Designing efficient AlGaN-based UV LED

Xizheng Fang

ECE ILLINOIS

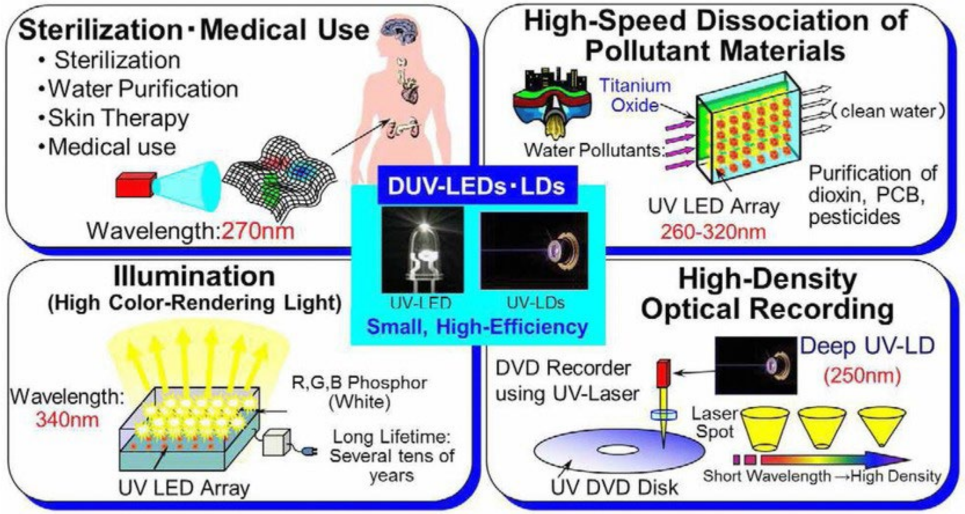
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Outline

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

Introduction

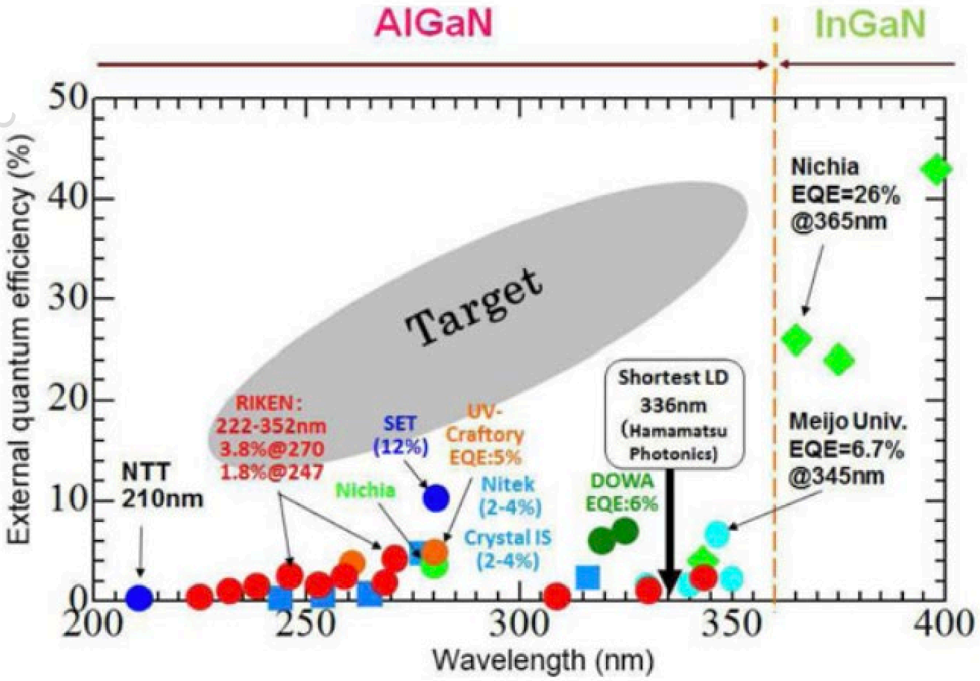
- AlGaN-based materials suitable for fabricating UV LED with applications in sterilization, illumination, optical sensing, etc.
  - Direct transition-type semiconductor in entire composition range
  - Possible to give high efficient light emissions from quantum wells
  - Possible to be either p- or n-type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



Other application fields:
- Sterilization, household air cleaners
- High speed purification of automobile exhaust gasses
- Optical sensing (luminescence analysis, surface analysis, UV sensing)
- Chemical and biochemical industry

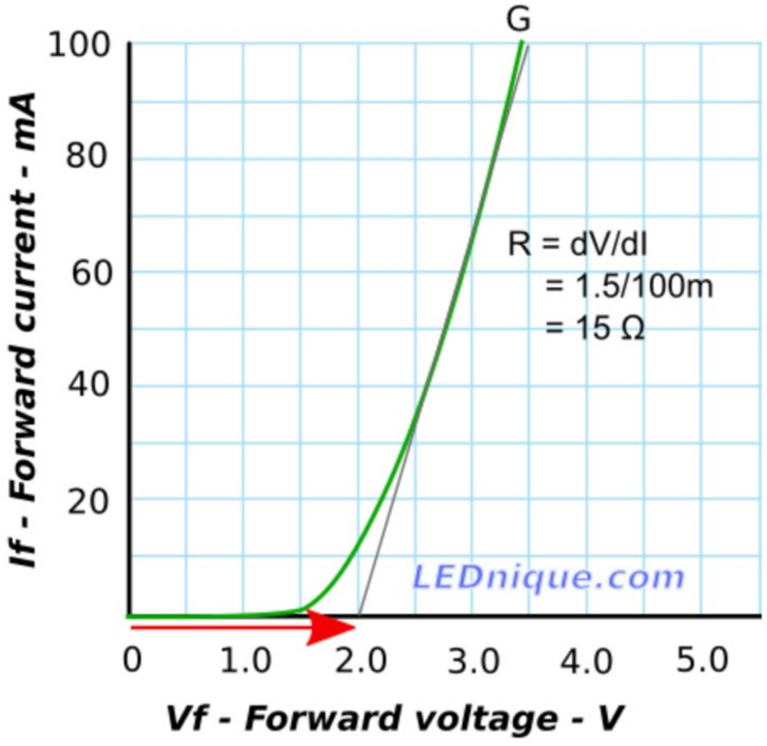
Challenges & motivation

- 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



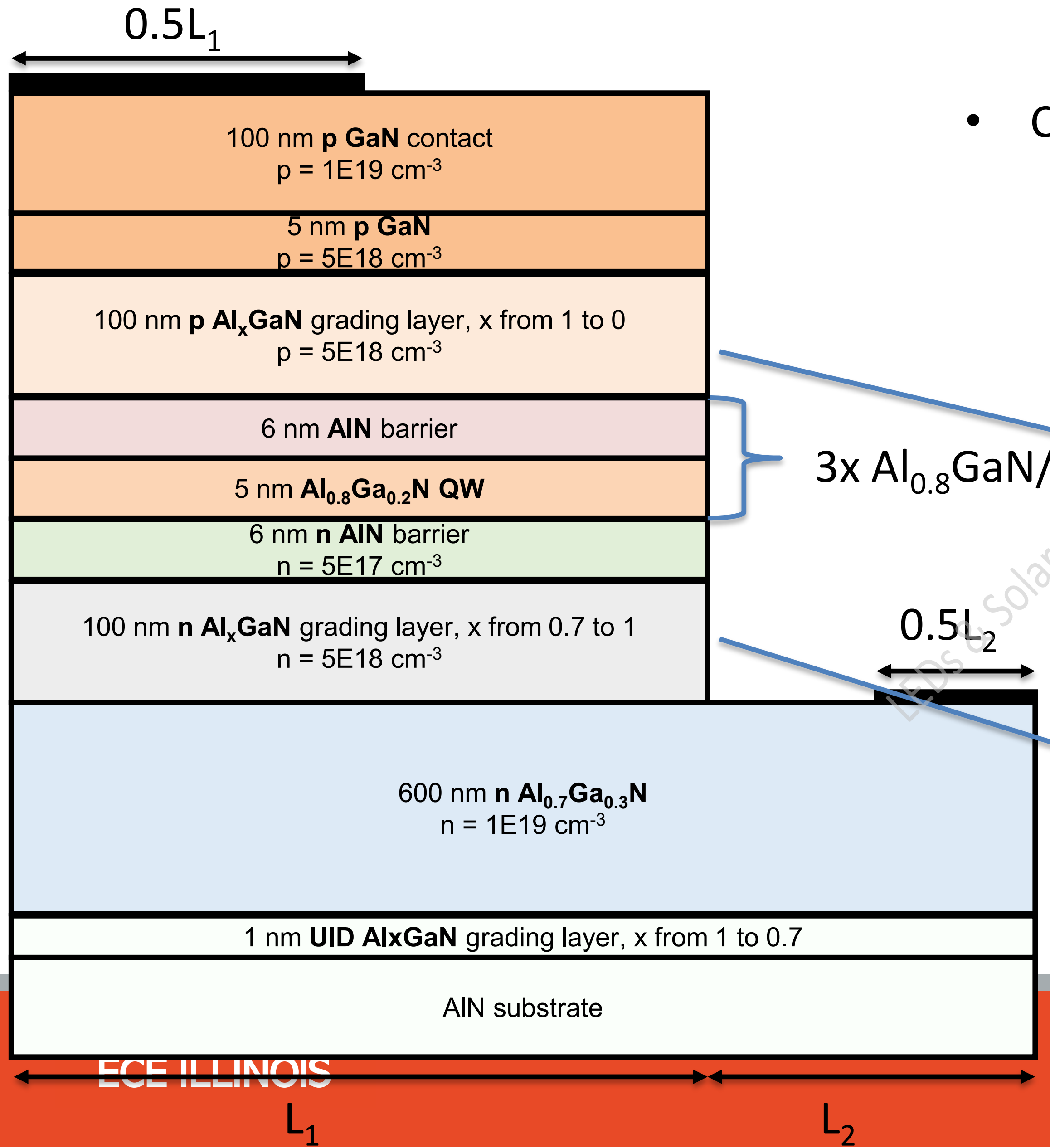
Technical background

- LED output power: $P_{out} = \eta_e V I$
- Internal resistance: $R = {}^{dV}/_{dI}$
  - 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
  - τ_{nr}, τ_r: non-radiative & radiative lifetimes



Design & calibrations

- Representative size: L_1:L_2 = 6um:1um
- Grading layers
  - Reduce internal resistance
  - Alleviate lattice mismatch
- Calibrations
  - P-GaN contact: p-GaN vs p-Al_xGaN/undoped GaN
  - Al_xGaN/AlN MQW: x spans from 0.6 to 0.82; AlN/GaN ultrathin structure
  - L_1:L_2 size calibration: 6um:1um, 12um:2um, 30um:5um, 60um:10um, 120um:20um



100 nm **p GaN** contact
p = 1E19 cm^{-3}

5 nm **p GaN**
p = 5E18 cm^{-3}

100 nm **p Al_xGaN** grading layer, x from 1 to 0
p = 5E18 cm^{-3}

6 nm **AlN** barrier

5 nm **$Al_{0.8}Ga_{0.2}N$ QW**

6 nm **n AlN** barrier
n = 5E17 cm^{-3}

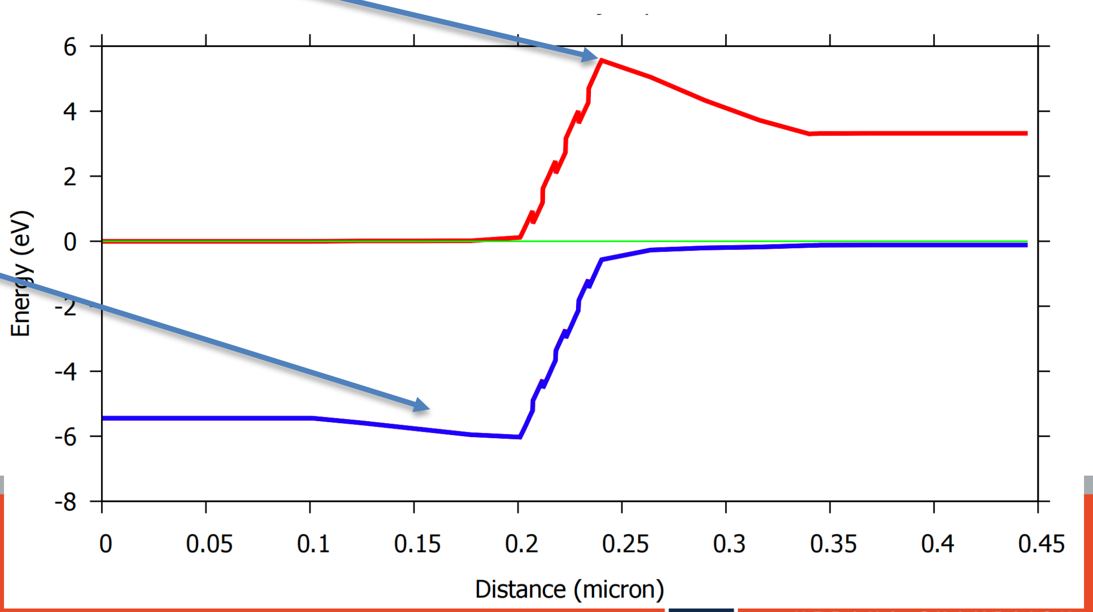
3x $Al_{0.8}$GaN/AlN QW structure

100 nm **n Al_xGaN** grading layer, x from 0.7 to 1
n = 5E18 cm^{-3}

600 nm **n $Al_{0.7}Ga_{0.3}N$**
n = 1E19 cm^{-3}

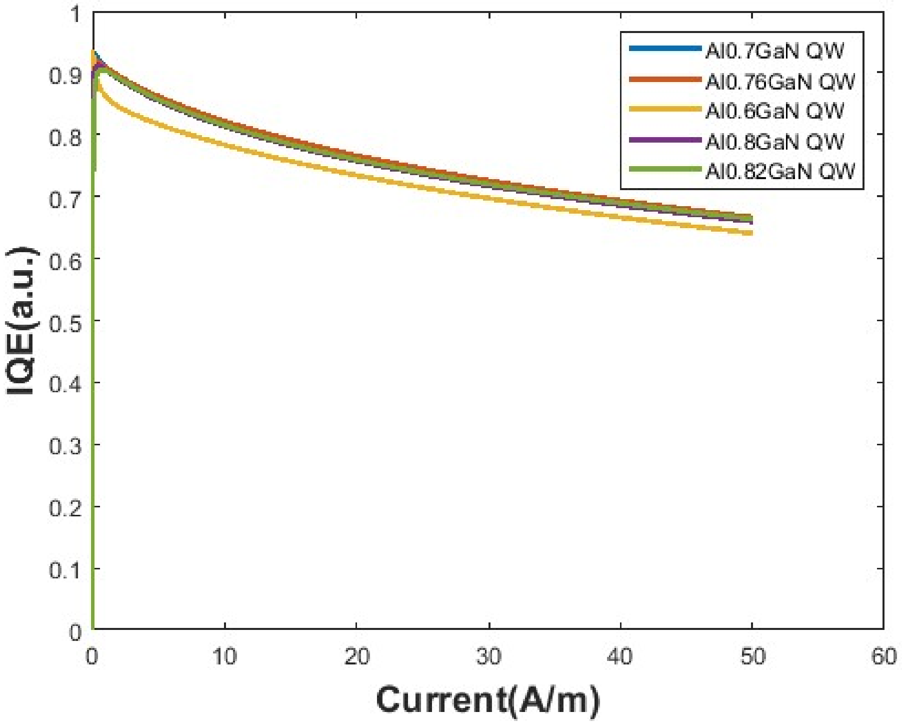
1 nm **UID AlxGaN** grading layer, x from 1 to 0.7

AlN substrate



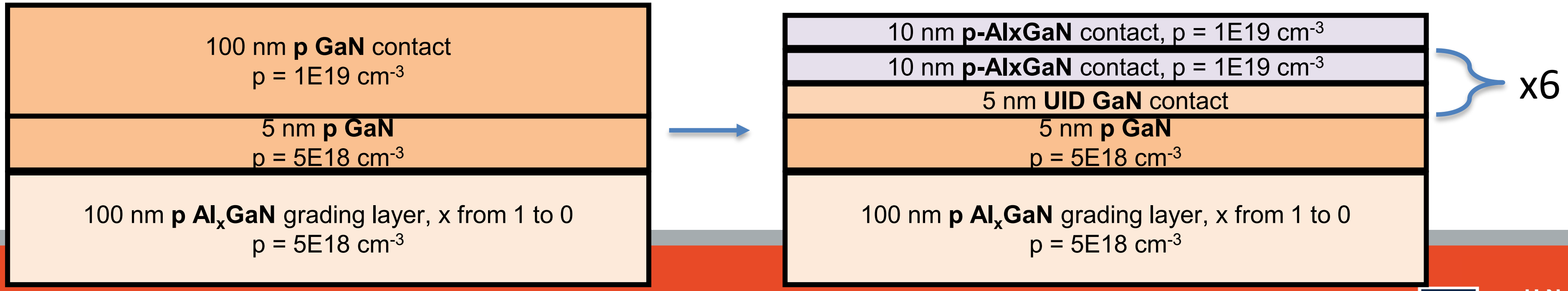
Simulation results - QW composition calibration

- 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



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10 nm **p-AlxGaN** contact, p = 1E19 cm^{-3}

10 nm **p-AlxGaN** contact, p = 1E19 cm^{-3}

5 nm **UID GaN** contact

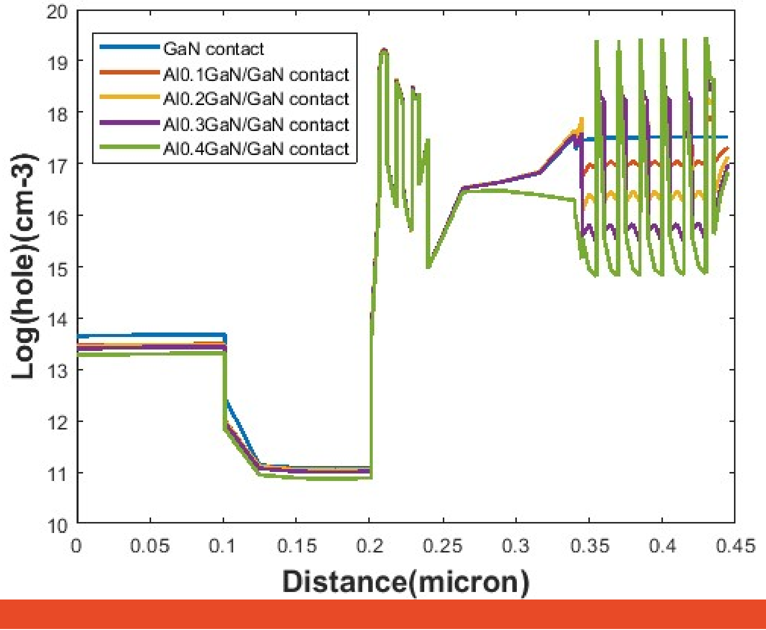
x6

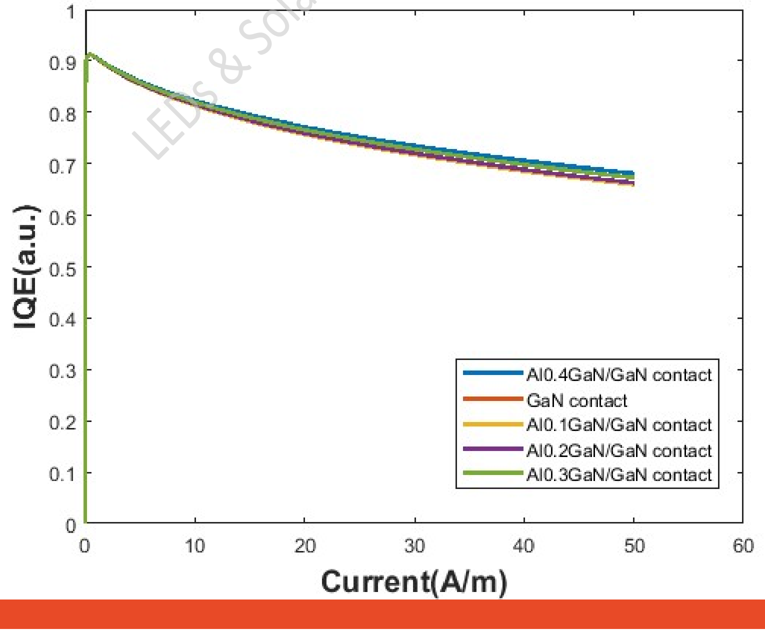
5 nm **p GaN**
p = 5E18 cm^{-3}

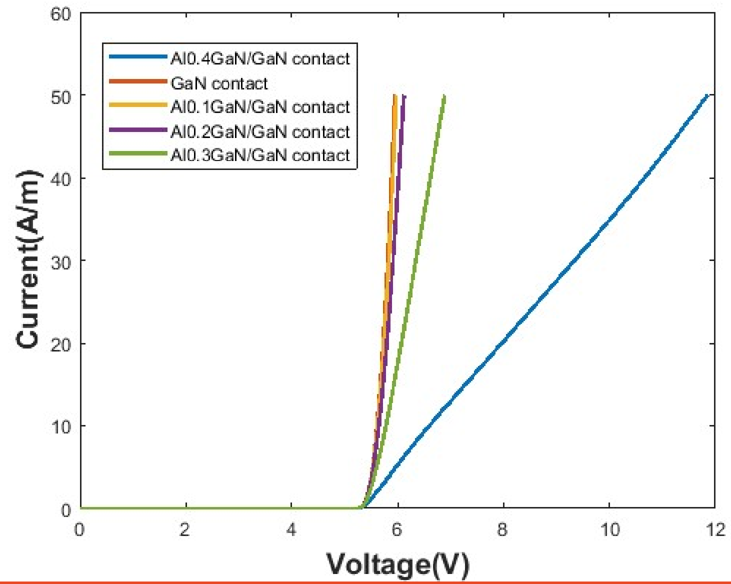
100 nm **p Al_xGaN** grading layer, x from 1 to 0
p = 5E18 cm^{-3}

Simulation results – p-contact structure calibration

- Simulation of p-AlxGaN/UID-GaN contact where x spans from 0 to 0.4
    - Though $Al_{0.4}GaN/GaN$ has slightly higher hole concentration & IQE, it has highest internal resistance
    - Though $Al_{0.2}GaN/GaN$ has slightly lower IQE & hole concentration, it has much lower resistance
    - Depending on applications, compromise must be made between these parameters

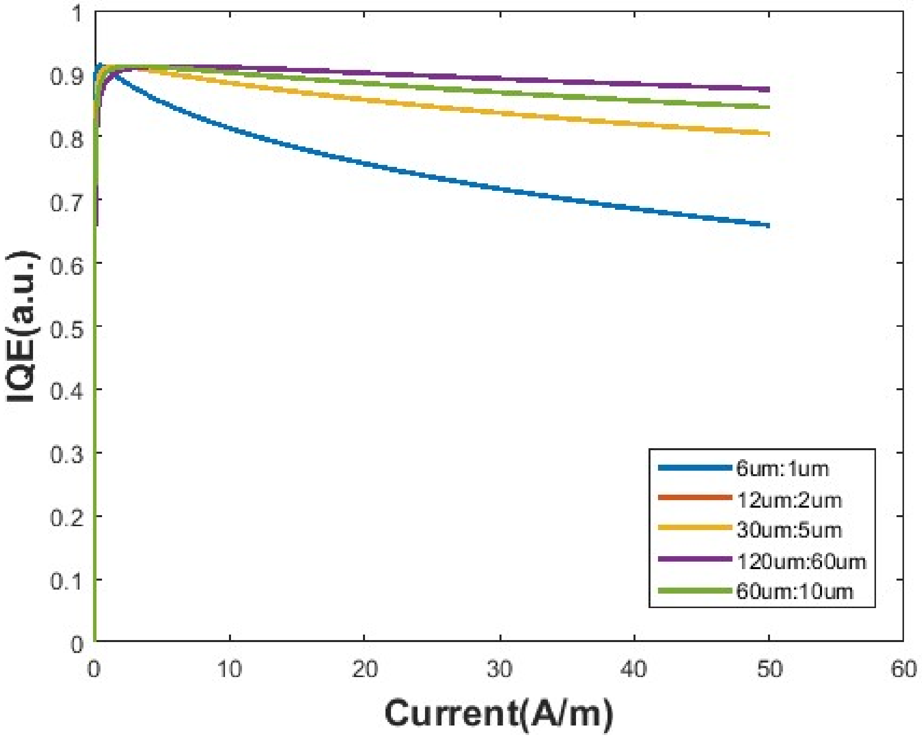






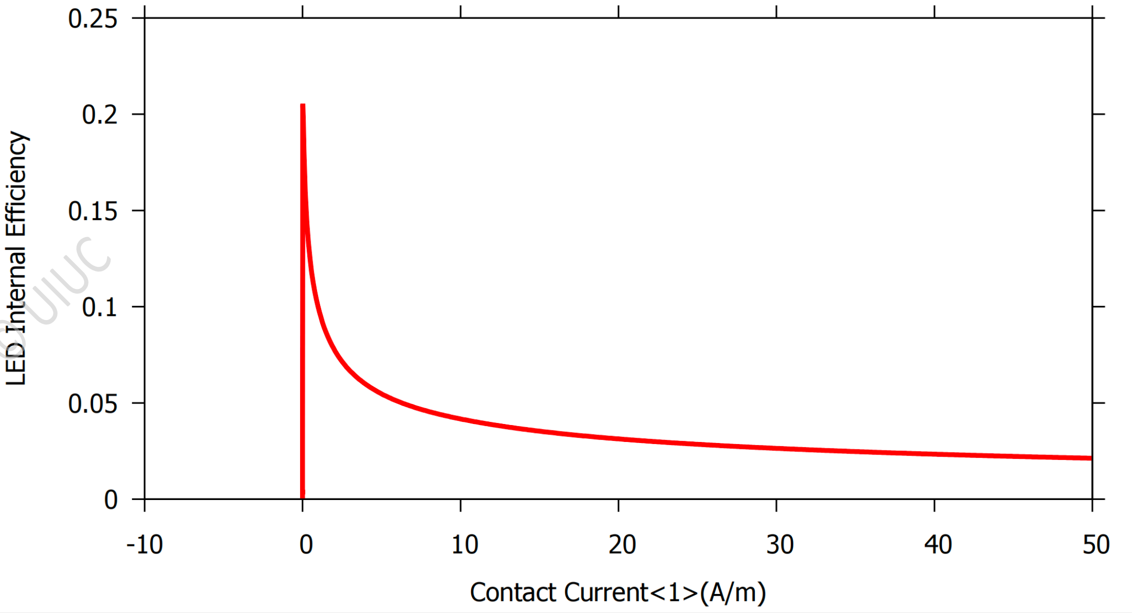
Simulation results – scaling effect

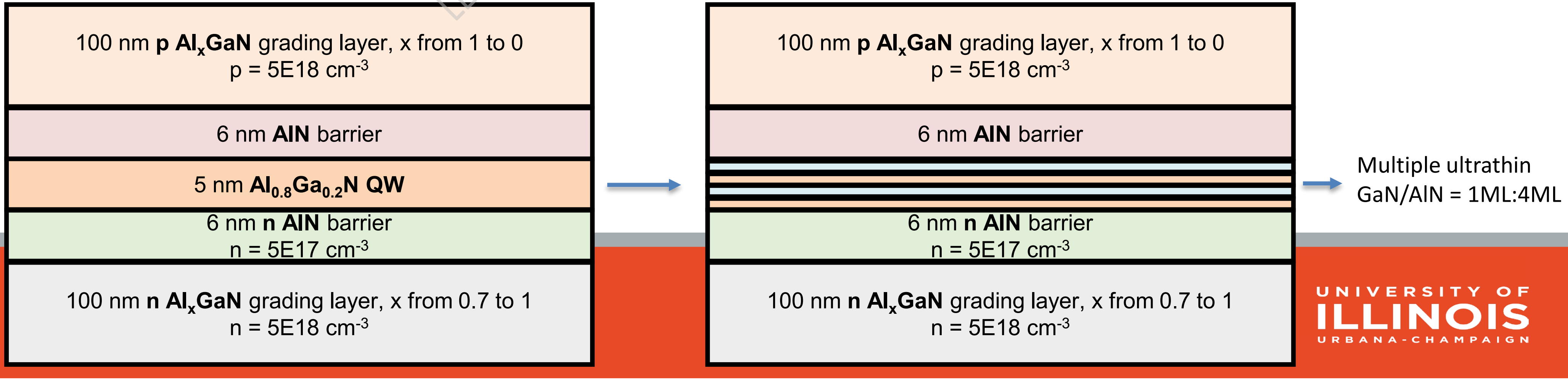
- Application such as sterilization for medical equipment & environmental detection needs UV micro-LED with a size of a few microns
- In micro-LEDs, smaller size means smaller IQE due to surface recombination & non-radiative recombination due to defects & impurities
- UV micro-LEDs can improve efficiency 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





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Multiple ultrathin
GaN/AlN = 1ML:4ML

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 L_1:L_2 = 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