Designing efficient AlGaN-based UV LED

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Outline

• Introduction & motivation
• Technical background
• Design & calibration
• Simulation results
• Conclusion & Future work
Introduction

- AlGaN-based materials suitable for fabricating UV LED with applications in sterilization, illumination, optical sensing, etc.
  - Direct transition-type semiconductor in entire composition range
  - Possible to give high efficient light emissions from quantum wells
  - Possible to be either p- or n-type semiconductors
  - Long life time & environmental friendly

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Challenges & motivation

- Recent UV LED progress
  - EQE > 10%
  - Output power: several tens to several thousands of megawatts
  - Target efficiency: >30%
- Limited applicability of AlGaN-based LED due to low working efficiency
  - High quality AlGaN-based materials hard to obtain
  - Low efficient in AlGaN doping
  - Low injection efficiency of both carriers simultaneously due to large carrier mobility difference
  - Quantum-confined Stark effect reduces probability of radiative recombination
  - Low light extraction efficiency
  - AlN with low threading dislocation hard to obtain
Technical background

- LED output power: \( P_{out} = \eta_e V I \)
- Internal resistance: \( R = \frac{dV}{dl} \)
  - Related to LED output power & efficiency due to heat generation
- Internal quantum efficiency (IQE)
  - \( \eta_i = \frac{B \Delta n^2}{A \Delta n + B \Delta n^2 + C \Delta n^3} = \frac{\tau_r^{-1}}{\tau_r^{-1} + \tau_{nr}^{-1}} \)
  - \( A,B,C \): Shockley-Reed-Hall, radiative, Auger recombination coefficient
  - \( \tau_{nr}, \tau_r \): non-radiative & radiative lifetimes
### Design & calibrations

- **Representative size:** $L_1:L_2 = 6\mu m:1\mu m$
- **Grading layers**
  - Reduce internal resistance
  - Alleviate lattice mismatch
- **Calibrations**
  - P-GaN contact: p-GaN vs p-$\text{Al}_x\text{GaN}$/undoped GaN
  - Al$_x$GaN/AlN MQW: $x$ spans from 0.6 to 0.82; AlN/GaN ultrathin structure
  - $L_1:L_2$ size calibration: 6\mu m:1\mu m, 12\mu m:2\mu m, 30\mu m:5\mu m, 60\mu m:10\mu m, 120\mu m:20\mu m

#### Materials:

- **AlN substrate**
- **1 nm UID Al$_x$GaN grading layer:** $x$ from 1 to 0.7
- **100 nm n Al$_x$GaN grading layer:** $x$ from 0.7 to 1, $n = 5 \times 10^{18} \text{ cm}^{-3}$
- **6 nm AlN barrier**
- **5 nm Al$_{0.8}$Ga$_{0.2}$N QW**
- **600 nm n Al$_{0.6}$Ga$_{0.4}$N**
  - $n = 1 \times 10^{19} \text{ cm}^{-3}$
- **100 nm p Al$_x$GaN grading layer:** $x$ from 1 to 0, $p = 5 \times 10^{18} \text{ cm}^{-3}$
- **5 nm p GaN**
  - $p = 5 \times 10^{18} \text{ cm}^{-3}$
- **100 nm p GaN contact**
  - $p = 1 \times 10^{19} \text{ cm}^{-3}$
- **5 nm p GaN**
  - $p = 5 \times 10^{18} \text{ cm}^{-3}$

#### Diagram:

- 3x Al$_{0.8}$GaN/AlN QW structure
- Representative size: $L_1:L_2 = 6\mu m:1\mu m$
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Simulation results - QW composition calibration

- Al composition effect on UV LED
  - Emission wavelength
  - Al composition ↑, bandgap ↑, better carrier confinement → higher IQE
  - However, Al composition too high → decreased IQE due to carriers trapped in defects in crystal structure
- Al composition spans from 0.6 to 0.82
  - Wavelength stays at around 220 nm
  - Increased IQE with increased Al composition. However, slower increase with higher Al composition
### Simulation results – p-contact structure calibration

- **Advantages of AlxGaN/GaN superlattice (SL)**
  - Acceptor can obtain electrons from minibands of SL rather than valence band → Low activation → High radiative recombination rate
  - Formation enthalpy of acceptor in AlN & GaN larger than in bulk AlGaN → Higher doping level → Ohmic contact
  - AlxGaN/GaN contact has higher bandgap than GaN contact → Low absorption possibility of DUV light → High light extraction efficiency

- **Disadvantage of SL**
  - High Al composition → Higher resistance

- **Simulation of p-AlxGaN/UID-GaN=10nm:5nm with x spanning from 0 to 0.4**
Simulation results – p-contact structure calibration

- Simulation of p-Al\textsubscript{x}Ga\textsubscript{1-x}N/UID-GaN contact where x spans from 0 to 0.4
  - Though Al\textsubscript{0.4}Ga\textsubscript{0.6}N/GaN has slightly higher hole concentration & IQE, it has highest internal resistance
  - Though Al\textsubscript{0.2}Ga\textsubscript{0.8}N/GaN has slightly lower IQE & hole concentration, it has much lower resistance
  - Depending on applications, compromise must be made between these parameters
Simulation results – scaling effect

- Application such as sterilization for medical equipment & environmental detection needs UV micro-LED with a size of a few microns
- In micro-LEDs, smaller size means smaller IQE due to surface recombination & non-radiative recombination due to defects & impurities
- UV micro-LEDs can improve efficiency due to relaxation of strain, enhancement of LEE, and mitigation of severe current crowding effect
- Simulation of various UV LED size($L_1:L_2$): 6um:1um, 12um:2um, 30um:5um, 60um:10um, 120um:20um
  - IQE doesn’t decrease strictly with size
  - 12um:2um has size 10x smaller, but IQE only ~3% smaller compared to 120um:20um
- Surface passivation & surface recombination can be included in future simulation
Future work - QW structure calibration

- Ultrathin AlN/GaN can against spatial separation of wave functions in QCSE → Increase transition energy between conduction & valence band → Increase radiative recombination probability
- Simulation of QW consists of multiple ultrathin GaN/AlN = 1ML:4ML
  - Drastic decrease in IQE
  - Wrong Crosslight setup
Conclusion

- IQE increases with Al composition in AlxGaN/AlN QW, but increases much slower when approaching 0.8.
- High Al composition p-AlxGaN/UID-GaN SL contact increases IQE & doping level but resistance decreases drastically when Al composition > 0.3.
- Small size of L₁:L₂ = 12um:2um exhibits decent IQE for a UV micro-LED.
- Future Work
  - Ultrathin GaN/AlN QW structure
  - N-dopant calibration to against DX-center
  - Include surface passivation & surface recombination in size simulation
Thanks

Q&A