*2017 U.S. Department of Energy Solid-State Lighting R&D Workshop*
*Feb. 2, 2017: Long Beach, CA, USA*

# Nitride-based tunnel junctions by MOCVD

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# Minimizing efficiency droop

## Stimulated emission

Carrier density clamped

GaInN VCSELs

Current confinement by TJ

## Cascaded LED

Large input power with multiple $V_{th}$

Tandem LEDs

Series connection by TJ

**Demonstration of a III-nitride vertical-cavity surface-emitting laser with a III-nitride tunnel junction intracavity contact**

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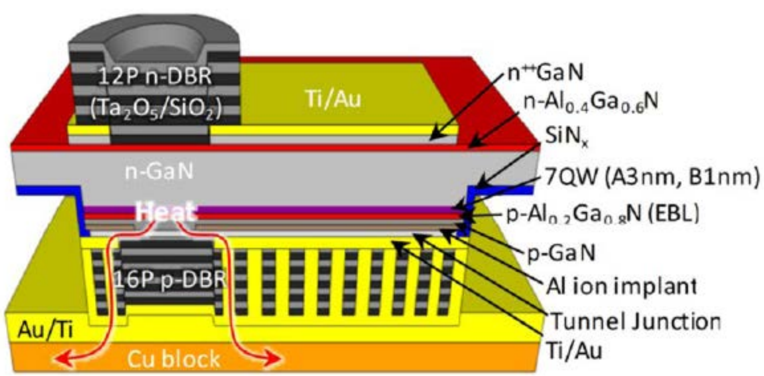
[1]*Materials Department, University of California, Santa Barbara, California 93106, USA*
[2]*Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106, USA*




**GaN-based three-junction cascaded light-emitting diode with low-resistance InGaN tunnel junctions**

Fatih Akyol[1*], Sriram Krishnamoorthy[1], Yuewei Zhang[1], and Siddharth Rajan[1,2]
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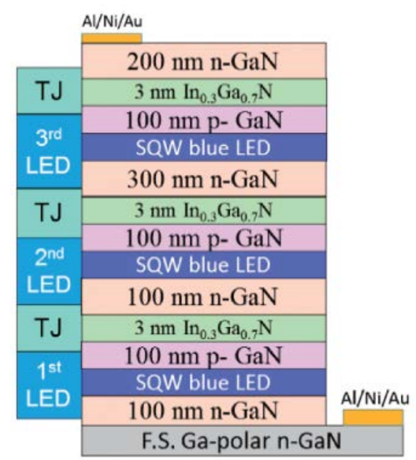


# Filling in green gap

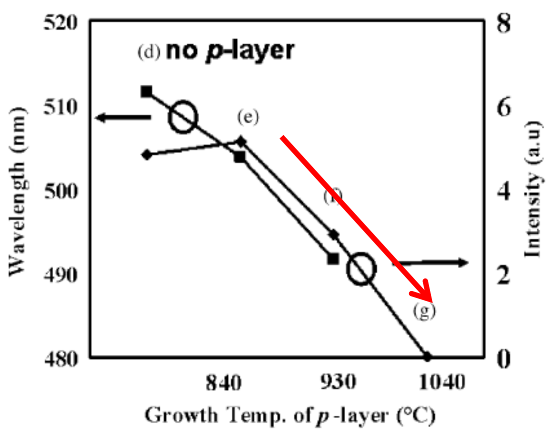
## Low-temperature-grown p-side structure

required to **suppress thermal damages** in long wavelength active regions

Effect of thermal annealing induced by p-type layer growth on blue and green LED performance

Wonseok Lee, Jae Limb, Jae-Hyun Ryou, Dongwon Yoo, Theodore Chung, Russell D. Dupuis*

*Center for Compound Semiconductors, School of Electrical and Computer Engineering, Georgia Institute of Technology, 777 Atlantic Drive NW, Atlanta, GA 30332-0250, USA*




Improvement of green LED by growing p-GaN on $In_{0.25}GaN/GaN$ MQWs at low temperature

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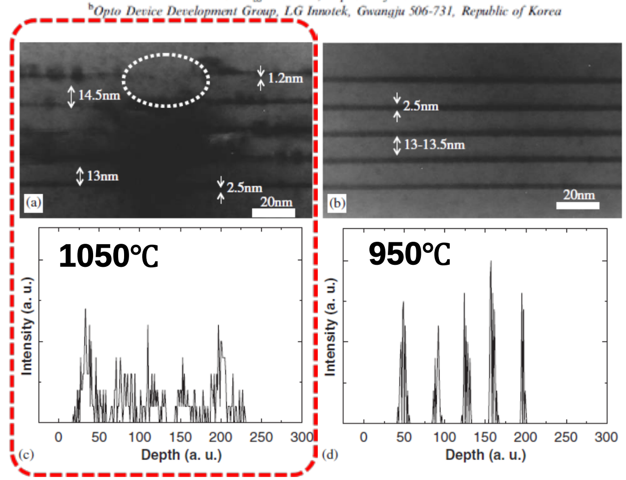



**n-GaN/tunnel junction/p-GaN** grown at low temperature could be a solution.

# Our approach for Nitride-based tunnel junctions

- **Our approach**
  - **MOCVD & GaInN**
  - **MOCVD**
    - suitable for mass production
    - poor Mg doping characteristics
      - Hydrogen passivation
      - Turn-off delay
  - **GaInN**
    - leverage polarization doping
    - narrow band gap

- **Today's content**

  ① **Lateral Mg activation**

  ② **GaInN tunnel junction**

  ③ **Graded tunnel junction**

# ①Lateral Mg activation

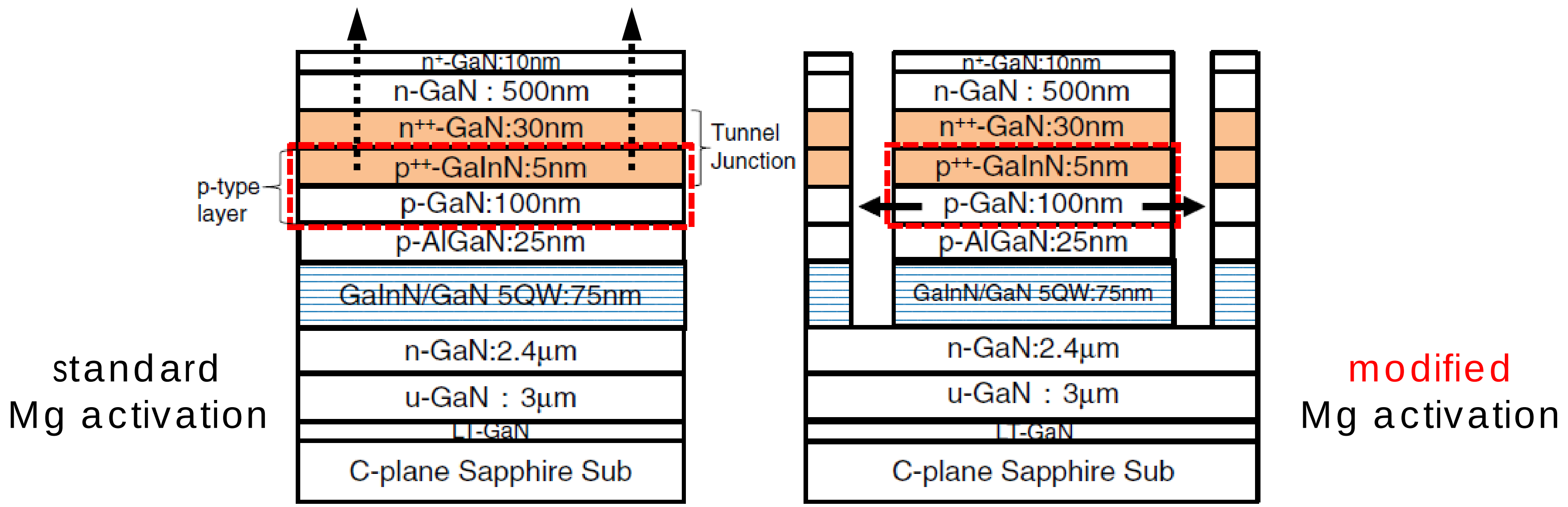
**TJ on LED: n-p-n structure**

**- Poor hydrogen diffusions reported in n-type materials**

ex. Si : J. I. Pankove, et al., Appl. Phys. Lett. 47 (1985)748.
InP : G. R. Antell, et al., Appl. Phys. Lett. 53 (1988) 758.

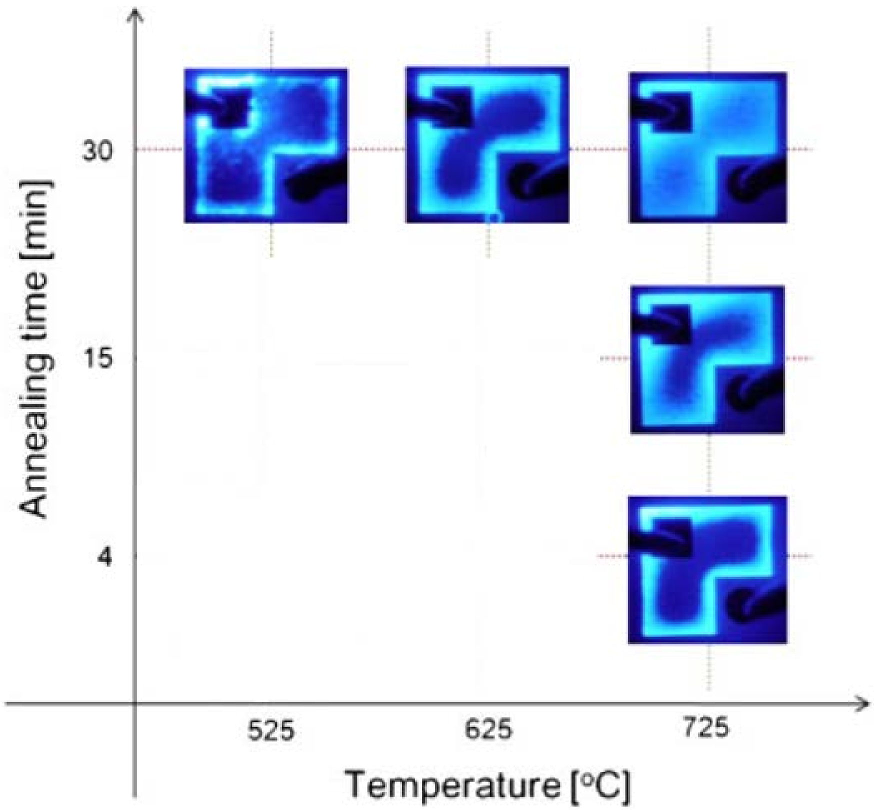
**- Insufficient Mg activation could happen due to the poor diffusions**

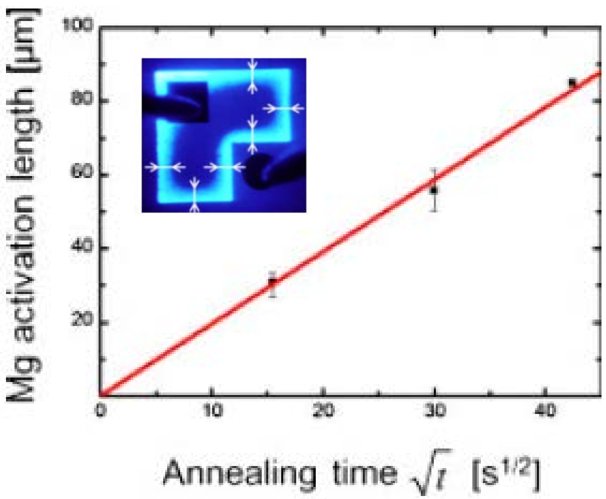
**Modified Mg activation**: thermal annealing **through the sidewalls:**
Hydrogen could diffuse along lateral directions



# ①Lateral Mg activation

**Modified Mg activation: under various annealing time and temperature**




Dominated by some diffusion process

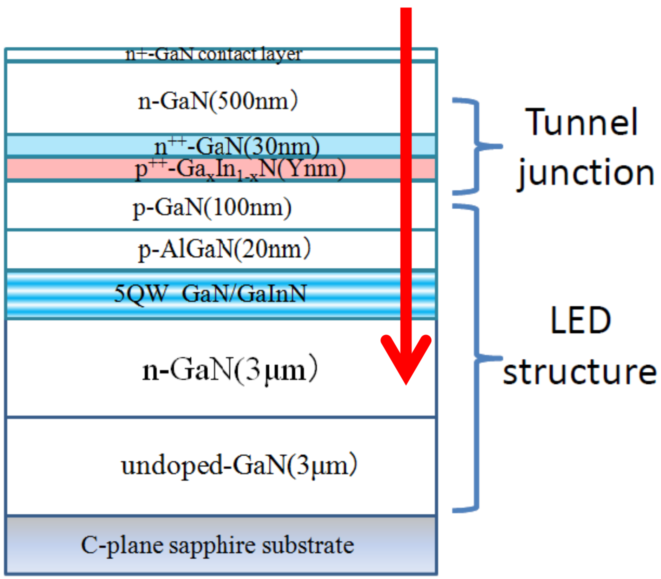
Mg activation proceeded along lateral directions

Y. Kuwano et al.
Jpn. J. Appl. Phys. 52 (2013) 08JK12

# ②GaInN tunnel junctions

## GaInN TJ on std-sized LED

to estimate voltage drop at TJs by comparing with std. Ni/Au p-contact LED




**300×300 μm$^2$**

**Tunnel junction:**
**Si-doped GaN (<u>2~3e20</u>)**
**Mg-doped GaInN (<u>1~2e20</u>)**

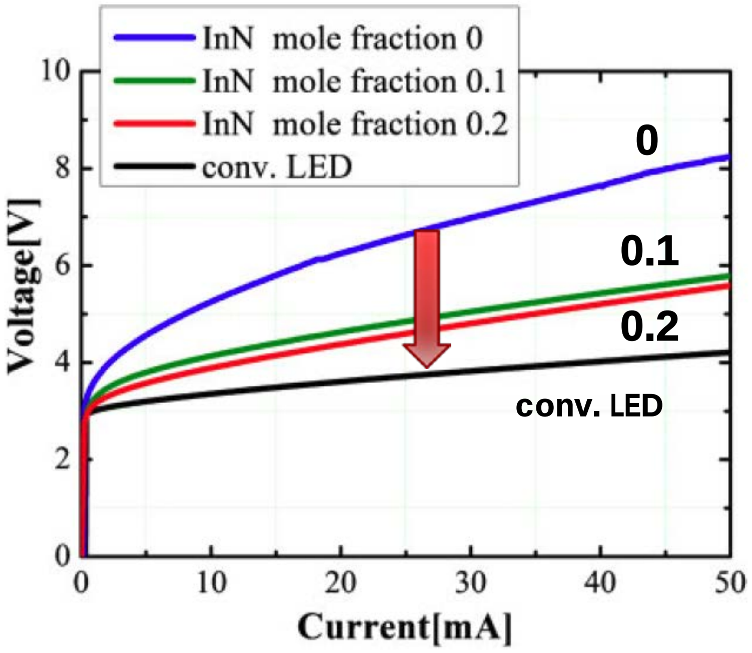
### InN mole fraction dependence of voltage drop at the TJs

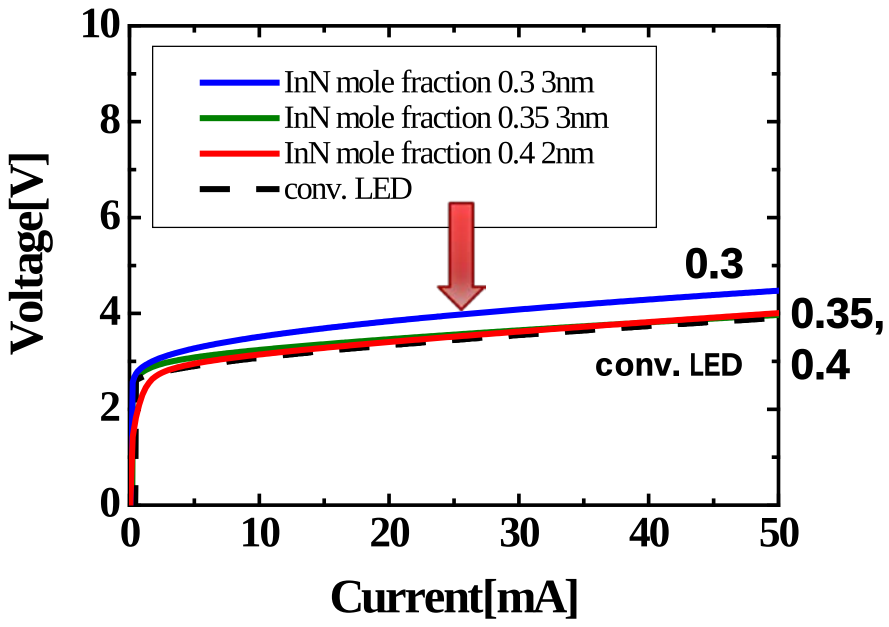
| InN mole fraction | GaInN thickness (nm) |
|---|---|
| **0** | 7.5 |
| **0.1** | 7.5 |
| **0.2** | 3 |
| **0.3** | 3 |
| **0.35** | 3 |
| **0.4** | 2 |

M. Kaga et al. Jpn. J. Appl. Phys. 52 (2013) 08JH06
D. Minamikawa et al. PSS (b) 252 (2015) 1127

# ②GaInN tunnel junctions

**I-V curves of various GaInN TJs on LEDs**



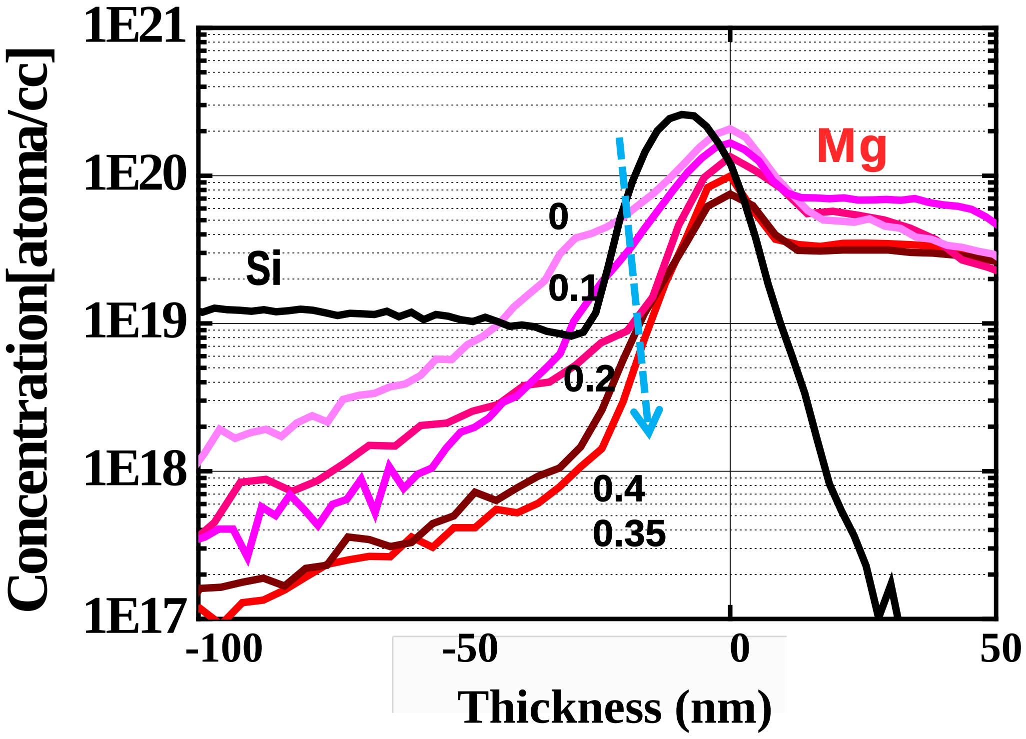

**higher InN mole fraction in TJs ⇒ lower voltage drop**

Resistivity of 35 and 40% GaInN TJs seems comparable
to that of conv. p-contact (at low current density)

# ②Mg profiles in GaInN tunnel junctions

**Another reason for lower resistivity of TJs with higher InN mole fraction**

steeper Mg turn-off profile ⇒ thinner tunneling thickness



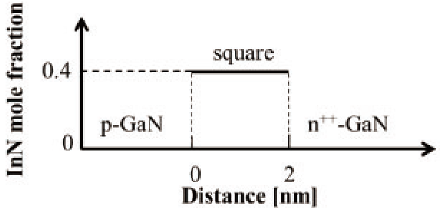

In surfactant and/or low temperature growth suppress Mg segregation

cf. K. Tomita et al., JAP 104, 014906 (2008)

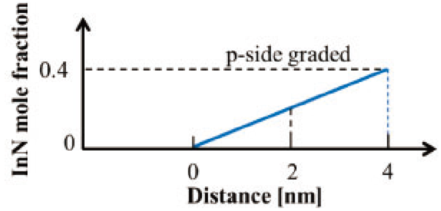
# ③Graded tunnel junctions

**Graded GaInN tunnel junctions for minimizing “energy spikes”**

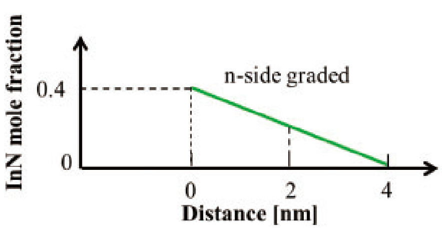
Design of InN mole fraction in TJ



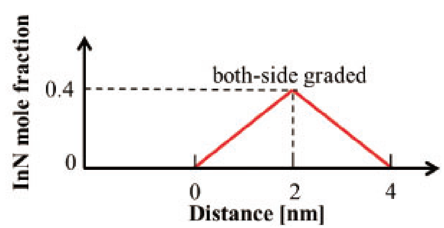

**square (best so far)**




**p-graded**

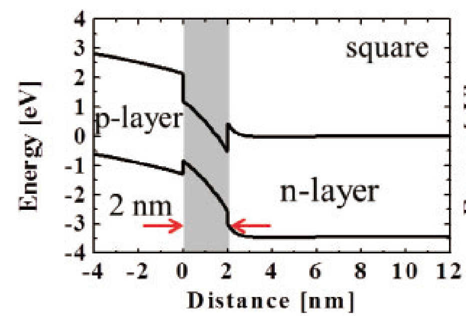



**n-graded**

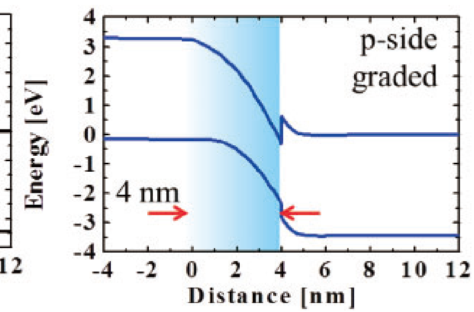



**both-graded**

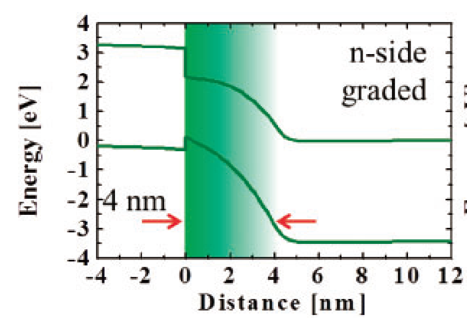
Calculated band profiles



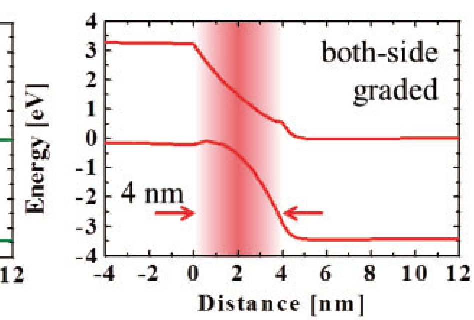

**square (best so far)**




**p-graded**




**n-graded**




**both-graded**

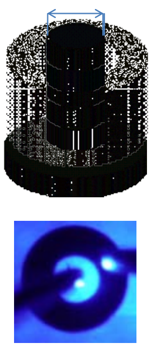
D. Takasuka et al., APEX 9 (2016) 081005

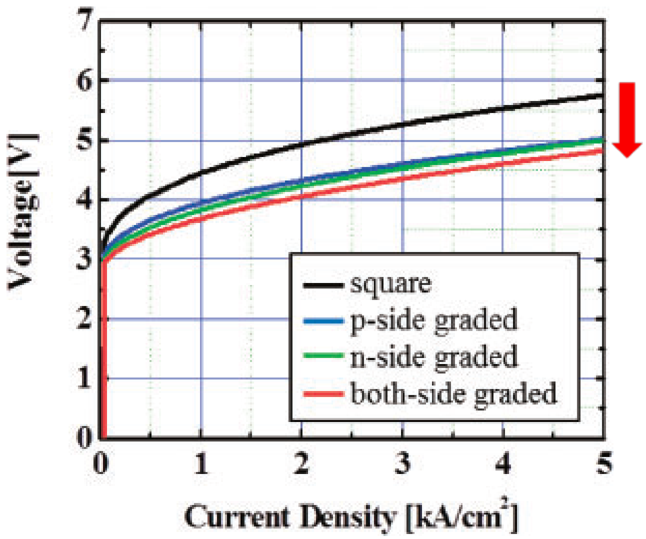
# ③Graded tunnel junctions

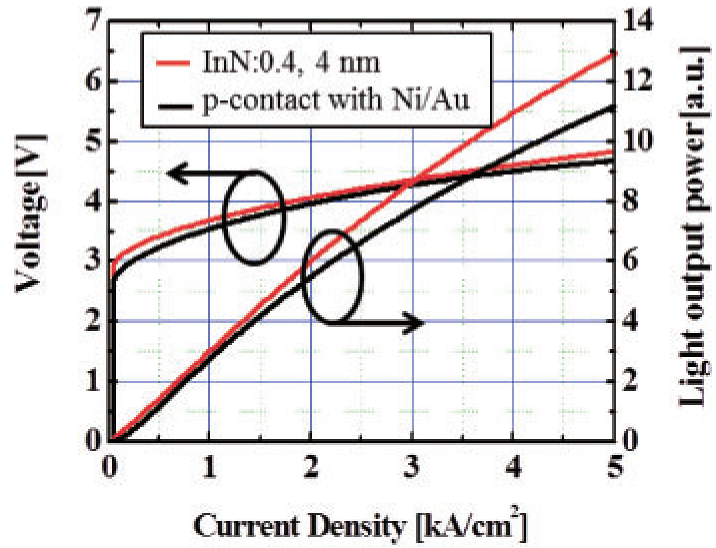
**I-V curves (under high current density) of graded GaInN TJs on micro-LEDs**

**Comparison with std. Ni/Au p-contact**

25 μmΦ





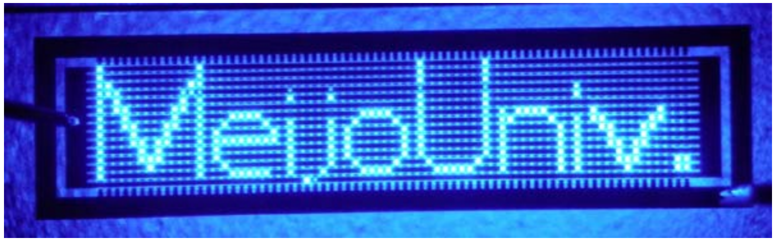

Our lowest voltage was obtained from **both-side graded**

The same characteristics: $\mathbf{r_s = 2.3 \times 10^{-4}\ \Omega cm^2}$

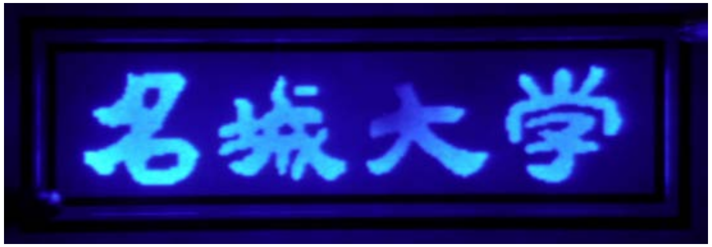
# Summary

- **Low resistive MOCVD-grown nitride-based tunnel junctions**
  - Specific series resistance: $2.3\times10^{-4}\ \Omega cm^2$
    - Lateral Mg activation
    - Graded GaInN (~40%) tunnel junctions

- **Nitride-based tunnel junction is ready to be used in various optoelectronic devices.**




Micro-LED array with TJs




Micro-LED indicator with TJs