The effect of reactor pressure on the electrical and structural properties of InN epilayers grown by HPCVD

Phys 8510-Solid State Physics
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Outline

➢ Introduction:
  InN properties and application
  InN growth techniques and limitation

➢ Growth procedure

➢ Results and Discussion
  IR reflectance spectroscopy
  X-ray diffraction
  Raman spectroscopy

➢ Summary

➢ Acknowledgement
Introduction

Properties and application:

- InN is a promising material for electronic devices. Transistors with high mobility (higher-peak drift velocity and high-peak overshoot velocity)

- InN & alloy GaN and AlN extend the emission of nitride based LEDs from UV to IR region

- InN-GaN (InGaN) heterostructure optoelectronic devices
  - LEDs
  - Lasers
  - Solar Cells

- InGaN - environment-friendly red emitter with no toxic element
- InN has the lowest effective mass - high mobility (than other III-nitride)
  - at 300K: $4400\text{cm}^2\text{V}^{-1}\text{S}^{-1}(\text{InN}), 1000\text{cm}^2\text{V}^{-1}\text{S}^{-1}(\text{GaN})$
  - at 77K: $30\ 000\text{cm}^2\text{V}^{-1}\text{S}^{-1}(\text{InN}), 6000\text{cm}^2\text{V}^{-1}\text{S}^{-1}(\text{GaN})$

- InN based Optical fibers wavelength (small bandgap-0.69eV)
InN growth techniques and limitation

• Growth Methods
  – OMCVD
  – MBE
  – MOVBE
  – HPCVD

• Growth Limitation
  • lack of suitable substrate (lattice mismatch)
  • poor thermal stability of InN (low dissociation temperature)
Introduction

- Low InN dissociation temperature requires low growth temperature
- Source materials - TMI and NH₃
- Low growth temp. restrict low decomposition rate of NH₃
- Higher temp. bring thermal etching
- In contrast, low growth temp. dominate formation of In droplets (shortage of reactive nitrogen)
- Affect to InN properties
- Crystalline improved with temperature within the dissociation limit

High pressure growth

Allow to use high temperature growth
Reduce migration of the deposited materials
Growth procedure

- Substrate (GaN/Sapphire)
- Source: NH$_3$ and TMI
- Pressure: 2.5 bar to 18.5 bar
- Temperature: 750°C to 865°C
- Growth time: 90 minutes
Results and Discussion

Characterization methods

IR Reflection Method:

• The Mid-IR reflectance measurements were performed at room temperature using Perkin-Elmer system 2000 FTIR spectrometer with a liquid nitrogen cooled MCT detector and KBr beam splitter

• The wavelength range : 450-7000 cm⁻¹

• near-normal incident configuration, with a n angle of incident of 8°.
Results and Discussion

Modeling of IR Reflection of a Multilayer Stack

$E_k^+$ - amplitude of the electric field vector of incident waves for $k$ interface

$E_k^-$ - amplitude of the electric field vector of reflected waves for $k$ interface
Results and Discussion

Modeling of IR Reflection of a Multilayer Stack

\[
\begin{bmatrix}
E^+_0 \\
E^-_0
\end{bmatrix} = \frac{[M_1] \cdot [M_2] \cdot \ldots \cdot [M_{k+1}]}{t_1 \cdot t_2 \cdot \ldots \cdot t_{k+1}} \begin{bmatrix}
E^+_k \\
E^-_k
\end{bmatrix}
\]

\[
\begin{bmatrix}
a & b \\
c & d
\end{bmatrix} = \begin{bmatrix}
1 & r_{01} \\
r_{01} & 1
\end{bmatrix} \cdot \begin{bmatrix}
1 & r_{12} e^{-2i \Phi_1} \\
r_{12} e^{2i \Phi_1} & 1
\end{bmatrix} \cdot \begin{bmatrix}
1 & r_{23} e^{-2i \Phi_2} \\
r_{23} e^{2i \Phi_2} & 1
\end{bmatrix} \cdot \ldots \cdot \begin{bmatrix}
1 & r_{(k-1)k} e^{-2i \Phi_k} \\
r_{(k-1)k} e^{2i \Phi_k} & 1
\end{bmatrix}
\]

Complex Reflectance amplitude:

\[
\Phi_k = \frac{2 \pi d_k}{\lambda} \sqrt{\frac{\varepsilon_k - \varepsilon_0 \sin^2 \varphi}{\varepsilon_k}} \quad (k \geq 1)
\]

Reflectivity:

\[
R = \frac{c \cdot c^*}{a \cdot a^*}
\]

N. Dietz, Material Science and Engineering B87(2001)1-22
Results and Discussion

Dielectric Function: Lorentz and Drude model

\[ \varepsilon(\omega) = \varepsilon_\infty \left[ 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma \omega} + \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_{TO}^2 - \omega^2 - i\gamma_p \omega} \right] \]

Where,

\( \varepsilon_\infty \) - High frequency dielectric constant

\( \omega_{TO} \) - Frequency of TO phonon

\( \omega_{LO} \) - Frequency of LO phonon

\( \gamma_p \) - Broadening const of optical phonon oscillator

\( \omega_p \) - Plasma frequency

\( \Gamma \) – Damping const of plasma oscillator

Free carrier contribution

Lattice contribution

Free carrier concentration:

\[ n_c = \frac{\omega_p^2 \cdot m_{eff} \cdot \varepsilon_\infty \cdot \varepsilon_0}{\bar{\varepsilon}^2} \]

Mobility \( \mu \):

\[ \mu = \frac{e}{m_{eff} \cdot \Gamma} \]

Results and Discussion

IR Reflection Method:

A simple schematic diagram for the FTIR- reflection spectrometer
Results and Discussion

IR Reflection Method:

Experimental (solid line) and best fit (dotted line) IR reflectance spectra for a InN /GaN/ Sapphire film grown at 800°C and 10 bar reactor pressure. Inset illustrates the layer structure were used for best fit.
## Results and Discussion

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>D (nm)</th>
<th>ε (high freq.)</th>
<th>Palsma freq. (cm⁻¹)</th>
<th>Damping const. (cm⁻¹)</th>
<th>Mobility (cm²V⁻¹S⁻¹)</th>
<th>Free carrier con. (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>452.1</td>
<td>5.61</td>
<td>3720.4</td>
<td>1180.2</td>
<td>87.9</td>
<td>7.78 x 10¹⁹</td>
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<tr>
<td></td>
<td>195.5</td>
<td>6.03</td>
<td>4808.5</td>
<td>224.1</td>
<td>460</td>
<td>1.39 x 10²⁰</td>
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<tr>
<td>7.5</td>
<td>34.1</td>
<td>5.84</td>
<td>1048.0</td>
<td>1033.7</td>
<td>110</td>
<td>6.44 x 10¹⁸</td>
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<tr>
<td></td>
<td>325.7</td>
<td>6.59</td>
<td>3710.6</td>
<td>1046.8</td>
<td>99.1</td>
<td>9.11 x 10¹⁹</td>
</tr>
<tr>
<td>10.0</td>
<td>33.1</td>
<td>6.63</td>
<td>1316.9</td>
<td>881.1</td>
<td>120</td>
<td>1.15 x 10¹⁹</td>
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<tr>
<td></td>
<td>275.8</td>
<td>6.57</td>
<td>3970</td>
<td>742.2</td>
<td>140</td>
<td>1.04 x 10²⁰</td>
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<tr>
<td>12.5</td>
<td>62.2</td>
<td>6.08</td>
<td>492.4</td>
<td>378.5</td>
<td>270</td>
<td>1.49 x 10¹⁹</td>
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<tr>
<td></td>
<td>189.3</td>
<td>6.54</td>
<td>4286.8</td>
<td>686.2</td>
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<td>1.21 x 10²⁰</td>
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<tr>
<td>15.0</td>
<td>10.0</td>
<td>7.69</td>
<td>983.9</td>
<td>872.7</td>
<td>120</td>
<td>7.47 x 10¹⁸</td>
</tr>
<tr>
<td></td>
<td>307.4</td>
<td>5.29</td>
<td>3543.8</td>
<td>592.5</td>
<td>180</td>
<td>6.62 x 10¹⁹</td>
</tr>
<tr>
<td>18.5</td>
<td>21.2</td>
<td>7.19</td>
<td>1608.3</td>
<td>1518.0</td>
<td>68.4</td>
<td>1.87 x 10¹⁹</td>
</tr>
<tr>
<td></td>
<td>248.5</td>
<td>6.15</td>
<td>3522.2</td>
<td>485.1</td>
<td>210</td>
<td>7.66 x 10¹⁹</td>
</tr>
</tbody>
</table>

The parameters obtained from the best fits of IR spectra for different pressure samples. First and second row each pressure are for 1st and 2nd InN layers parameter respectively. The effective mass for InN and GaN were taken as 0.09m₀ and 0.2m₀ respectively.
Results and Discussion

IR Reflection Method:

Free carrier concentrations of InN-1st layer as a function of reactor pressure. Data is fitted to a 3rd order polynomial fit and 10% error has considered for each data point.

Mobility as function of growth temperature
Results and Discussion

IR Reflection Method:

**Figure 3** Free carrier concentration of InN-2nd layer vs. reactor pressure. Data is fitted to a 3rd linear fit and 10% error has considered for each data point.

Mobility of the carriers of the InN bulk layer as function of reactor pressure. Mobility was calculated by using Eq.3 and effective mass were taken 0.09m₀.

Mobility as function of growth temperature

Results and Discussion

IR Reflection Method:

Growth rate as a function of reactor pressure. Thicknesses are obtained by IR reflection fitting and thicknesses were divided by growth time (1.5h) to calculate the growth rate. The data were fitted to an exponential decay and 10% error was considered for each data point.
**Results and Discussion**

**IR Reflection Method:**

The FWHM of the Raman $E_2$ (high) of the InN epilayers grown GaN templates vs. reactor pressure.

Raman $E_2$ (high) FWHM represent the local order of crystalline quality.

**Experimental and fitted Raman spectra for 10 bar.**
Results and Discussion

XRD (2θ-ω scans):

Crystalline properties of the InN epi-films have been investigated by X’pert Pro MRD PANalytical high resolution X-ray diffraction

- Strain analysis
- Phase analysis
- Lattice constant

http://www.charfac.umn.edu/instruments/in-plane_diffraction.pdf
Results and Discussion

XRD (2θ-ω scans):

Figure 15: (a) HRXRD diffractometer. (b) Illustration of the Euler angles and the angles Ω and 2θ
Results of InN on GaN/Sapph. (30-36 deg, 2θ-ω scans)-pressure 10 bar

<table>
<thead>
<tr>
<th>Point</th>
<th>InN Peak Position</th>
<th>InN FWHM</th>
<th>GaN Peak Position</th>
<th>GaN FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>31.32663</td>
<td>147.7</td>
<td>34.53838</td>
<td>28.2</td>
</tr>
</tbody>
</table>
Results and Discussion

XRD FWHM ($2\theta-\omega$ scan in triple crystal geometry) of InN peak ((0002) Bragg reflex at about 31.33°) as function of the reactor pressure.
Summary

- The electronic and structural properties of the InN layers as a function of reactor pressure have been studied.

- The free carrier concentration and mobility shows the pressure dependent behavior. In addition, lowest free carrier concentration and highest mobility of the bulk InN layers are $1.5 \times 10^{18} \text{cm}^{-3}$ and $270 \text{cm}^2\text{V}^{-1}\text{S}^{-1}$ respectively.

- However, to achieve low free carrier concentration, further study will be needed on surface H, C, and etc.
Summary

- Raman study shows the local crystalline ordering decreases with the reactor pressure while the long-rang ordering shows influence of the reactor pressure.

- Our study shows that around 10.0-12.5 bar has the better long-range ordering of the crystal structural and electrical properties. Further studies are conducting at this pressure with V/III ratio to understand the surface chemistry.
Acknowledgement

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