History of InGaN-based LED

SHUJI NAKAMURA

SOLID STATE LIGHTING AND ENERGY ELECTRONICS CENTER
MATERIALS AND ECE DEPARTMENTS
UNIVERSITY OF CALIFORNIA, SANTA BARBARA, U.S.A.
Historical: LED Efficiency

InGaN DH-LED & QW-LED by Nakamura et al., 1993, 1995

GaN p-n Homojunction LED by Akasaki & Amano, 1989

AlGaNp/GaAs

AlGaNp/GaP

InGaN (green)

InGaN (blue)

White LED (R&D Demo, 2014)

Fluorescent

Compact Fluorescent

Unfiltered Incandescent

Thomas Edison's First Bulb

InGaN DH-LED & QW-LED by Nakamura et al., 1993, 1995

Oil Lamp

GaAsP

GaAsP: N

GaN MIS LED by Maruska et al., 1973

GaP: Zn, O

First GaN p-n Homo-junction LED in 1989

Table I. The electrical properties of the as-grown and the LEEBI treated GaN:Mg with Mg concentration of $2 \times 10^{20}$ cm$^{-3}$. We assume the thickness of the LEEBI treated GaN:Mg film to be 500 nm.

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<tr>
<th></th>
<th>LEEBI treated</th>
<th>As grown</th>
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<tbody>
<tr>
<td></td>
<td>$\rho \sim 35 \Omega \cdot$ cm, $p \sim 2 \times 10^{16}$ cm$^{-3}$, $\mu \sim 8$ cm$^2$/V$\cdot$s</td>
<td>highly resistive, $\rho &gt; 10^8$ $\Omega \cdot$ cm</td>
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Output Power: No data
WPE: No data
EL Peak wavelength: 430 nm

Fig. 3. The structure of the p-n junction LED.

Ga$_2$O$_3$ p-n Homo-junction LED in 1991


Output power: 40$\mu$W at 20mA
WPE: 0.18%
EL Peak wavelength: 430 nm
Homo-junction vs. Double Heterostructure

Energy Band Diagrams

Homojunction LED

Double Heterostructure LED

Internal Quantum Efficiency

\[ \eta_{IQE} = \frac{\text{Light generated}}{\text{Electrons injected}} = \frac{R_{\text{radiative}}}{R_{\text{radiative}} + R_{\text{non-radiative}}} = \frac{Bn^2}{An + Bn^2 + Cn^3} \]

Double heterostructures increase carrier concentrations \((n)\) in the active layer and enhance radiative recombination rates (more light generated).
InGaN growth in 1991

Despite numerous attempts by researchers in the 1970s—1980s, high quality InGaN films with room temperature band-to-band emission had not been achieved.

InGaN Growth:
- **Poor quality** at low T
- Low incorporation at high T
- **Hard to control In concentration**
- High impurity incorporation
- Heavily defected

InGaN Luminescence:
- **No band-to-band emission at room temperature** (fundamental for any LED&LD device)
- **Significant defect emission**

High Quality InGaN Layers in 1992

Enabling Technology: Two-Flow MOCVD

High Quality InGaN Growth with Band-to-Band Emission

Controllably vary Indium Concentration and hence color


RT Photoluminescence Spectra of InGaN

Wavelength vs. Indium Fraction
First High Brightness InGaN LED


**Breakthrough Device with Exceptional Brightness**
(1.5 mW Output Power, 2.7% EQE @ 450 nm (Blue))

Thickness of InGaN Active Layer: 100nm-500nm

Blue InGaN **Double Heterostructure (DH)** LED

![Diagram of Blue InGaN Double Heterostructure LED](image)

Output Power vs. Current

![Graph showing output power vs. current](image)
1\textsuperscript{st} InGaN QW Blue/Green/Yellow LEDs


High Brightness LEDs of \textit{varying colors} by increasing Indium content.

(4 mW Output Power, 7.3\% EQE (2.7 times higher than DH) \textit{@} 450 nm (Blue))

Demonstration of First \textit{QW active layer with a thickness of 2nm-3nm}

Green SQW LED

Quantum Wells

Output Power vs. Current

\begin{itemize}
    \item DC R.T.
    \item (a) blue SQW LED
    \item (b) green SQW LED
    \item (c) yellow SQW LED
\end{itemize}

\begin{align*}
    \text{Output Power (mW)} = \text{12} & \quad \text{at 100 mA} \\
    \text{Output Power (mW)} = \text{8} & \quad \text{at 80 mA} \\
    \text{Output Power (mW)} = \text{4} & \quad \text{at 60 mA} \\
    \text{Output Power (mW)} = \text{2} & \quad \text{at 40 mA} \\
    \text{Output Power (mW)} = \text{0} & \quad \text{at 0 mA}
\end{align*}
High Dislocation density in high efficiency InGaN-based LED in 1995

InGaN based LED is so efficient??
EQE: 4%
Dislocation Density: $> 2 \times 10^{10} \text{ cm}^{-2}$
EL Peak wavelength: 430 nm

Comparison InGaN vs. other LEDs

*Inhomogeneous*: (InGaN)

Bright (!) despite high defects

Higher currents mask inhomogeneity effects (valleys fill up)


*Homogeneous*: (GaN)

Dim as defects “swallow” electrons without producing light

Alloy Fluctuations of InGaN form the localized states

Possible Origins of High Efficiency

**Indium Fluctuations** form localized states:

Separate carriers from defects

**Indium in Active Layer**

Random Binomial Distribution

Atom Probe Tomography, D. Browne et al., UCSB