Inhomogeneous electron distribution in InN nanocolumns

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Electronic, transport and optical properties of low-dimensional systems
WS10-ETOLDs.
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Nitride semiconductors: GaN, AlN, InN

Bandgap of Ga$_{1-x}$In$_x$N – Solar spectrum
High efficiency solar cells.

Wurtzite structure
Non-centrosymmetric

Polar and non-polar surfaces

Banding parameter = 1.43 eV

Bandgap of Ga$_{1-x}$In$_x$N – Solar flux

High efficiency solar cells.
Indium nitride

Low crystalline quality layers. Bandgap ($E_G$): 1.9 eV

High density of electrons (donors)

Electron effective mass very small

Large shift of the absorption edge (Burstein-Moss).

Free electron concentration remains high: $n_e > 3 \times 10^{17}$ cm$^{-3}$

2002

High crystalline quality. Reassigned $E_G$: 0.67 eV.
Surface electron accumulation layer.

Polar surfaces: Intrinsic

Non-polar surfaces

\begin{align*}
\text{Intrinsic}^1 & & \text{Extrinsic}^2 & & \text{No accumulation}^3
\end{align*}
Nanocolumns (NCs)

Why NCs?

- Higher surface/volume ratio.
- Lower density of dislocations.
- Increase radiative recombination.

NCs grow spontaneously along c-axis. Most surface is non-polar.

Non polar surfaces properties can be studied in more detail.
InN NCs: samples

- Growth: Plasma-assisted MBE.
- N₂-rich conditions
- Growth time: 300 m.

TS, Indium beam equivalent pressure (BEP), N₂-flux: variables.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$T_S$ ($\pm$C)</th>
<th>In-BEP (mbar)</th>
<th>$N^f_{\text{flux}}$ (sccm)</th>
<th>$P_{RF}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G053</td>
<td>400</td>
<td>3:0 £ 10⁻⁸</td>
<td>2.0</td>
<td>500</td>
</tr>
<tr>
<td>G071</td>
<td>475</td>
<td>3:0 £ 10⁻⁸</td>
<td>2.0</td>
<td>500</td>
</tr>
<tr>
<td>G047</td>
<td>500</td>
<td>3:0 £ 10⁻⁸</td>
<td>2.0</td>
<td>500</td>
</tr>
<tr>
<td>G041</td>
<td>500</td>
<td>1:5 £ 10⁻⁸</td>
<td>1.5</td>
<td>400</td>
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<tr>
<td>G044</td>
<td>500</td>
<td>3:0 £ 10⁻⁸</td>
<td>1.5</td>
<td>450</td>
</tr>
<tr>
<td>G136</td>
<td>475</td>
<td>3:0 £ 10⁻⁸</td>
<td>1.5</td>
<td>450</td>
</tr>
</tbody>
</table>
Morphology

Growth conditions strongly affect NCs morphology.

\( T_S = 400^\circ \text{C} \): Coalescence

\( T_S = 500^\circ \text{C} \): Baseball-bate shape

\( T_S = 475^\circ \text{C} \): Tapering - bimodal

\( T_S = 500^\circ \text{C} \): Homogeneous NCs

Diameters: 80-150 nm (30 nm)

Heights: 200-600 nm (1500 nm)
Raman scattering spectroscopy

Allowed modes: $A_1(LO) - E_2^h$

$E_2^h$ mode: narrow peak
Strain free NCs
($^2xx < 0.1\%$)

Forbidden modes

Plasmon - LO phonon coupled mode (PLP$^-$)

Scattering at lateral walls.

Backscattering $Z(X, \rightarrow) - Z$
Raman scattering spectroscopy

Coupled - uncoupled modes coexist

Two regions with different $n_e$

Forbidden modes. Lateral walls.

Intensity (arb. units)

Raman shift (cm$^{-1}$)

PLP$^-$ and $E_1$(LO) modes intensity are correlated.

Electron accumulation layer at non-polar surfaces.
Photoluminescence: growth conditions

In-BEP and N₂ – flux effect

**TS effect**

- **T=7K**
  - 475°C
  - 500°C
  - 400°C

Intensity (arb. units) vs. Energy (eV)

- In: $3.0 \times 10^{-8}$ mbar
- N₂: 1.5 sccm
- In: $3.0 \times 10^{-8}$ mbar
- N₂: 2 sccm
Energy, intensity and FWHM are correlated.

Temperature dependence

Two non-radiative channels.

\[ I(T) = I_0 \left(1 + A \exp\left(-\frac{E_1}{kT}\right) + B \exp\left(-\frac{E_2}{kT}\right)\right) \]

E\(_1\): 5-10 meV. Shallow acceptors

E\(_2\): 40-50 meV. Deep acceptors
Photoluminescence excitation (PLE)

- 10K.
- Excitation: Halogen lamp + monochromator.
- Detection: N$_2$-cooled InAs Photodiode.
- Spectral resolution: <1.5 meV
**PLE: characteristics**

Line-shape similar to bulk material.

Featureless – High electron concentration

\[ E_{\text{abs}} \text{ higher than InN bandgap} \]
Accumulation layer: growth conditions

PLE is different for each sample.

Energy and FWHM of the PL peak increase as $E_{\text{abs}}$ increase.

PL peak energy does not follow $E_{\text{abs}}$ variation.

PLE is different for each sample.
**Broadening**

PL does not depend on $E_{\text{exc}}$.

$E_{\text{abs}}$ does not depend on $E_{\text{det}}$.

Homogeneous broadening
Schematic NC image

Hole depletion
Low PL efficiency

Lower $e^-$ concentration.
Low PL efficiency.

High PL efficiency.

Different $N_D$ and $N_{SS}$. 

Degenerated electrons
Fermi level
Acceptor level

Energy (eV)

$r$ (nm)

CB
VB

(1)
(2)
(3)
Conclusions

• Optical properties and morphology of the nanocolumns are strongly affected by the growth conditions.

• There is electron accumulation at the non-polar surfaces of InN.

• Photoluminescence in InN nanocolumns comes from degenerated electrons recombining with localized holes.

• Differences in the photoluminescence are attributed to different volume and surface charge for each sample. Electron accumulation at non-polar surfaces is not intrinsic.
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