Ultra-Low Resistance GaN/InGaN/GaN Tunnel Junctions with Indium Content < 15%

Fatih Akyol, Sriram Krishnamoorthy, Yuewei Zhang, Siddharth Rajan

The Ohio State University

IWN, Oct 6th 2016

Funding: NSF EECS-1408416
Outline

- Motivation
- Background
- GaN/InGaN/GaN tunnel junctions with low (<15%) Indium content
- Summary
Interband Tunnel Junctions

**TJ in forward bias**

- Electron $\leftrightarrow$ hole carrier conversion

$$E_c + E_{f,n}$$

- Injection of holes into p-type material
- Applications: LEDs, lasers

**TJ in reverse bias**

- Recombination of electrons and holes by tunneling
- Applications: Solar cells

$$E_c - E_{f,p}$$
LEDs with Tunnel Junctions

- Non-equilibrium hole injection through interband tunneling.
LEDs with Tunnel Junctions

- Conventional LEDs:
  - Efficiency Droop
  - Large LED chips operating at low current have to be used for high output power

![Graph showing normalized EQE vs. current density with EQE_{peak} and EQE_{op} labeled, along with J_{op}. The graph indicates a decrease in EQE from EQE_{peak} to EQE_{op} with an approximate drop of 10% to 30%.]
LEDs with Tunnel Junctions

- Conventional LEDs:
  - Efficiency Droop
  - Large LED chips operating at low current has to be used for high output power

- Cascaded LEDs:
  - High input power density: High voltage, carrier regeneration

- Multi-color LEDs

**Appl. Phys. Lett. 103, 081107 (2013)**
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Previous Work on Tunnel Junctions

**Standard p+ / n+ Tunnel Junctions**

- Large $E_g$
  - Wide depletion region, large energy barrier
- Doping restrictions
- n+ GaN / p+ GaN: High turn-on voltage (>1 V) and differential resistance ~0.02 $\Omega \cdot \text{cm}^2$ [1]
- n+ GaN / p+ InGaN: differential resistance ~6 x 10^{-3} $\Omega \cdot \text{cm}^2$ [2]

Previous Work on Tunnel Junctions

Standard p+ / n+ Tunnel Junctions
- Large $E_g$
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Polarization Engineered Tunnel Junctions
- High density polarization dipole sheet charge
  - Reduction of depletion width
- Reduced tunneling barrier
- GaN/InGaN/GaN Junctions: Low resistance $\sim 1 \times 10^{-4} \, \Omega \cdot \text{cm}^2$ [1]
- AlGaN/InGaN/AlGaN Junctions: $\sim 5 \times 10^{-4} \, \Omega \cdot \text{cm}^2$ [2,3]

UV TJs
1) S. Krishnamoorthy APL 102, 113503 (2013) (OSU)
2) Y. Zhang, APL, 106 (14), 141103 (2015).
3) Y. Zhang, APL 109 (12), 121102
Previous Work on Tunnel Junctions

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- High density polarization dipole sheet charge
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GaN Tunnel homojunction with heavy Si and Mg doping
- Heavy doping (> $1 \times 10^{20} \text{cm}^{-3}$)
  - Reduction of depletion width
- Polarization direction independent
  - Design flexibility, p-side down LEDs, solar cells

Previous Work on Tunnel Junctions

GaN Tunnel homojunction with heavy Si and Mg doping

- NPN diode grown by Ammonia MBE
- Using Si: $2 \times 10^{20} \text{cm}^{-3}$ & Mg: $1 \times 10^{20} \text{cm}^{-3}$, NPN diode dif. resistance $\sim 2 \times 10^{-4} \Omega \cdot \text{cm}^2$ at $10 \text{kA/cm}^2$ [1]

EPFL, Switzerland
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- VCSEL: MOCVD active region + Ammonia MBE n++ [2]
- Replace ITO with GaN TJ
- VCSEL with TJ showed $\sim 1.5$ V higher


EPFL, Switzerland

UCSB

Akyol.4@osu.edu; rajan@ece.osu.edu
Stand alone Homojunction TJs

- MBE growth
- Very high doping
- Sharp doping profile

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<thead>
<tr>
<th>Sample</th>
<th>Si-doping (cm$^{-3}$)</th>
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- Increasing Si & Mg doping boosts both forward and reverse tunneling

F. Akyol et al.
Stand alone Homojunction TJs

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- NDR observed from various devices in sample C
- Repeatable with (+) and (-) multiple voltage sweep
- Increasing Si & Mg doping boosts both forward and reverse tunneling
- Band-tail states might enable forward tunneling
- Nitride solar cells: Contacts & multi-junction
- NDR can enable new devices for logic and high frequency applications

F. Akyol et al.
Previous Work on Tunnel Junctions

Tunnel junctions are now feasible in a large range of band gaps
# Recent Reports of GaN NPN diodes

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<tr>
<th>Institution (Author)</th>
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<th>TJ Design</th>
<th>Doping</th>
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<th>R at high current</th>
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Can we combine heavy doping with polarization engineering for even lower resistance?
Combining polarization & heavy doping

To get more MOCVD-compatible conditions: can we combine both techniques?

- Introducing InGaN could reduce the required doping density
- Increasing doping density could reduce InGaN composition

Advantages:
Lower absorption
Lower defect generation
Outline

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GaN/InGaN/GaN TJs with low In\%: Design

Epitaxial Design

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<tr>
<th>Sample</th>
<th>InGaN thickness</th>
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<td>A</td>
<td>0 nm</td>
</tr>
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<td>B</td>
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<td>C</td>
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- **n++GaN:** 20 nm, Si: $1 \times 10^{20}$ cm$^{-3}$
- **n-GaN:** 130 nm, Si: $1 \times 10^{19}$ cm$^{-3}$
- **n++GaN:** 10 nm, Si: $5 \times 10^{20}$ cm$^{-3}$
- **p++In$_{0.12}$Ga$_{0.88}$N:** 0 nm - 5 nm, Mg: $1.5 \times 10^{20}$ cm$^{-3}$
- **p++GaN:** 20 nm, Mg: $5 \times 10^{20}$ cm$^{-3}$
- **p+GaN:** 280 nm, Mg: $6 \times 10^{19}$ cm$^{-3}$
- **uid-GaN:** 20 nm
- **n-GaN:** 100 nm, Si: $1 \times 10^{19}$ cm$^{-3}$
- **MOCVD Si:GaN substrate**
GaN/InGaN/GaN TJs with low In%: Design

### Epitaxial Design

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Thickness</th>
<th>Composition</th>
<th>Si Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>n++GaN</td>
<td>20 nm</td>
<td>0% In</td>
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<td>n-GaN</td>
<td>130 nm</td>
<td>In$<em>{12}$Ga$</em>{88}$N</td>
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<td>2% In</td>
<td>$5 \times 10^{20}$ cm$^{-3}$</td>
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<td>p++In$<em>{12}$Ga$</em>{88}$N</td>
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<td>Si: GaN</td>
<td>MOCVD</td>
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#### Tunnel Junction
- 300 nm In$_{0.12}$Ga$_{0.88}$N
- uid-GaN: 100 nm

#### PIN Diode
- MOCVD Si:GaN substrate

In$_{0.12}$Ga$_{0.78}$N intensity vs. angle (arcs)
GaN/InGaN/GaN TJs with low In%: I-V

- Good rectification for all samples
- ~7-8 orders between -6 V and 6 V
GaN/InGaN/GaN TJs with low In%: I-V

- Good rectification for all samples
- ~7-8 orders between -6 V and 6 V
- At 20 A/cm²
  - Sample A: 3.3 V
  - Sample B: 3.3 V
  - Sample C: 3.18 V
  - Sample D: 3.96 V
- Lowest voltage drop from 3 nm InGaN (sample C)

---

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GaN/InGaN/GaN TJs with low In%: I-V

- Measured up to cw current of 30 kA/cm²
- At 5 kA/cm²
  - Sample A: 4.78 V
  - Sample B: 4.56 V
  - **Sample C: 4.04 V**
  - Sample D: 5.34 V

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GaN/InGaN/GaN TJs with low In%: I-V

- Sample C => lowest resistance at both low & high current
- At 20 A/cm²:
  - Sample A: R=8.9 x 10⁻³ Ω.cm²
  - Sample B: R=9.5 x 10⁻³ Ω.cm²
  - Sample C: R=5.7 x 10⁻³ Ω.cm²
  - Sample D: R=1.7 x 10⁻² Ω.cm²

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n++GaN: 20 nm
Si: 1x10²⁰ cm⁻³

n-GaN 130 nm
Si: 1x10¹⁹ cm⁻³

n++GaN: 10 nm
Si: 5x10²⁰ cm⁻³

p++In₀.₁₂Ga₀.₈₈N: 0 nm - 5 nm
Mg: 1.5 x 10²⁰ cm⁻³

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Mg: 6x10¹⁹ cm⁻³

uid-GaN 20 nm

n-GaN: 100 nm
Si: 1x10¹⁹ cm⁻³

MOCVD Si:GaN substrate

Tunnel Junction

PIN Diode

0-> 3 nm
5 nm

Current (kA/cm²)
Voltage (V)

Differential Resistance (ohm.cm²)
GaN/InGaN/GaN TJs with low In%

Zero-bias energy-band diagram

- Lower tunneling width and barrier
- Further increase in InGaN thickness increases tunneling width (due to lower Mg doping in the InGaN layer)

✓ Lower tunneling width and barrier
✓ Further increase in InGaN thickness increases tunneling width (due to lower Mg doping in the InGaN layer)
Comparison of high current TJ resistance

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- Polarization engineering combined with high doping can enable low voltage drop
- Low Indium composition reduces the absorption losses
- Further optimization may be possible with reduced doping density for MOCVD compatible conditions

Summary

Systematic study on low In content (<15%) InGaN TJs with heavy Si and Mg doping

- Reduced voltage drop obtained from 3 nm InGaN sample compared to GaN tunnel homojunction
- Further increase of InGaN thickness increases turn-on voltage
- Keeping In-composition low for visible transparent TJ, record low voltage drop demonstrated

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Backup slides
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<td>p++GaN: 20 nm</td>
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<tr>
<td>Mg: 5 x 10^{20} cm^{-3}</td>
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<tr>
<td>p+GaN:280 nm</td>
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<tr>
<td>Mg: 6x10^{19} cm^{-3}</td>
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<tr>
<td>uid-GaN: 20 nm</td>
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<tr>
<td>n-GaN: 100 nm</td>
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<tr>
<td>Si: 1x10^{19} cm^{-3}</td>
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<tr>
<td>MOCVD Si:GaN substrate</td>
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</tbody>
</table>

- XRD data fits well with 12% and very different from the fits with 25% and 40%
- Indium content < 15%

SAMPLE C
Intensity (a.u.)
ω−2θ (arcsecs)

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