Ultra-Low Resistance GaN Tunnel Homojunctions with Repeatable Negative Differential Resistance and 150 kA/cm² Current

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The Ohio State University

Acknowledgements: National Science Foundation
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Outline

- Motivation
- Background
  - Stand-alone GaN tunnel homojunctions
  - NPN Diode using a GaN tunnel homojunction
- Summary
Interband Tunnel Junctions

**TJ in reverse bias**

- $E_c$
- $E_f, p$
- $E_f, n$
- $E_v$

**TJ in forward bias**

+ $E_c$
- $E_f, p$
- $E_f, n$
- $E_v$

*Electron $\leftrightarrow$ hole carrier conversion*

- Injection of holes into p-type material
- Applications: LEDs, lasers
- Recombination of electrons and holes by tunneling
- Applications: Solar cells
LEDs with Tunnel Junctions

- Top emitting
  - No need to flip-chip
  - Low contact resistance to n-GaN
  - High conductivity in n-layers
  - Especially for UV LEDs, lasers
  - Overcome absorption losses
LEDs with Tunnel Junctions

- Conventional LEDs:
  - Efficiency Droop limits high input power density
  - High power output at low input current using large LED chips
- Cascaded LEDs:
  - High input power density: High voltage, carrier regeneration
- Multi-color LEDs

Efficiency Droop: $\sim 10\%$ to $30\%$

Cascaded LED Structure

- MQW LED_{n+2}
- TJ_{n+1}
- MQW LED_{n+1}
- TJ_{n}
- MQW LED_{n}
- TJ_{n-1}

- Electron
- Hole
- Inter-band Tunneling

*Appl. Phys. Lett. 103*, 081107 (2013)*
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Early 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 $\sim 0.02 \ \Omega . \text{cm}^2$ [1]
- n+ GaN / p+ InGaN: differential resistance $\sim 6 \times 10^{-3} \ \Omega . \text{cm}^2$[2]

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Early Work on Tunnel Junctions

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- 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/AlN/GaN Junctions: Resistive $\sim 1 \ \Omega \cdot \text{cm}^2$ [1,2]
- GaN/InGaN/GaN Junctions: Low resistance $\sim 1 \times 10^{-4} \ \Omega \cdot \text{cm}^2$ [3]
- AlGaN/InGaN/AlGaN Junctions [4,5]

1) M. J. Grundmann, PhD Dissertation (UCSB)
2) J. Simon et.al., *PRL* 103, 026801 (2009) (Notre Dame)
3) S. Krishnamoorthy APL 102, 113503 (2013) (OSU)
Early Work on Tunnel Junctions

**Standard p+ / n+ Tunnel Junctions**
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**Polarization Engineered Tunnel Junctions**
- 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, visible transparent, p-side down LEDs, solar cells

Early Work on Tunnel Junctions

GaN Tunnel homojunction with heavy Si and Mg doping
- Heavy doping ($> 1 \times 10^{20} \text{cm}^{-3}$)
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- NPN diode grown by Ammonia MBE
- Using Si: $2 \times 10^{20}$ cm$^{-3}$ & Mg: $1 \times 10^{20}$ cm$^{-3}$, NPN diode dif. resistance $\sim 2 \times 10^{-4}$ $\Omega$.cm$^2$ at 10 kA/cm$^2$ [1]

EPFL, Switzerland
Early Work on Tunnel Junctions

GaN Tunnel homojunction with heavy Si and Mg doping
- Heavy doping (> 1 x 10^{20} cm^{-3})
- Reduction of depletion width
- Polarization direction independent
- Design flexibility, visible transparent, p-side down LEDs, solar cells

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

VCSEL: MOCVD active region + Ammonia MBE n++ [2]
- Replace lossy ITO with GaN TJ
- VCSEL with TJ showed ~1.5 V higher


EPFL, Switzerland

UCSB
Polarization-Engineered Tunnel Junctions

- AlN barrier TJ: M. J. Grundmann, PhD Dissertation (UCSB)
- InGaN/GaN/InGaN: S. Krishnamoorthy *APL* 102, 113503 (2013)
- 55%AlGaN /InGaN/ 55%AlGaN: Y. Zhang et al. 73rd Device Res. Conf.
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GaN Homo-tunnel Junctions: stand alone

**Epitaxial Design**

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<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Doping</th>
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<tbody>
<tr>
<td>p++GaN</td>
<td>20 nm</td>
<td>3x10^{20} cm^{-3}</td>
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**Sample	Si-doping (cm^{-3})	Mg-doping (cm^{-3})**

- A: 2x10^{20}     3x10^{20}
- B: 4x10^{20}     3x10^{20}
- C: 4x10^{20}     5x10^{20}

**MBE growth**
- Very high doping
- Sharp doping profile
GaN Homo-tunnel Junctions: stand alone

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MBE growth
✓ Very high doping
✓ Sharp doping profile

AFM scan
5 x 5 μm², rms~0.5 nm

STEM z-contrast scan
✓ No defects observed
✓ Defects < 5.9 x 10⁸ cm⁻²
GaN Homo-tunnel Junctions: stand alone

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MBE growth

✓ Very high doping
✓ Sharp doping profile

Sample A:

✓ ~ 100 A/cm$^2$ at -1 V
✓ Lower forward current
GaN Homo-tunnel Junctions: stand alone

Epitaxial Design

- Sample A:
  - ~ 100 A/cm² at -1 V
  - Lower forward current
- Sample B:
  - ~ 500 A/cm² at -1 V
  - Higher forward current ~130 A/cm² at -1 V

MBE growth
- Very high doping
- Sharp doping profile

Sample | Si-doping (cm⁻³) | Mg-doping (cm⁻³)
--- | --- | ---
A | 2x10²⁰ | 3x10²⁰
B | 4x10²⁰ | 3x10²⁰
C | 4x10²⁰ | 5x10²⁰

TJ

- p++GaN: 20nm
- Mg: 3x10²⁰ cm⁻³
- p+GaN: 180 nm
- Mg: 1x10²⁰ cm⁻³
- p++GaN: 20 nm
- n++GaN: 10 nm
- n-GaN 100 nm
- Si: 4x10¹⁹ cm⁻³
- MOCVD Si:GaN substrate

Current (A/cm²)

Voltage (V)
GaN Homo-tunnel Junctions: stand alone

Sample A:
- ~100 A/cm² at -1 V
- Lower forward current

Sample B:
- ~500 A/cm² at -1 V (limited by p-contact)
- Forward current ~125 A/cm² at -1 V

Sample C:
- ~750 A/cm² at -1 V (limited by p-contact)
- Forward current ~190 A/cm² at -1 V
- Negative differential resistance (NDR) observed first time in Nitride p-n diodes

Epitaxial Design
- Very high doping
- Sharp doping profile

MBE growth

TJ

Epitaxial Design
- Very high doping
- Sharp doping profile

Sample | Si-doping (cm⁻³) | Mg-doping (cm⁻³)
-------|-----------------|------------------
A      | 2x10²⁰          | 3x10²⁰           |
B      | 4x10²⁰          | 3x10²⁰           |
C      | 4x10²⁰          | 5x10²⁰           |

Current (A/cm²) vs Voltage (V)

- Sample A:
  - ~100 A/cm² at -1 V
  - Lower forward current
- Sample B:
  - ~500 A/cm² at -1 V (limited by p-contact)
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MOCVD Si:GaN substrate

MBE growth
- Very high doping
- Sharp doping profile
GaN Homo-tunnel Junctions: stand alone

Epitaxial Design

- **p++GaN**: 20nm
- **Mg**: $3 \times 10^{20}$ cm$^{-3}$
- **p+GaN**: 180 nm
- **Mg**: $1 \times 10^{20}$ cm$^{-3}$
- **p++GaN**: 20 nm
- **n++GaN**: 10 nm
- **n-GaN**: 100 nm
  - Si: $4 \times 10^{19}$ cm$^{-3}$
- **MOCVD Si**: GaN substrate

**MBE growth**
- ✔ Very high doping
- ✔ Sharp doping profile

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- NDR observed from various devices in sample C (peak to valley ratio (PVCR) $\sim 1.1$)
- Peak current of $\sim 300-350$ A/cm$^2$ at $V = 1.6 - 1.7$ V
- 1 A/cm$^2$ at $V = 0.01$ V, excellent for solar cells
GaN Homo-tunnel Junctions: stand alone

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MBE growth
- Very high doping
- Sharp doping profile

- Repeatable with (+) and (-) voltage sweep
- Negligible degradation with multiple scans
GaN Homo-tunnel Junctions: stand alone

Epitaxial Design

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MBE growth
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What can enable the peak forward tunneling current at ~1.6 V?

Sample | Si-doping (cm\(^{-3}\)) | Mg-doping (cm\(^{-3}\))
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A      | 2x10\(^{20}\)  | 3x10\(^{20}\) |
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Epitaxial Design

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MOCVD Si:GaN substrate

Repeatable with (+) and (-) voltage sweep
Negligible degradation with multiple scans
GaN Homo-tunnel Junctions: Band-tail states

- Fermi-level pinned above the valance band
  - No states for tunneling at zero bias
  - Can only tunnel under reverse bias

Introducing band-tail states in p-GaN
- States for tunneling at zero & forward bias
GaN Homo-tunnel Junctions: Band-tail states

- Introducing band-tail states in p-GaN
- States for tunneling at zero & forward bias

Kane’s formula of density of states (DOS):

$$\rho(E) = \frac{(2m)^{3/2}}{2\pi^2\hbar^3} \eta^{1/2} y(E/\eta)$$

Kane’s function:

$$y(x) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{x} \sqrt{x-\zeta} \exp\left(-\zeta^2\right) d\zeta$$

- Band tail states can be responsible for forward tunneling at high (~1.6 V) forward voltage
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Schematic energy band diagram

- N-type contacts in both terminals => Low contact resistance
- Increased Si & Mg doping compared to the report of Malinverni et al. (Si: $2 \times 10^{20}$ cm$^{-3}$ & Mg: $1 \times 10^{20}$ cm$^{-3}$)

GaN Homo-tunnel Junctions: NPN diode

- Forward voltage of 3.3 V at 20 A/cm²
- Differential resistance $4 \times 10^{-5}$ ohm.cm² at 10 kA/cm²
- Reaching record high 150 kA/cm² at 7.6 V
- Lowest reported differential resistance of $1 \times 10^{-5}$ ohm.cm² at 150 kA/cm²
GaN Homo-tunnel Junctions: NPN diode

- Forward voltage of 3.3 V at 20 A/cm²
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- Reaching record high 150 kA/cm² at 7.6 V
- Lowest reported differential resistance of $1 \times 10^{-5}$ ohm.cm² at 150 kA/cm²
Summary

- First GaN Esaki diodes demonstrated with repeatable NDR characteristics
  - Peak forward current ~300-350 A/cm² at ~1.6 V
  - Band-tail states can be responsible

- Highest c.w. current operation of any Nitride bipolar device with lowest TJ resistance
  - Tunneling current up to 150 kA/cm²
  - Lowest reported tunneling resistance in Nitrides
    - $4 \times 10^{-5}$ ohm.cm² at 10 kA/cm²
    - $1 \times 10^{-5}$ ohm.cm² at 150 kA/cm²

F. Akyol et al.