Graded P-AlGaN Superlattice for Reduced Electron Leakage in Tunnel-Injected UVC LEDs

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Outline: Tunnel-injected UV LED

• Motivation

• Polarization engineered III-Nitride tunnel junctions

• Tunneling junction for hole injection into UV LEDs.
  • Effect of graded p-AlGaN layer on UV-A LEDs
  • Effect of graded p-AlGaN superlattice

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## Motivation

UV lighting market is increasing.
UV LEDs are replacing the traditional UV lamps.

<table>
<thead>
<tr>
<th>UV C</th>
<th>UV B</th>
<th>UV A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disinfection</td>
<td>Medical imaging</td>
<td>UV curing</td>
</tr>
<tr>
<td>Sterilization</td>
<td>Protein analysis</td>
<td>Printing</td>
</tr>
<tr>
<td>Sensing</td>
<td>Drug discovery</td>
<td>Sensing</td>
</tr>
<tr>
<td></td>
<td>DNA sequencing</td>
<td>Phototherapy</td>
</tr>
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</table>


**Tunnel-injected UV LEDs**
Why we need tunnel-injected UV LEDs

Conventional UV LEDs

- P-type contact
- P-GaN
- P-AlGaN/AlGaN SL
- P-AlGaN
- MQW
- N-AlGaN

- $N_a = 1 \times 10^{19} \text{ cm}^{-3}$
- GaN: 140 meV,
  - $N_a^- = 7 \times 10^{17} \text{ cm}^{-3}$
- AlN: 630 meV,
  - $N_a^- = 6 \times 10^{13} \text{ cm}^{-3}$

- Dramatic decrease of WPE for shorter wavelengths.
- WPE < 6% for state-of-the-art UV LEDs
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- Absorbs UV light
- Poor current spreading
- High series resistance
- Poor hole injection

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TJ-UV LEDs
- N-type contact
- N-AlGaN
- Tunnel Junction
- P-AlGaN
- MQW
- N-AlGaN

Low contact resistance
Reflective contact
Translucent
Excellent current spreading
Low resistance, low voltage drop
Efficient hole injection

Light extraction efficiency
Injection efficiency

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- Reflective contact
- Transparent
- Excellent current spreading
- Low resistance, low voltage drop
- Efficient hole injection

New challenge:

Are we able to achieve efficient tunnel junction for high bandgap AlGaN material?
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Overview of the tunnel junction technology

Deep UV LEDs require even wider bandgap.

Deep UV LEDs require even wider bandgap.

S. Krishnamoorthy, APL 102, 113503 (2013)
F. Akyol, APL 108 (13), 131103 (2016).
Y. Zhang, APL, 106 (14), 141103 (2015).

J Speck, APL 107 (9), 091105 (2015)
T. Takeuchi, JJAP 52 (8S), 08JH06 (2013)

Polarization engineered tunnel junctions at OSU

- InP
- GaAs
- AlGaAs/InAlGaP
- GaN
- Al0.55Ga0.45N
- Al0.3Ga0.7N
- GaSb/InAs

Bandgap (eV)

TJ resistance (Ω cm^2)
Modeling of tunnel junction structures

$\text{Al}_{0.7}\text{Ga}_{0.3}\text{N} / (\text{In}_{0.3}\text{Ga}_{0.7}\text{N})$

50 nm n-$\text{Al}_{x}\text{Ga}_{1-x}\text{N}$
[Si] = $1 \times 10^{20}$ cm$^{-3}$

500 nm p-$\text{Al}_{x}\text{Ga}_{1-x}\text{N}$
[Mg] = $5 \times 10^{19}$ cm$^{-3}$

Charge profile

$\text{Al/ In compositions}$

$\text{Nd}^+$

$\text{Na}^-$

Tunnel-injected UV LEDs

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- 50 nm n-Al\(_{x}\)Ga\(_{1-x}\)N
  - [Si] = 5\times10^{19} \text{ cm}^{-3}

- 4 nm In\(_{y}\)Ga\(_{1-y}\)N

\[ \text{Al/ In compositions} \]

\[ \text{Charge profile} \]

\[ \text{Energy (eV)} \]

- Equilibrium

\[ \text{Thickness (nm)} \]

- Depletion charges

\[ +\sigma \]

\[ -\sigma \]

Tunnel-injected UV LEDs
Modeling of tunnel junction structures

$Al_{0.7}Ga_{0.3}N / (In_{0.3}Ga_{0.7}N)$

J Simon, Science 327 (5961), 60 (2010)
D. Jena, APL 81, 4395 (2002).
Modeling of tunnel junction structures

- Polarization engineering enables low tunneling resistance and voltage drop.

J Simon, Science 327 (5961), 60 (2010)
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Effect of graded p-AlGaN layer – UV-A LED

- MBE growth
- Sharp interfaces
- No need for annealing activation of Mg in the embedded p-AlGaN layer

Y. Zhang, APL, 106 (14), 141103 (2015).
Y. Zhang, APEX 9 (5), 052102 (2016)
Effect of graded p-AlGaN layer – UV-A LED

- P-AlGaN grading
  - Polarization field assists acceptor ionization
  - Higher barrier to block overflowing electrons

Sample 1

- n+ Al$_{0.3}$Ga$_{0.7}$N
- 15 nm graded n++ AlGaN
- 4 nm 25% InGaN
- p-Al$_{0.3}$Ga$_{0.7}$N
- 12 nm Al$_{0.46}$Ga$_{0.54}$N
- QW ×3
- 50 nm n-Al$_{0.3}$Ga$_{0.7}$N
- n+ Al$_{0.3}$Ga$_{0.7}$N
- Al$_{0.3}$Ga$_{0.7}$N Template

Sample 2

- n+ Al$_{0.3}$Ga$_{0.7}$N
- 15 nm graded n++ AlGaN
- 4 nm 25% InGaN
- Graded p-AlGaN
- Al$_{0.75}$Ga$_{0.25}$N
- 1.5 nm AlN
- 50 nm n-Al$_{0.3}$Ga$_{0.7}$N
- n+ Al$_{0.3}$Ga$_{0.7}$N
- Al$_{0.3}$Ga$_{0.7}$N Template

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The sample with graded p-AlGaN layer shows increased EQE/WPE.

- Peak EQE = 3.37%, peak WPE = 1.53% achieved at 325 nm.
Effect of graded p-AlGaN layer – UV-A LED

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- Peak EQE = 3.37%, peak WPE = 1.53% achieved at 325 nm.

Record efficiencies at this wavelengths
**Application for UV-C LEDs**

### UV-C LED

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<td>P</td>
<td>Al&lt;sub&gt;0.7Ga0.3&lt;/sub&gt;N</td>
</tr>
<tr>
<td></td>
<td>p-AlGaN</td>
</tr>
<tr>
<td></td>
<td>Al&lt;sub&gt;0.92Ga0.08&lt;/sub&gt;N</td>
</tr>
<tr>
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<td>8 nm AlN</td>
</tr>
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**UV-C LEDs:**
- Thermal activated hole density is low
  => Polarization charge is important
Application for UV-C LEDs

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<td>×3</td>
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UV-C LEDs:
- Thermal activated hole density is low
- Polarization charge is important

- Low light emission
- Soft turn-on. Voltage at 20 A/cm² is 3.96 V.
Application for UV-C LEDs

Possible limitations:

- Insufficient hole injection
- Electron overflow
- Leakage through defects/ dislocations
Application for UV-C LEDs

Possible limitations:
• Insufficient hole injection
• Electron overflow
• Leakage through defects/dislocations

Graded p-AlGaN superlattice
• Increase hole concentration in p-AlGaN
• Polarization barriers
• Release strain
Deep UV LEDs – graded p-AlGaN superlattice

- 150 nm n+ Al_{0.7}Ga_{0.3}N
- 5 nm graded n++ AlGaN
- 4 nm 20% InGaN
- 50 nm Graded p-AlGaN (SL)
- 8 nm AlN
- 3.5 nm Barrier
- 3 nm QW
- 6 nm Barrier
- 50 nm n-Al_{0.7}Ga_{0.3}N
- 450 nm n+ Al_{0.7}Ga_{0.3}N
- Al_{0.7}Ga_{0.3}N template

- A: P-Al_{x}Ga_{1-x}N
  - x: 92% -> 64%

- B: 0.5/0.5 nm-Al_{x}Ga_{1-x}N/Al_{y}Ga_{1-y}N SL
  - x: 92% -> 64%
  - y: 100% -> 75%

- C: 1.8/1.8 nm-Al_{x}Ga_{1-x}N/Al_{y}Ga_{1-y}N SL
  - x: 92% -> 64%
  - y: 100% -> 75%

- D: 3.0/3.0 nm-Al_{x}Ga_{1-x}N/Al_{y}Ga_{1-y}N SL
  - x: 92% -> 64%
  - y: 100% -> 75%

Grown by MBE
Deep UV LEDs – graded p-AlGaN superlattice

![Graph 1: Current Density vs. Voltage](image1)

![Graph 2: Voltage at 20 A/cm² vs. Layer Thickness](image2)
Deep UV LEDs – graded p-AlGaN superlattice

- **Graph 1:**
  - Plot of Current Density (A/cm$^2$) vs. Voltage (V)
  - Two curves:
    - Orange: No SL
    - Purple: 0.5/0.5 nm SL

- **Graph 2:**
  - Plot of Voltage at 20 A/cm$^2$ vs. Layer thickness in p-AlGaN SL (nm)
  - Points labeled A and B

- **Table:**
  - Voltage at 20 A/cm$^2$
  - Resistance at 2 kA/cm$^2$

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Deep UV LEDs – graded p-AlGaN superlattice

- A → C: Lower leakage, but higher on-resistance
  - Lower electron leakage/ overflow
Deep UV LEDs – graded p-AlGaN superlattice

- C -> D: Higher on-resistance, but also higher leakage
- Hole transport is blocked by valence band fluctuations
  ⇒ Higher threshold voltage for hole transport
  ⇒ Higher vertical resistance
Deep UV LEDs – graded p-AlGaN superlattice

Light emission at 282 nm.
Highest emission power of 76 uW at 20 mA for sample D.

C -> D:
- Higher hole concentration
- Poorer vertical conduction
Sample C showed peak EQE/ WPE at 200 A/cm² – reduced overflow
Sample B/ D did not saturate till high current – electron leakage leads to low internal quantum efficiency.
Deep UV LEDs – graded p-AlGaN superlattice

Low efficiency:
- Low IQE – optimize material quality
- Hole injection is still not efficient – optimize TJ performance
Deep UV LEDs – graded p-AlGaN superlattice

First demonstration of Al$_{0.7}$Ga$_{0.3}$N tunnel junction with Eg > 5.2 eV.

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  - Single peak emission at 282 nm
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- First report of tunneling hole injection through wide band gap Al$_{0.7}$Ga$_{0.3}$N tunnel Junctions with Eg > 5.2 eV.
  - Single peak emission at 282 nm

- Graded p-AlGaN SL leads to reduced electron leakage.
  - The sample with 1.8/1.8 nm graded SL shows lowest leakage