2 summarizes the process flow.

Fig 3.2 Schematic cross-section of the deposited layers.

The polycrystalline InP was grown at different growth conditions i.e, growth time, PH3 source flow, substrate type, and PH3 stabilization. Detailed growth parameters and sample descriptions are given in Table 3.1.
Table 3.1 Summary of samples and growth conditions.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Seed type</th>
<th>Growth time (min)</th>
<th>PH$_3$ source flow (sccm)</th>
<th>PH$_3$ stabilization</th>
<th>Substrate type</th>
<th>Growth temperature (°C)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>In$_2$O$_3$</td>
<td>5</td>
<td>120</td>
<td>0</td>
<td>Si(001)</td>
<td>530</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>In$_2$O$_3$</td>
<td>20</td>
<td>120</td>
<td>0</td>
<td>Si(001)</td>
<td>530</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>In$_2$O$_3$</td>
<td>5</td>
<td>60</td>
<td>0</td>
<td>Si(001)</td>
<td>530</td>
<td>Filtering InCl$_3$ solution</td>
</tr>
<tr>
<td>D</td>
<td>In$_2$O$_3$</td>
<td>5</td>
<td>60</td>
<td>0</td>
<td>Si(001)</td>
<td>530</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>In$_2$O$_3$</td>
<td>5</td>
<td>120</td>
<td>0</td>
<td>Si(001)</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>In</td>
<td>5</td>
<td>120</td>
<td>10</td>
<td>Si(001)</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>In</td>
<td>5</td>
<td>120</td>
<td>50</td>
<td>Si(001)</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>In</td>
<td>5</td>
<td>120</td>
<td>50</td>
<td>Si(111)</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>In</td>
<td>15</td>
<td>120</td>
<td>10</td>
<td>Si(001)</td>
<td>550</td>
<td>Sulfur doping</td>
</tr>
<tr>
<td>J</td>
<td>In</td>
<td>15</td>
<td>120</td>
<td>10</td>
<td>Si(111)</td>
<td>550</td>
<td>Sulfur doping</td>
</tr>
<tr>
<td>K</td>
<td>In</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Si (001)</td>
<td>0</td>
<td>In thin film</td>
</tr>
<tr>
<td>L</td>
<td>In</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Si (111)</td>
<td>0</td>
<td>In thin film</td>
</tr>
<tr>
<td>M</td>
<td>In$_2$O$_3$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Si (001)</td>
<td>0</td>
<td>In$_2$O$_3$ thin film</td>
</tr>
</tbody>
</table>

After each step, i.e. after depositing In and In$_2$O$_3$ and after conversion to InP, all samples were characterized by Atomic Force Microscopy (AFM), Photoluminescence (PL), Raman spectroscopy, Scanning Electron Microscopy (SEM) and High Resolution Powder X-ray Diffraction (XRD).

### 3.1.2 Structural Properties of Polycrystalline Material

Polycrystalline materials are solids that are composed of many crystallites of varying size and orientation. The variation of crystallite orientation can be random (called random texture) or directed, possibly due to growth and processing conditions. Fig 3.3
shows a polycrystalline material grain structure [1].

Fig 3.3 Grain structure related with crystal orientation [1].

The figure clearly shows that each grain has only one kind of orientation of the crystallites. The formation of grain structure can be understood as the grain is grown from a single nucleus with random crystal orientation.

The line segment in Fig 3.3 shows the schematic of a grain boundary. Normally there are two kinds of grain boundaries, tilt and twist grain boundaries, as shown in Fig 3.4.

Fig 3.4 Schematic of grain boundaries a) tilt boundary b) twist boundary.

These two kinds of grain boundary will often prevent the defect diffusion between neighbor grains. Another important factor that affects the surface roughness is
different growth rate in each crystal orientation. The growth rate of InP at each crystal orientation was discussed in previous work [2]. Fig 3.5 shows the growth rate for each crystal orientation at different growth temperature.

![Fig 3.5 Rapid epitaxial growth of conducting and insulating III-V compounds on (001), (110), (111)A, (311)A and (311)B surfaces by HVPE [2].](image)

The surface morphology can depend on growth temperature, since the growth rate of each orientation are different.

### 3.1.3 Optical Properties InP

InP has wide applications in semiconductor device due to its direct band gap. The band gap is called “direct” if the momentum vector of electrons and holes is the same both at the edges of conduction and valence band; a recombination process between electron and hole can directly emit a photon. In an “indirect” gap the momentum vectors at the edges of conduction and valence band are shifted, a photon cannot be emitted without the assistance of a phonon from a crystal lattice. The high efficiency of photon emission from direct band gap material makes it more suitable for
fabricating semiconductor devices. The schematics of the recombination process are shown in Fig 3.6.

![Schematic of the valence band, direct bandgap and indirect bandgap conduction bands.](image)

The curves I, II, and III in the valence band are called heavy hole, light hole, and split-off hole states, respectively [3].

### 3.2 Characterization Methods

#### 3.2.1 Powder X-ray Diffraction

When an X-ray is shined on a crystal, it diffracts in a characteristic pattern. In powder X-ray diffraction, the diffraction pattern is obtained from polycrystalline material rather than from a single crystal. Powder X-ray gives information about the position, intensity, and width, and shape of diffraction peaks, for different crystal orientations. The working principle is shown in Fig 3.7 [4].
The powder XRD can provide information about the deposited InP like:

1) **Crystallinity**

Powder XRD can be used to determine the crystallinity by comparing the integrated intensity of the background pattern to that of the sharp peaks. The intensity of powder XRD can be expressed by [5],

\[
I_{\text{powder}}(q) = \sum_{i=1}^{N} \sum_{j=1}^{N} f_i(q) f_j(q) \frac{\sin(qr_{ij})}{qr_{ij}}
\]

**Equation 3.4**

Where the magnitude of the scattering vector \( q \) is in reciprocal lattice distance units, \( N \) is the number of atoms, \( f_i(q) \) is the atomic scattering factor for atom \( i \) and scattering vector \( q \), while \( r_{ij} \) is the distance between atom \( i \) and atom \( j \). One can also use this to predict the effect of crystallite shape on detected diffraction peaks, even if in some directions the cluster is only one atom thick.

The degree of crystallinity can be estimated by FWHM of each crystallite peak [6],
The crystallite size calculation is according to Debye–Scherrer equation.

**Equation 3.5**  \[ \beta = \frac{0.9 \lambda}{FWHM \cos \theta} \]

Where \( \lambda \) is the x-ray wavelength, FWHM is the line width and \( \theta \) is the Bragg angle.

The \( \beta \) values can be obtained for each crystalline orientation.

2) **Grain Orientation**

Fig 3.8 [7] shows how different grain orientation related with different XRD peak position.

![Fig 3.8 Grain orientation correspond to XRD peak position [7].](image)

For every set of planes, there will be a small percentage of crystallites that are properly oriented to diffract (the plane perpendicularly bisects the incident and diffracted beams). Basic assumptions of powder diffraction are that, for every set of planes, there are an equal number of crystallites that will diffract and that there are a statistically relevant number of crystallites, not just one or two [7].

3) **Micro-Strain Calculation**

Generally speaking, micro-strains correspond to atom displacements with respect to their position in crystals which are free of any defects. In 1953, Williamson and Hall
[4] suggested a simple method for solving the XRD broadening due to crystallite size and micro-strain in polycrystalline materials/powders. It was found that both the size of the crystals and the presence of crystallographic distortions lead to Lorentzian diffraction intensity distributions. The estimation of micro-strain and effective crystallite size is given by.

\[
\frac{\beta \cos \theta}{\lambda} = \frac{1}{L} + \eta \frac{\sin \theta}{\lambda}
\]

Equation 3.6
Where \( \beta \) total broadening of each peak in XRD spectrum, \( L \) is the effective crystallite size, \( \theta \) is Bragg angle, \( \lambda \) is the incident X-ray wavelength and \( \eta \) is micro-strain. If we plot \( (\beta \cos \theta)/\lambda \) according to \( (\sin \theta)/\lambda \), we get a straight line with a \( y \) intercept equal to the inverse of the size and a slope equal to the value of the micro-strain. This plot is known as the Williamson-Hall plot.

4) Texture Coefficient

The texture coefficient (TC) represents the texture of a particular plane, whose deviation from unity implies the preferred growth. Quantitative information concerning the preferential crystallite orientation can be obtained by using the following relation [8].

\[
TC(hkl) = \frac{I(hkl)}{I_0(hkl)} \frac{1}{n} \sum^n_{n=1} \frac{I(hkl)}{I_0(hkl)}
\]

Equation 3.7
Where \( I(hkl) \) is the measured relative intensity of a plane \( (hkl) \), \( I_0(hkl) \) is the standard intensity of the plane \( (hkl) \) taken from the joint committee of powered diffraction standards (JCPDS) data and \( n \) is the number of reflections. The value \( TC(hkl) = 1 \)
represents films with randomly oriented crystallites, while higher values indicate the abundance of grains oriented in a given \((hkl)\) direction. The preferred orientation of each film, as a whole, was analyzed from the standard deviation \(\sigma\) of all \(TC(hkl)\) values as compared with randomly oriented samples as [8].

\[
\text{Equation 3.8} \quad \sigma = \sqrt{\frac{1}{n} \sum (TC(hkl) - 1)^2}
\]

\(\sigma\) values are used to compare the degree of orientation between different samples, so that lower \(\sigma\) values indicate more randomly oriented samples.

The Powder XRD was used in our experiment to analyze the structural quality of both the \(\text{In}_2\text{O}_3\) and InP films. With it we estimated the effective grain size and strain in the films.

**3.2.2 Atomic Force Microscopy**

AFM consists of a cantilever with a sharp tip (probe) at its end, which is used to scan the specimen surface. The cantilever is typically silicon or silicon nitride with a tip radius of curvature on the order of nanometers. When the tip is brought into proximity of a sample surface, forces between the tip and the sample lead to a deflection of the cantilever according to Hooke's law. Depending on the situation, forces that are measured in AFM include mechanical contact force, Van Der Waals Forces, Capillary Forces, Chemical Bonding, Electrostatic Forces, Magnetic Forces, Casimir Forces and Solvation Forces, etc. Along with these force, additional quantities may simultaneously be measured through the use of specialized types of probe [9]. Fig 3.9 shows the structure and general working principle of Atomic Force
3.2.3 Raman Spectroscopy

Raman spectroscopy is a spectroscopic technique used to observe vibrational, rotational, and other low-frequency modes in a system [11]. It relies on inelastic scattering, or Raman scattering, of monochromatic light, usually from a laser in the visible, near infrared, or near ultraviolet ranges. The laser light interacts with molecular vibrations, phonons or other excitations in the system, resulting in the energy of the laser photons being shifted up or down. The shift in energy gives information about the vibrational modes in the system. Infrared spectroscopy yields similar, but complementary, information. The Raman transition process is shown in Fig 3.10
Based on this working principle the Raman Spectroscopy can determine the quality of samples such as:

a) The material purity of the sample, by analysis the Raman peak position in spectrum.

b) The bandwidth related to the disorder lattice motion can be expressed by Equation 3.8[11].

\[
\Delta \omega = \left( \frac{1}{\lambda_0} - \frac{1}{\lambda_1} \right)
\]

Equation 3.9

Where \( \Delta \omega \) is the Raman shift expressed in wave number, \( \lambda_0 \) is the excitation wavelength, and \( \lambda_1 \) is the Raman wavelength.

**3.2.4 Photoluminescence**

PL (photoluminescence) is a process in which a substance absorbs photons and then
re-radiates photons. Quantum mechanically, this can be described as an excitation of electron to a higher energy state and then a return to a lower energy state accompanied by the emission of a photon. This is one of many forms of luminescence (light emission) and is distinguished by photo-excitation (excitation by photons). In our experiment case we use $\lambda=514$ nm as excitation source. The energy of this laser is 2.24eV, much higher than InP band gap 1.34 eV. The intensity of PL and line width of PL spectrum gives information about the optical quality of InP deposited.

3.2.5 Scanning Electron Microscopy

The Scanning electron microscopy (SEM) produces images by generating a beam of high-energy electrons to interact with the electrons in sample. Once the beam hits the sample, secondary electrons, Auger electron, backscattering electron and X-rays are ejected from the sample [12]. The detectors collect these electrons and convert them into a signal that is sent to a screen similar to a television screen, which produces the final image. The working principle of SEM is shown in Fig 3.11 [12].
Fig 3.11 Schematic of Scanning Electron Microscopy [12].
References


Chapter 4

Characterization Result and Discussion

4.1 Introduction

In this chapter the result of different characterization (i.e, PL, AFM, XRD, Raman Spectroscopy and SEM) of InP growth on both In$_2$O$_3$ and In metal will be discussed. The different growth conditions and their effects on surface morphology, structural quality, and optical quality will be addressed in detail. Our aim is to find a proper way to synthesize homogenous polycrystalline InP with high crystal quality and high optical quality.

4.2 Characterization of InP Grown on In$_2$O$_3$ Pre-coated Silicon Substrate

4.2.1 XRD Studies

In this section we present the powder XRD results from InP grown on sample A, B, C, E and M. The effect of different PH$_3$ flow on the resulting InP is explained by studying the XRD spectrum taken from sample M with PH$_3$ flow =0 standard cubic centimeter per minutes (sccm) (i.e., indium oxide film before growth of InP), and sample A and C from the InP film grown with PH$_3$ flow of 120 and 60 sccm, respectively. Fig 4.1 shows the X-ray diffraction pattern taken from these samples, with the mentioned experimental conditions.
Both samples A and C show multiple XRD diffraction peaks indicating the grown InP is polycrystalline. InP crystal planes (111), (200), (220), (311) and (222) were observed at 2θ = 26.28, 30.43, 43.60, 51.61 and 54.08, respectively, which are in a good agreement with standard InP JCPD data [00-032-0452]. However, we can still see that the indium oxide peaks (321), (431), (611) were also observed at 2θ = 33.1, 47.8, 56.4, respectively. Comparing the spectrum from sample A and C, when the PH₃ flow increases, the intensity of the InP diffraction peaks increases and that of the In₂O₃ peak values decreases. All of these results show that a higher PH₃ flow can enhance the In₂O₃ conversion to InP as well as the quality of poly-InP obtained. 

In Table 4.1 the analysis of grain distribution on the sample surface is illustrated by the texture coefficient of samples C and A, based on the assumption that each diffraction peak represents a different kind of grain.
Table 4.1 Texture coefficient of sample A and sample C which were grown at 60 and 120 sccm PH$_3$ source flow, respectively but with the same other growth conditions.

<table>
<thead>
<tr>
<th>Crystallites orientation</th>
<th>Texture coefficient</th>
<th>Sample A</th>
<th>Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP(111)</td>
<td>1.11</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>InP(200)</td>
<td>0.62</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>InP(220)</td>
<td>0.86</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>InP(311)</td>
<td>0.97</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>InP(222)</td>
<td>1.44</td>
<td>1.67</td>
<td></td>
</tr>
</tbody>
</table>

On a randomly oriented sample, all the texture coefficients must be equal to 1 for the five kinds of grain [1], and for the grain with the highest texture coefficient the layer will be preferentially orientated to the same crystallites orientation. As observed the InP (222) appears to be the favorite grain orientation on both samples. Furthermore, when comparing the layers, the sample which was grown at lower PH$_3$ source flow (sample C) demonstrates a tendency of grain growth towards (222) orientation.

By following the Equation 3.8, we can determine the degree of randomness or extent of texturing. The degree of randomness (equation 3.8) as measured by the texture coefficient was found to be 0.35 and 0.27, for sample C and A, respectively, indicating sample A is composed of relatively randomly oriented grains. Another important aspect for polycrystalline material is the size of crystallites. The size of crystallites was calculated from the XRD measurement by using Debye–Scherrer formula, equation 3.5.
As shown in the table, there is no difference in crystallites size of the InP (111) between two samples. However, a close look at the crystallite size calculated from each diffraction peak, the higher degree of crystallinity of InP(222) (the same crystalline phase as InP(111) was formed at lower PH$_3$ source flow, note this observation is in agreement with preferential grain growth trend obtained from analyzing the texture coefficient, i.e., the InP(222) continues to form bigger grains at lower PH$_3$ source flow.

Micro-strains correspond to atom displacements with respect to their position in crystals which are free of any defects [2] and its calculation can indicate the degree of imperfections in material. Usually, the imperfection can be represented as line defects, stacking faults and vacancies. Fig 4.2 shows the PH$_3$ source flow effect on effective strain which is calculated from Williamson and Hall linear plot [2].
Fig 4.2 WH linear plot of sample A and sample C which were grown at 120 and 60 sccm PH₃ source flow, respectively but with the same other growth conditions. The points indicate the data points while the line is the linear interpolation of these points.

The slope of the line gives the effective strain (in percentage unit), and was found to be 0.65% for sample A and 0.39% on sample C, thus a low level of strain in both samples but larger strain in InP of sample A.

To summarize, the effect of PH₃ source flow on growth of InP, it was shown that a higher PH₃ source flow can enhance the conversion process of In₂O₃ to InP. However, at higher PH₃ source flow, random grain growth and higher residual strain in the resulting InP film were observed. Therefore, further experiments by changing other growth parameters should be performed in order to improve the quality of InP layer grown at high PH₃ source flow.

To verify this, we conducted different experiments at different growth time and growth temperature but with the same PH₃ source flow (120 sccm). Fig 4.3 shows the XRD pattern from InP grown on In₂O₃ pre-coated silicon substrate of sample E and sample A at different growth temperatures.
Fig 4.3 XRD spectrum of InP grown on sample E and A at 610°C and 530°C, respectively but with the same other growth conditions.

The XRD spectrum from sample E clearly shows that a temperature of 610°C gives fewer InP diffraction peaks with reduced intensity. Whereas the diffraction peaks from Indium oxide grains seem to be unaffected. The observation can be attributed to the reduction of the nucleation site at high substrate temperature due to the increased tendency of clustering of the droplets of In$_2$O$_3$, resulting in only preferential nucleations to be formed on the In$_2$O$_3$ thin film, which leads to a reduced crystallite density.

To investigate the effect of growth time, Sample A and B were grown at the same growth condition but different growth time. The growth time for sample A is 5 minutes while that for sample B is 20 minutes. Fig 4.4 shows the powder XRD diffraction patterns of sample A and sample B.
As can be seen from Fig. 4.4, the longer growth time resulted in decrease in the intensity of In$_2$O$_3$ diffraction peaks and increase of the InP diffraction peak intensities. This observation leads us to the conclusion that conversion degree is strongly related with growth time. Longer growth times can result in larger amount of In$_2$O$_3$ converted to InP. Note that we assume the Indium oxide is converted to InP from In$_2$O$_3$ by PH$_3$ before and during the growth of InP from InCl$_3$ and PH$_3$.

Table 4.3 shows the texture coefficient of sample A and sample B for each diffraction peak.
Table 4.3 Texture coefficient of sample A and sample B which were grown at 5 and 20 minutes, respectively but with the same other growth conditions mentioned in table 3.1.

For both samples, grains with (222) diffraction peak are favored. The degree of randomness of the grains grown on these two samples as measured by texture coefficient is 0.27 and 0.31 for sample A and sample B respectively. It indicates that the grains grown on sample A for short time are more random compared to the grains on sample B. The crystallite size from each diffraction peak is calculated in the same way as we discussed previously and presented in table 4.4.

Table 4.4 Average crystallites size of sample A and sample B grown for 5 and 20 minutes, respectively but with the same other growth conditions.

The crystallite size calculated from the strongest diffraction peak, InP (111) is same for the two samples.

The residual strain in the samples is determined by Williamson and Hall method using
linear interpolation of the data points as mentioned previously (Fig 4.5).

![Fig 4.5 WH linear plot of sample A and sample B grown for 5 and 20 minutes respectively but with the same other growth conditions. The points indicate the data points while the line is the linear interpolation of these points.](image)

The strain value for sample A was found to be 0.65% and for sample B is 0.45%. The longer growth time results in a reduction of the residual strain in sample B. This may be due to the simultaneous annealing that takes place during growth, i.e., longer annealing time for longer growth time.

### 4.2.2 Surface Morphology

Samples A, B, C and M were characterized by AFM and the root mean square surface roughness was extracted. Sample M, the In$_2$O$_3$ film was characterized prior to growth and Fig 4.6 depicts the AFM image of this film before growth of InP.
Fig 4.6 AFM 10×10 µm² surface graph of sample M (0 sccm PH₃ source flow).

The average surface roughness (Rₐ) was 3.71 nm. The AFM image shown in figure 4.6 is a representative and homogeneous layer of indium oxide that was achieved over a large area by spin coating. The effect of different growth parameters on the surface morphology of the resulting InP film is investigated. Fig 4.7 depicts the AFM images of sample A and B grown under 120 and 60 sccm of PH₃ source flows.

Fig 4.7 AFM 20×20 µm² surface image of InP grown on sample A and C at the different PH₃ source flow sample A (120sccm) (left) sample C (60 sccm) (right), with the same other growth conditions.

The surface roughness was 463 nm and 1944 nm for sample A and sample C,
respectively, which indicates that higher PH$_3$ source flow will result in less surface roughness and thus a better surface morphology. Lower PH$_3$ source flow will cause island structures.

As discussed before the increase of growth time results in uniform grain distribution, which is also supported by the AFM image as shown in Fig 4.8

Fig 4.8 depicts the AFM images of samples A and B grown for different time.

![AFM images of samples A and B](image)

Fig 4.8 AFM 20×20 µm$^2$ surface graph of the different growth time sample A (5 min) (left) sample B (20 min) (right), with the same other growth conditions.

The surface roughness is 463 nm for sample A and 442 nm for sample B. This result shows that longer growth time can result in slightly better surface morphology. The longer growth time creates more possibility for adatoms to diffuse and migrates into stable site. The reconstruction of the surface reduces surface roughness.

### 4.2.3 Raman Studies

Samples A, B, and C were characterized by Raman spectroscopy to analyze material purity and lattice vibration in grains. Fig 4.9 shows the Raman spectrum for samples
grown with different PH$_3$ source flows.

Fig 4.9 Raman spectrum of sample A and C which were grown at 60 and 120 sccm PH$_3$ source flow, respectively but with the same other growth conditions.

The first order anti-Stokes Transverse Optical phonon ($\Gamma$TO) and Longitude Optical phonon ($\Gamma$LO) peaks of InP were observed at ~308 cm$^{-1}$ and ~350 cm$^{-1}$, respectively, demonstrating a blue shift as compared to what was reported in the literature for a single-crystalline InP ($\Gamma$TO at 304cm$^{-1}$ and $\Gamma$LO at 345cm$^{-1}$ ) [4]. The Raman spectra of samples A and B are shown in Fig 4.10.

Fig 4.10 Raman spectrum of sample A and sample B grown for 5 and 20 minutes, respectively but with the same other growth conditions.
As observed from Fig 4.10, the first order anti-stokes $\Gamma$TO and $\Gamma$LO position for sample B are located at $305\text{cm}^{-1}$ and $345\text{cm}^{-1}$ respectively indicating that the poly InP on sample B, grown for longer time is less strained. Note that this observation from Raman studies is in agreement with the observations from our XRD studies in the previous sections.

### 4.2.4 Micro-Photoluminescence Studies

In this section, the photoluminescence measurement results of samples A, B, and C are discussed. The optical characteristics are related with peak position and peak intensity of the PL spectrum. The higher carrier density and smoother surface of the sample can contribute to a stronger PL intensity. The residual strain in sample is responsible for the PL peak position shift [5]. The reduced (increased) material bandgap can decrease (increase) the direct recombination energy, resulting in peak position shift in the PL spectrum. Fig 4.11 shows the PL spectrum taken from the two samples, sample A and C which were grown with different PH$_3$ source flow.

![PL spectrum](image)

**Fig 4.11** PL spectrum of sample C and A which were grown at 60 and 120 sccm PH$_3$ source flow, respectively but with the same other growth conditions.
Sample C, grown with PH$_3$ source flow of 60 sccm gives poor luminescence, which may be explained by the high surface roughness that is responsible for enhancing scattering process.

The effect of growth time on optical property was studied by PL of two samples, sample A and B grown for 5 and 20 minutes respectively (Fig 4.12)

![Fig 4.12 PL spectrum of sample B and sample A grown for 20 and 5 minutes, respectively but with the same other growth conditions.](image)

As can be seen from Fig 4.12, sample B gives higher luminescence intensity. During longer growth time, the simultaneous annealing process leads to a material with better optical and morphological quality by reducing the strain and hence enhanced PL intensity.
4.3 Characterization of InP Grown on In Pre-coated Silicon Substrate

4.3.1 XRD Studies

In the previous section we showed that by using an indium oxide precoated Si substrate, good quality polycrystalline InP was achieved by optimizing the growth conditions, however, we still see from the XRD studies that indium oxide is not completely consumed.

With the desire to synthesize high quality InP, the replacement of intermediate material might be an option. We investigate the possibility of using In metal deposited on Si as a seed layer for InP growth in HVPE. In this experiment we have studied the effect of substrate orientation (Si (001) and Si (111)) on In film and InP grown from the In film. Similar to what we have done in the study of InP growth on indium oxide we have studied the effect of different growth conditions on the InP grown on In pre-coated Si. Samples F, G, H, I, J and K (as referenced in Table 3.1) were characterized by powder XRD for composition, crystallite size and distribution.

The XRD curves of samples H and G is shown in Fig 4.13. Both samples were grown at same temperature (610°C) and time (5 min). The difference is that the substrates of Si (100) and Si (111) were used for samples G and H respectively.
As can be seen from Fig 4.13, the InP on Si (111), sample H shows no In$_2$O$_3$ peaks as InP on Si(001), in sample G. Similar to what we have seen in the case of InP grown from In$_2$O$_3$ in section 4.1, polycrystalline InP with (111), (200), (220), (311), (222) crystal planes appeared at 2$\theta$ = 26.28, 30.43, 43.60, 51.62 and 54.09. We can also see that there are In and In$_2$O$_3$ diffraction peaks. While the In could be left over from the conversion/phosphidation during growth, the presence of In$_2$O$_3$ in the final InP film on Si (001) is somewhat unclear at this stage. However one possible reason could be the oxidation of Indium during the deposition of indium metal which later left unconverted to InP during growth. However, we didn’t make such an observation on Si (111) substrate which is the subject of current investigation.

Fig 4.14 compares the XRD mappings of the In thin film on Si (001) substrate with the final InP grown on same.
Fig 4.14 XRD mappings of the In film (sample K) and the Grown InP (sample G) on Si (001) substrate.

Fig 4.15 shows the XRD curves of the In thin film on Si (111) substrate compared with the grown polycrystalline InP.

Fig 4.15 XRD mappings of the In film (sample L) and the grown InP (sample H) on Si (111) substrate.

As observed from Fig 4.15 In$_2$O$_3$ diffraction peak is not seen on sample L and H, and all the In(101) was converted to InP, (all the In is consumed to form InP). We have calculated the texture coefficient of each film to compare the degree of randomness in grain distribution.

Table 4.5 represents the effect of substrate orientation, (Si (100) sample G and Si (111)
sample H) on texture coefficient.

<table>
<thead>
<tr>
<th>Crystallites orientation</th>
<th>Texture coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample G</td>
</tr>
<tr>
<td>InP(111)</td>
<td>1.20</td>
</tr>
<tr>
<td>InP(200)</td>
<td>0.68</td>
</tr>
<tr>
<td>InP(220)</td>
<td>0.89</td>
</tr>
<tr>
<td>InP(311)</td>
<td>1.13</td>
</tr>
<tr>
<td>InP(222)</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Table 4.5 Texture coefficient of sample G and H grown on Si (001) and Si (111) substrate, respectively but with the same other growth conditions mentioned in table 3.1.

The results indicate that InP (111) grains are the favored grain type in both samples. The degree of randomness as measured by the texture coefficients of the samples is 0.19 and 0.41 for InP on Si (001) substrate and InP on Si (111) substrate respectively indicating more random grains of InP grown on Si (001) substrate. We have calculated the average crystallite size for each samples and Table 4.6 lists the effect of substrate orientation on grain size.

<table>
<thead>
<tr>
<th>Crystallites orientation</th>
<th>Average crystallite grain size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample H</td>
</tr>
<tr>
<td>InP(111)</td>
<td>739</td>
</tr>
<tr>
<td>InP(200)</td>
<td>710</td>
</tr>
<tr>
<td>InP(220)</td>
<td>1373</td>
</tr>
<tr>
<td>InP(311)</td>
<td>1425</td>
</tr>
<tr>
<td>InP(222)</td>
<td>1358</td>
</tr>
</tbody>
</table>

Table 4.6 Average crystallite size of InP grains of sample H and sample G grown on Si (111) and Si (001) substrate, respectively but with the same other growth conditions mentioned in table 3.1.
The results show that InP (111) grain on Si (111) substrate has smaller average crystallites size.

We calculated the residual strain in the InP layer grown on both substrates by using Williamson and Hall method as shown in previous section. Fig 4.16 depicts the W. H linear plot for these two samples.

Fig 4.16 WH linear of sample H and sample G grown on Si (111) and Si (001) substrate, respectively but with the same other growth conditions. The points are data points while the line is the linear interpolation of these points.

The strain values are 0.62% for sample G and 0.41% for sample H indicating that the InP grown on Si (100) is more strained.

### 4.3.2 Surface Morphology

In this section we present the results of the AFM characterization of samples G, H, I, J, K and L. The In metal on Si substrates was characterized by AFM for surface morphology prior to growth of poly-InP. Fig 4.17 depicts the AFM images of the In film on Si (111) (sample L) and on Si (100) (sample K).
Fig 4.17 AFM 10×10 µm² surface graph of intermediate material on different substrate type sample L (Si (001)) (left) sample K (Si (111)) (right).

The surface roughness values are 17.4 nm and 25.6 nm for sample L and sample K, respectively. The process of deposition of In is the same for on both substrates and the observed morphology difference is most likely due to the surface structure of the substrates.

The effect of different substrate orientation on the surface morphology of the grown InP film is investigated.

The InP grown on In pre coated substrates were characterized by AFM. Fig 4.18 shows the surface morphology of polycrystalline InP grown on Si (100) sample G (left) and Si (111) sample H (right).
Fig 4.18 AFM 20×20 µm² surface image of InP grown on different sample G (Si (001) (left) and sample H (Si (111) (right); all growth conditions are the same.

The surface roughnesses evaluated by AFM are 392 nm and 314 nm for sample G and sample H, respectively. As discussed previously with texture coefficient results, highly textured InP (111) grain was formed on Si (111) substrate. A homogenous grain distribution can create a uniformed sample surface, thus, better surface morphology can be obtained.

4.3.3 Raman Studies

The polycrystalline InP grown on In pre-coated Silicon, showed better surface morphology with homogenous grain size and distribution and higher degree of crystallinity. In this section, we present the Raman spectroscopy results of sample G, H, I and J. The Raman spectra recorded from sample H and G are shown in Figure 4.19
As can be seen from Fig 4.22, the anti-stokes $\Gamma_{TO}$ and $\Gamma_{LO}$ are found at 304\,cm$^{-1}$ and 345\,cm$^{-1}$. No red nor blue shift is observed with respect to that reported in the literature for a single-crystalline InP ($\Gamma_{TO}$ at 304\,cm$^{-1}$ and $\Gamma_{LO}$ at 345\,cm$^{-1}$) [4], which indicates a strain free material. The narrow and high intensity peaks for both samples demonstrate ordered lattice vibration. A good crystal quality is observed.

4.3.4 Micro-Photoluminescence Studies

The effect of substrate on the optical quality of the grown InP layer was studied by PL characterization of sample G (Si (001)) and H (Si (111)). Both samples were grown in the same growth run (Fig. 4.20).
Fig 4.20 PL spectrum of InP on sample H and G grown on Si (111) and Si (001) substrate, respectively with the same other growth conditions. It can be noted that no noticeable difference in optical quality is observed from the PL spectra except slight reduction of PL intensity for sample G. The FWHM was 28.17 nm and 27.57 nm for sample G and sample H, respectively. As discussed in the previous section, the InP grown on Si (111), sample H, is homogeneous in grain size and distribution. This is may be responsible for the slightly higher PL intensity.

We have investigated the possibility to dope the polycrystalline InP by sulfur (n-type dopant). Alternating layers of sulfur doped InP doped with sulfur and un-doped (with doped layer at the tope) was grown on sample I and sample J and without doping on sample G and H. Note that Si (111) is used as substrate for sample I and G whereas Si(001) was used for sample J and H. Similarly, InP was grown on samples J and G with sulfur and no sulfur doping.

Figure 4.21 shows the Normalized PL spectra taken from these samples.
Fig 4.21 Normalized PL spectrum of InP on samples I, J, H, and G.

As can be seen in the Fig 4.21, FWHMs of PL spectra of samples I and J are larger than that of samples G and H. The peak position of doped samples is shifted towards the shorter wavelength (blue shifted). This is due to Brustin Moss effect caused by the sulfur doping. The Burstein–Moss effect is the process by which the apparent bandgap of a semiconductor is increased when the absorption edge is pushed to higher energies as a result of all states close to the conduction band being populated [5].

4.3.5 Scanning Electron Microscopy Studies

The cross sections of samples with alternating layers of sulfur doped and undoped InP, samples I and J were studied by SEM after stain etching. Fig 4.22 depicts the cross section SEM of the alternating layer of InP/InP:S/ on the two Si substrates.
Fig 4.22 SEM Cross-section of alternating layers of InP/InP:S grown on Si (001) substrate, sample J (left) and Si (111) substrate, sample I (right) both samples were grown at the same growth run.

The black and white contrast in Fig 4.22 can be attributed to “doping contrast”. The low doped region appears dark while high doped region appear bright [6]. The different electron density region in material can create the different image contrast. Thus doping of polycrystalline InP can be done in HVPE in a controlled way.
References


Chapter 5

Conclusions and Future Outlook

Indium oxide and In thin films were used as a seed layer for the growth of polycrystalline InP. InP was grown from these seed layers under different growth conditions. Both the seed and the final InP layers were characterized by multiple characterization techniques. High resolution powder XRD was used to study the structural quality of the films. Atomic Force Microscopy was used to study the surface morphology of the films while Micro-photoluminescence and Raman spectroscopies were used to study the optical quality of the grown InP films. The effect of different growth parameters were investigated with the help of these characterization methods. It was found that the longer growth time with higher phosphine flow and lower growth temperature were favored for the growth of InP on indium oxide. The same holds true to prepare InP on Si via the In thin film intermediated. By using In as a seed layer it was also possible to grow InP at higher temperature than what was used in the growth of InP on indium oxide. High optical and structural quality InP was grown on Si by using both kinds of seed layers, however, using In as seed layer on Si (111) substrate gave compositionally purer and structurally better InP with better optical quality.

It was shown that the deposited film is strain free. That may be because, before the start of InP growth on both kind of seeds from InCl$_3$ and PH$_3$, the In/ In$_2$O$_3$ film form droplets and phospidisation begins so that the droplets become InP from the outside to
in. So when the growth starts, the droplets get bigger and coalesce to form bigger grains. The InP lattice does not feel the influence of the Silicon lattice. Thus, this method of depositing InP is generic and it can be used to deposit InP on cheap substrates like glass and flexible substrates like metal foils. We also achieved Sulfur doping of the polycrystalline InP in a controlled way.

Though the optical and structural qualities of the deposited InP films were characterized and shown to be good, the electrical properties of the films and the heterojunction between InP and Si are of paramount importance for solar cell application. Future works related to this work include electrical characterizations such as Hall mobility and I-V measurements, verification of the possibility to use the method to grow InP on metal/flexible substrates and fabrication and characterization of solar cell device.