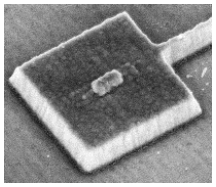
2019 NSF STC Virtual Site Visit
February 8, 2019

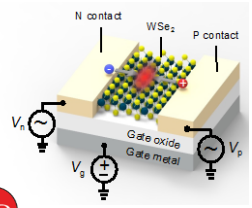
Theme III: Nanophotonics For Energy-Efficient Communications

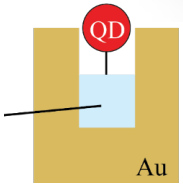
Theme Leader: Ming C. Wu

Current Theme Projects & PI's

➢ Optical antenna-enhanced nanoLED







- Electrical injection III-V antenna-LEDs
  [Wu, Yablonovitch, UCB; Kim, MIT]
- Monolayer TMDC antenna-LEDs
  [Wu, Javey, Yablonovitch, UCB]
- Quantum dot antenna-LED
  [Wu, Bartl, UCB; Bulovic, MIT]





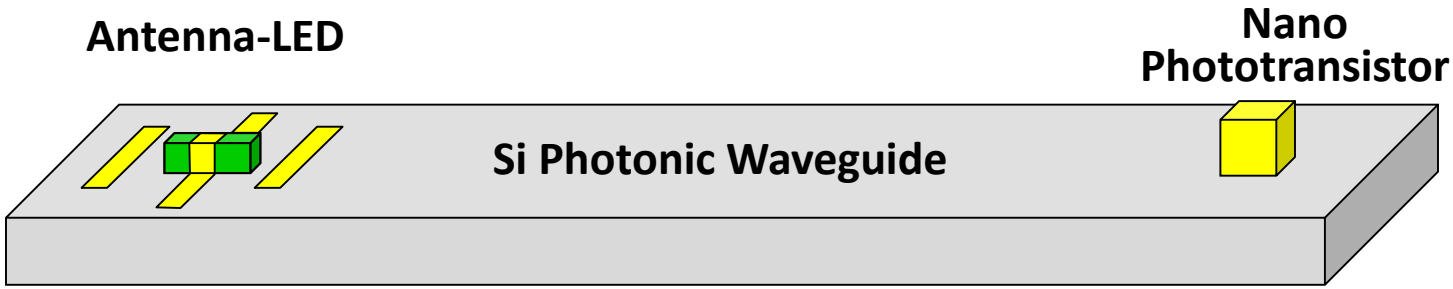

➢ Link modeling and system analysis
[Stojanovic, UCB]

Team Members

- Theme III inter-institutional postdoc
  - Seth Fortuna
- Graduate Students:
  - Matin Amani, Nicolas Andrade, Kevin Han, Sean Hooten, Jonas Kapraun, Shiekh Uddin, George Zhang (UCB)
- Undergrad:
  - Joy Cho (UCB)
- Postdocs:
  - Der-hsien Lien, Kyungmok Kwon
- Alum
  - Sujay Desai (Intel), Peida Zhao (Lam), Chris Heidelberger (MIT-Lincoln Lab), Indrasen Bhattacharya (KLA-Tencor), Kevin Messer (Magic Leap), Christopher Keraly (PARC), Ryan Going (Infinera), Michael Eggleston (Bell Labs), Wilson Ko (OURS), Yue Lu (DiDi), Geun Ho Anh (PhD at Stanford)

Theme Overview

- **Main goal: Dramatically improve the interconnect energy efficiency to 20 aJ/bit @ 20 photons/bit**
  (Current state of the art: 100s fJ/bit @ 10,000 ph/bit)



Our Approach

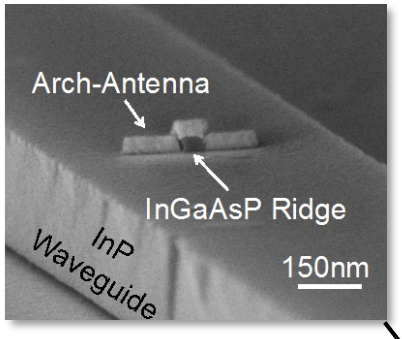
Antenna-Enhanced LED

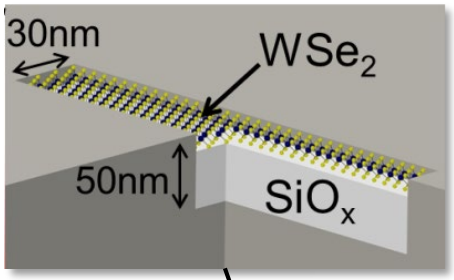
- **No threshold (DC bias)**
- **Use optical antenna to enhance spontaneous emission rate**
- **Faster than laser**

Ultra-Sensitive Photoreceivers

- **Ultralow capacitance (< 100aF) to enlarge photo signal**
- **Integrate PD with first gain stage to eliminate wire capacitance**

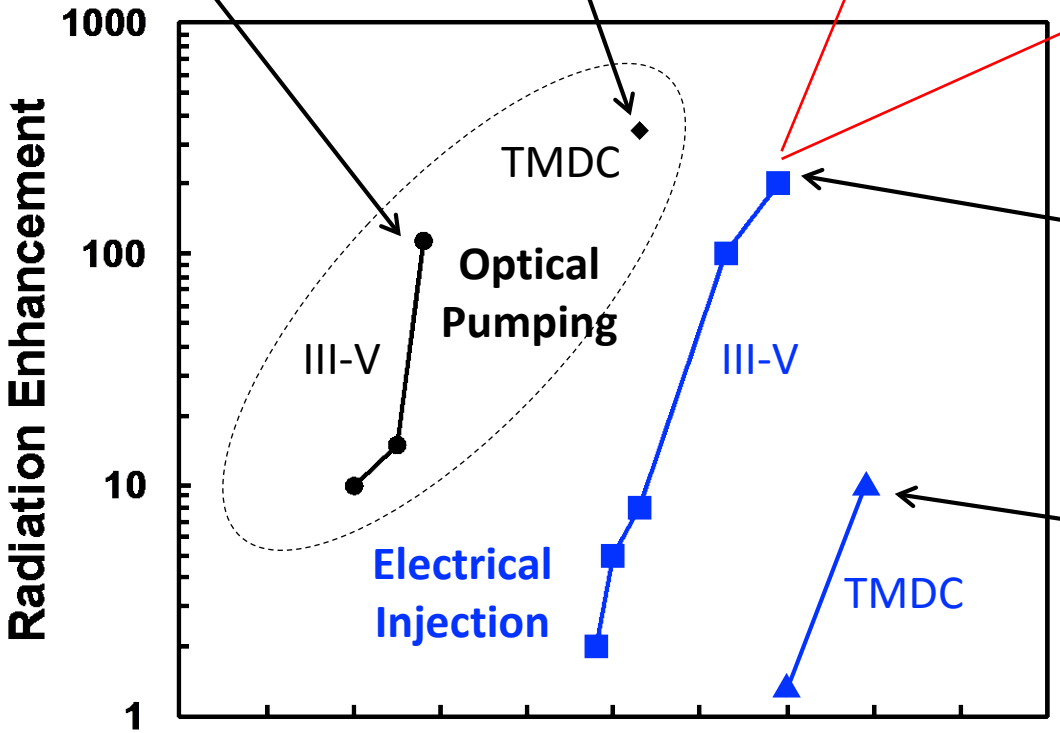
Progress of Antenna LED under E³S

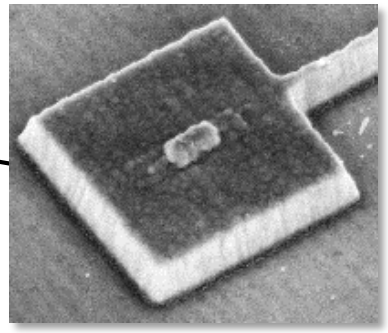


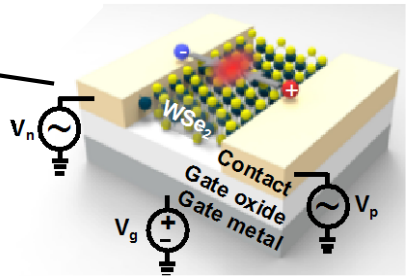


Current Focus:

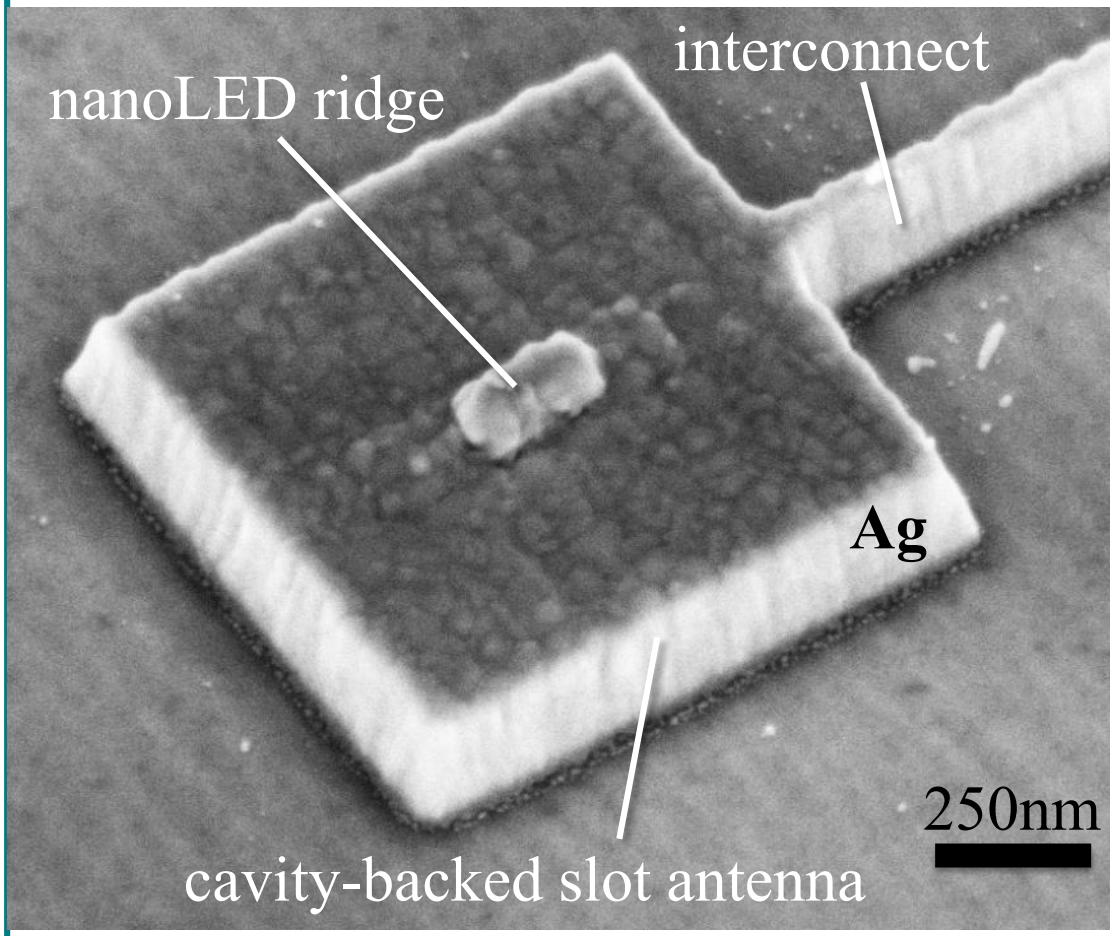
- Temporal response
- Efficiency
- Output power
- Waveguide coupling
- Link demo

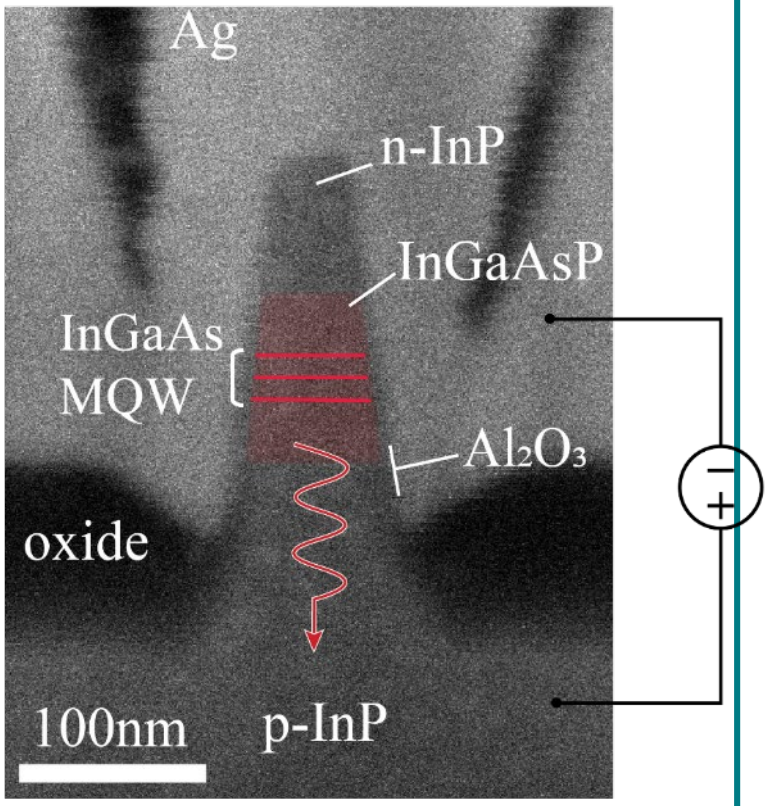




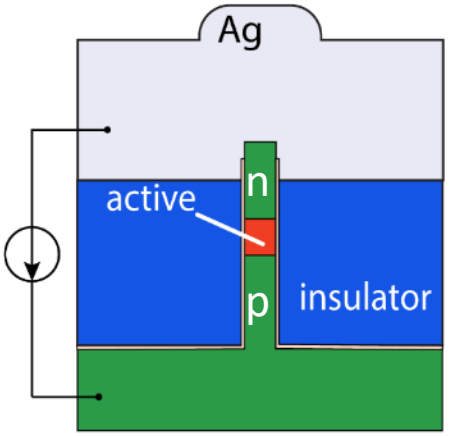


Electrically-injected III-V antenna-LED

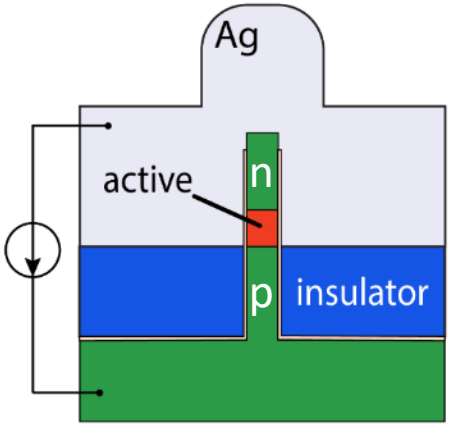




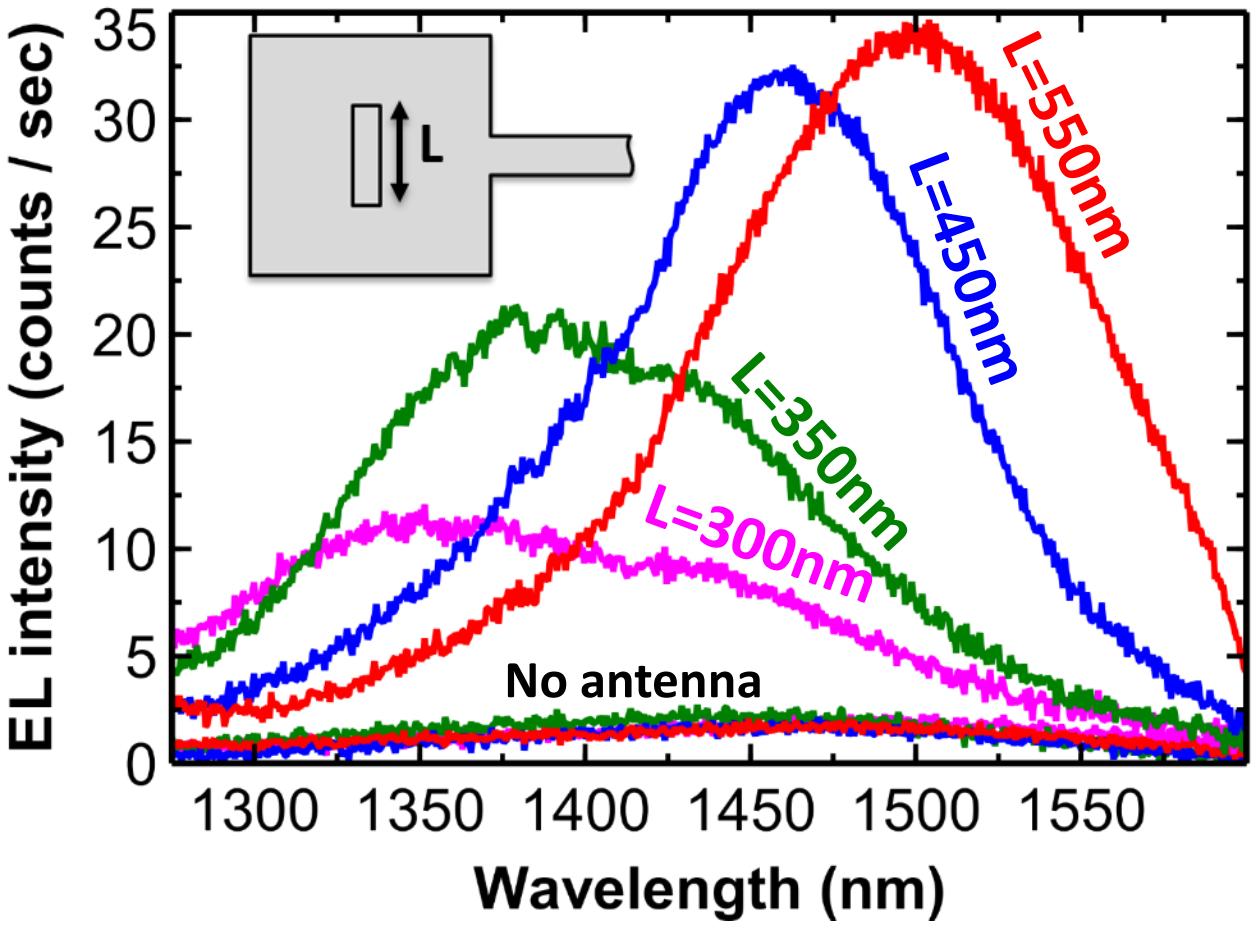
Antenna-enhanced electroluminescence



No antenna



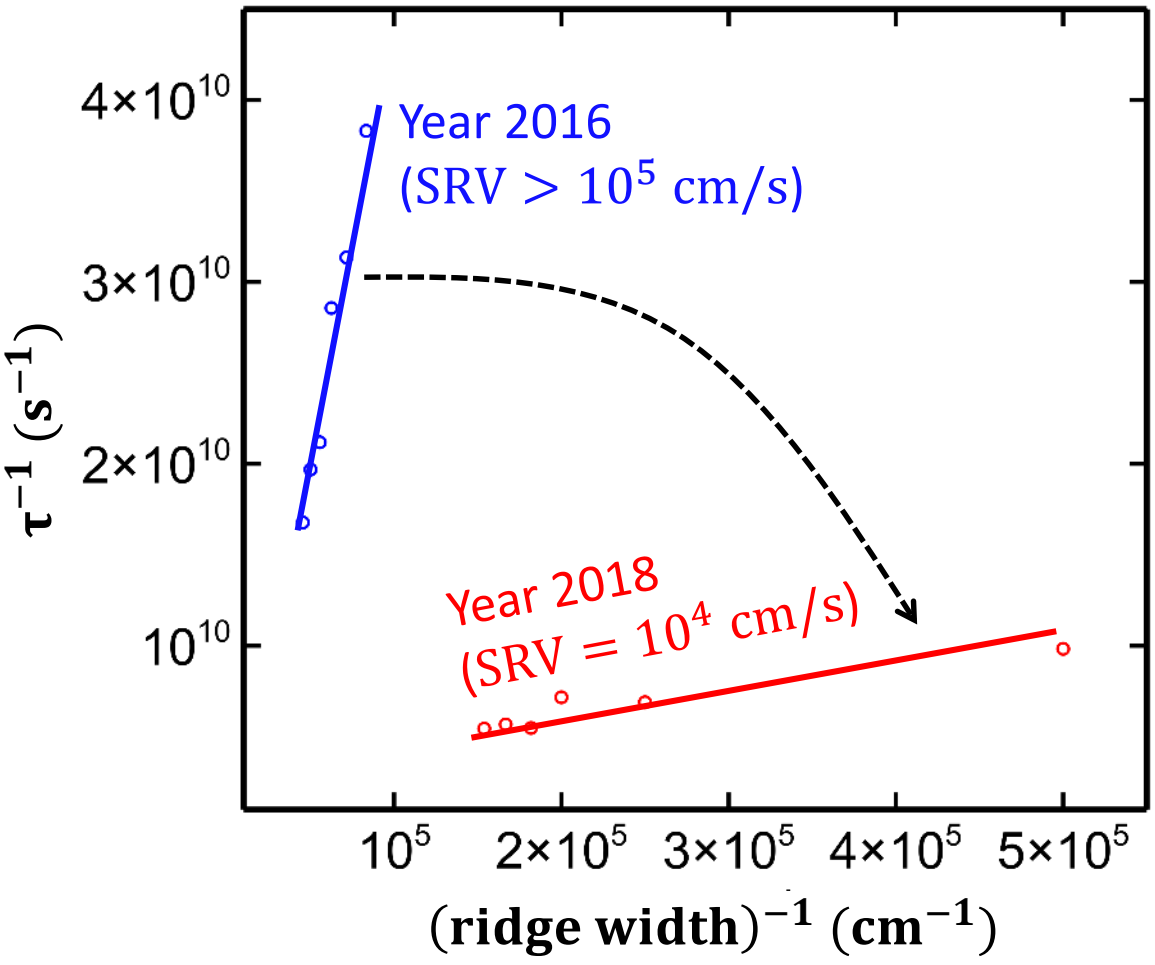
Antenna-LED



Fortuna et al. ISLC 2016

Controlling non-radiative recombination at surface

Photoluminescence decay time vs ridge width



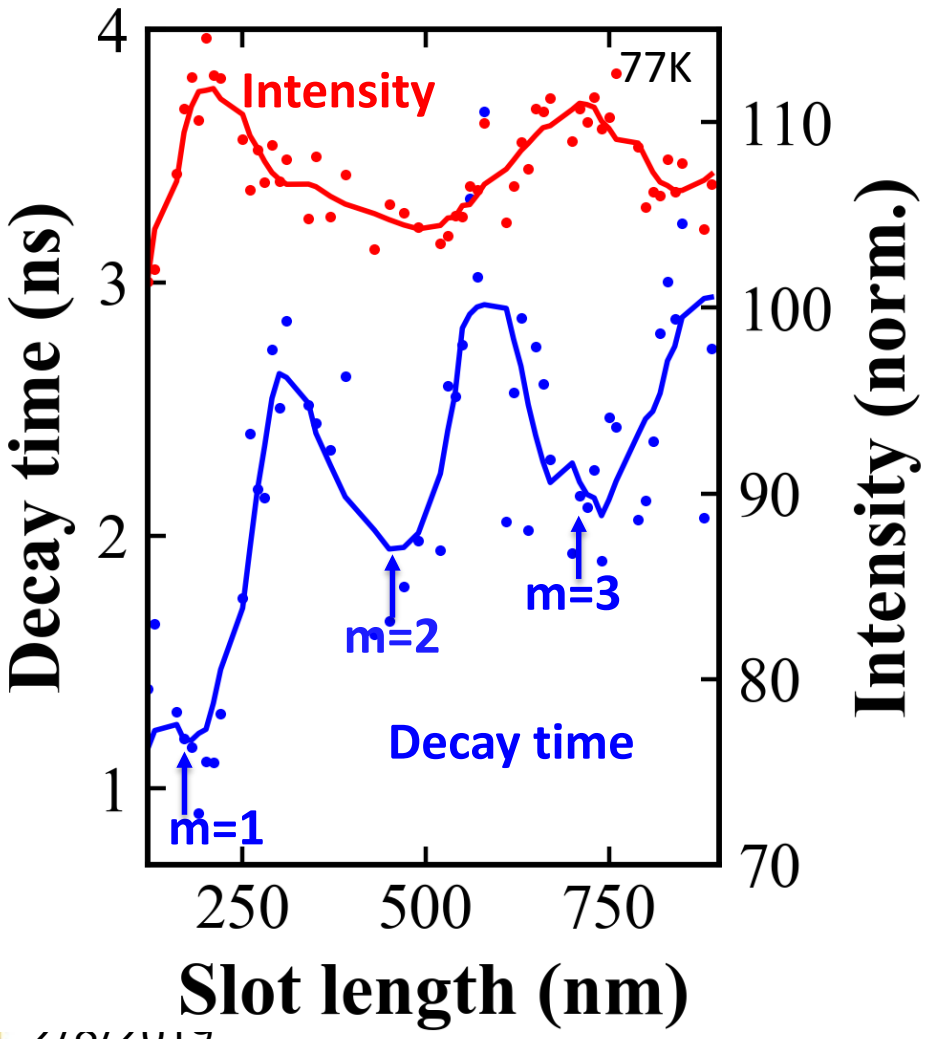
Key process steps:

1. Post–etch surface clean: Dilute TMAH followed by buffered HF leaves behind pristine surface.

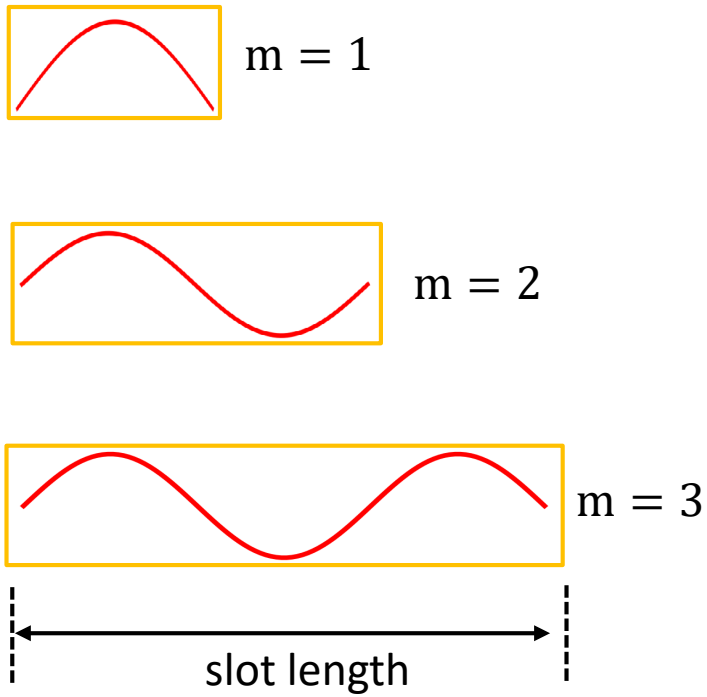
2. Surface protection: "Thick" 15nm ALD-deposited Al_2O_3 protects active region surface.

3. Active region passivation Ammonium sulfide treatment followed by low-temperature (150°C) Al_2O_3 ALD.

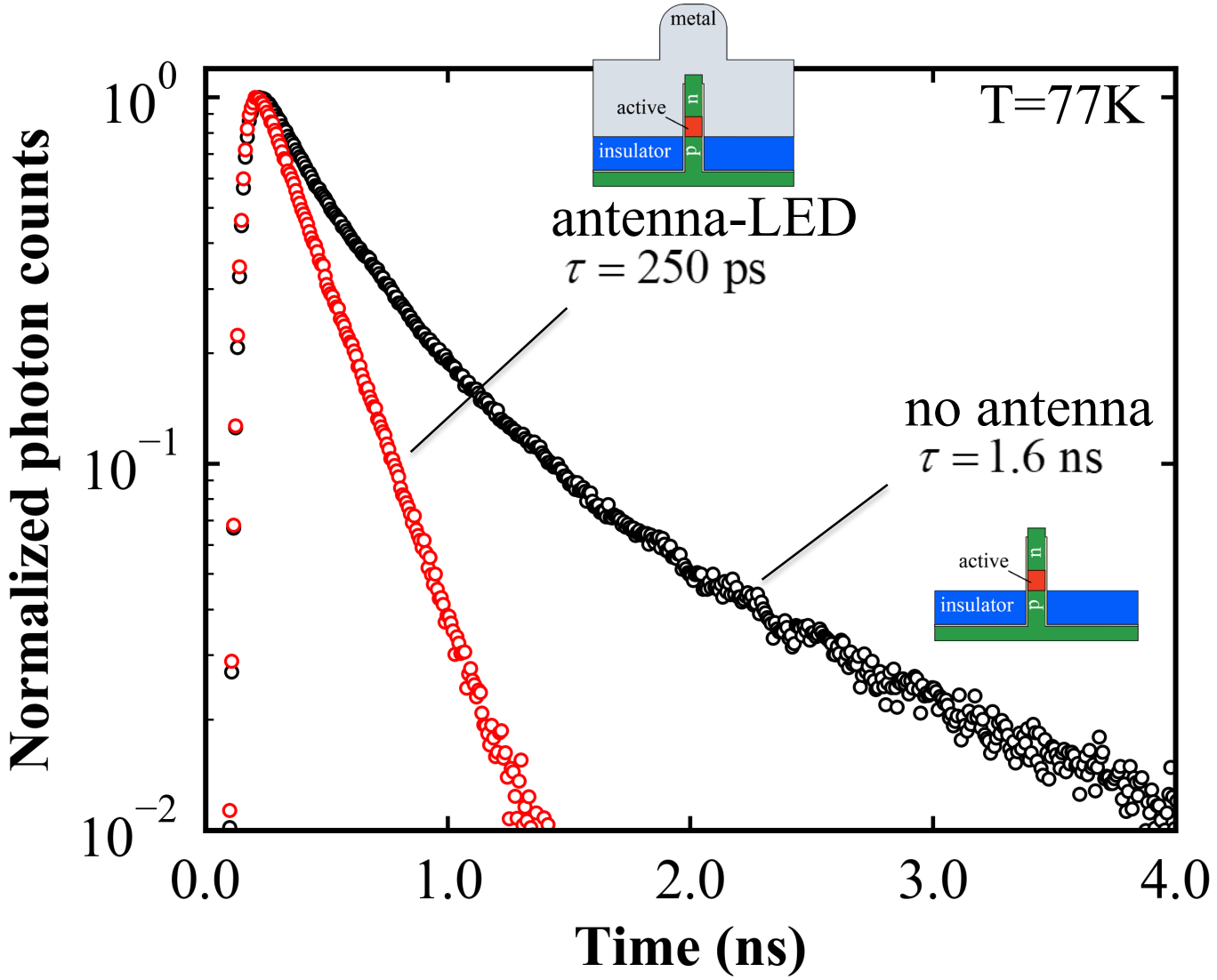
Milestone achieved: Clear antenna enhancement observed with time-resolved measurement



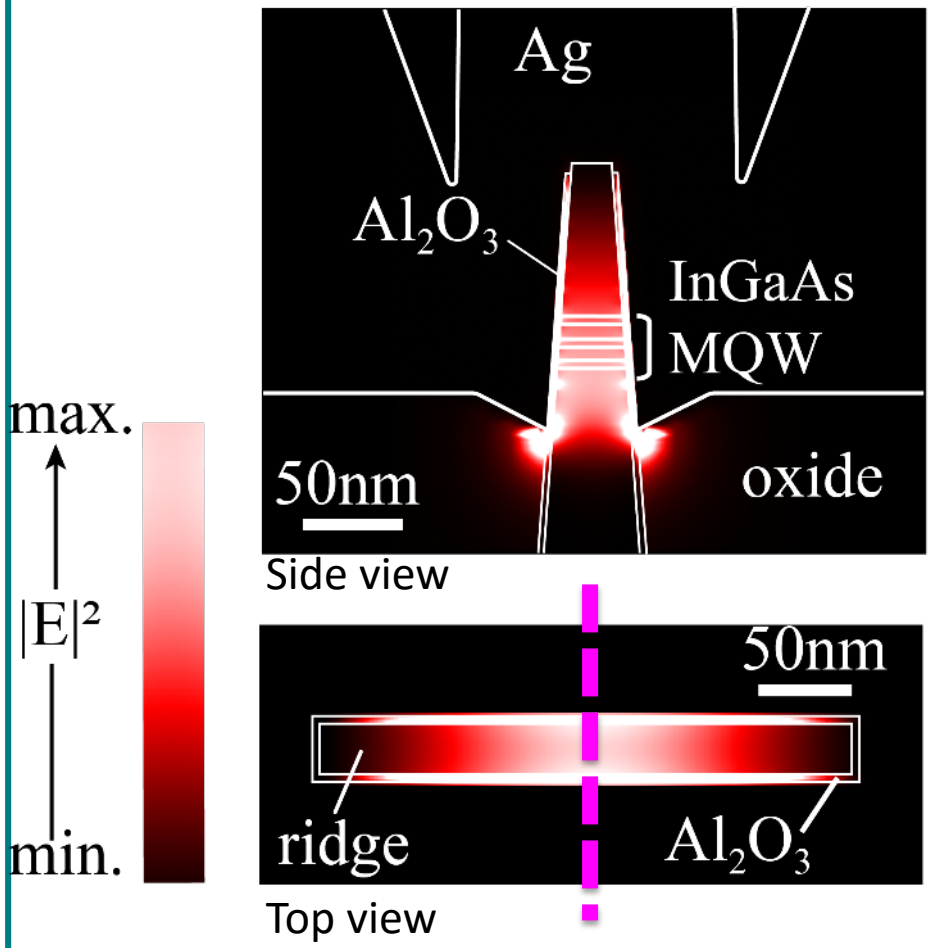
Antenna mode within slot

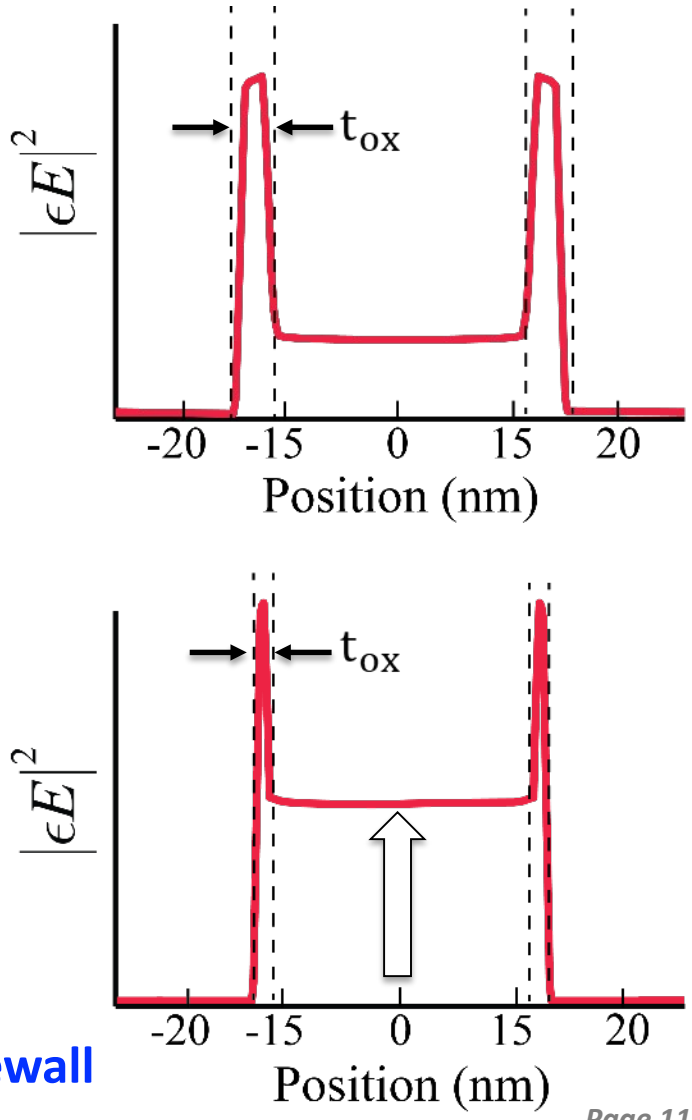


250 ps decay time in highly-scaled (30nm wide) device



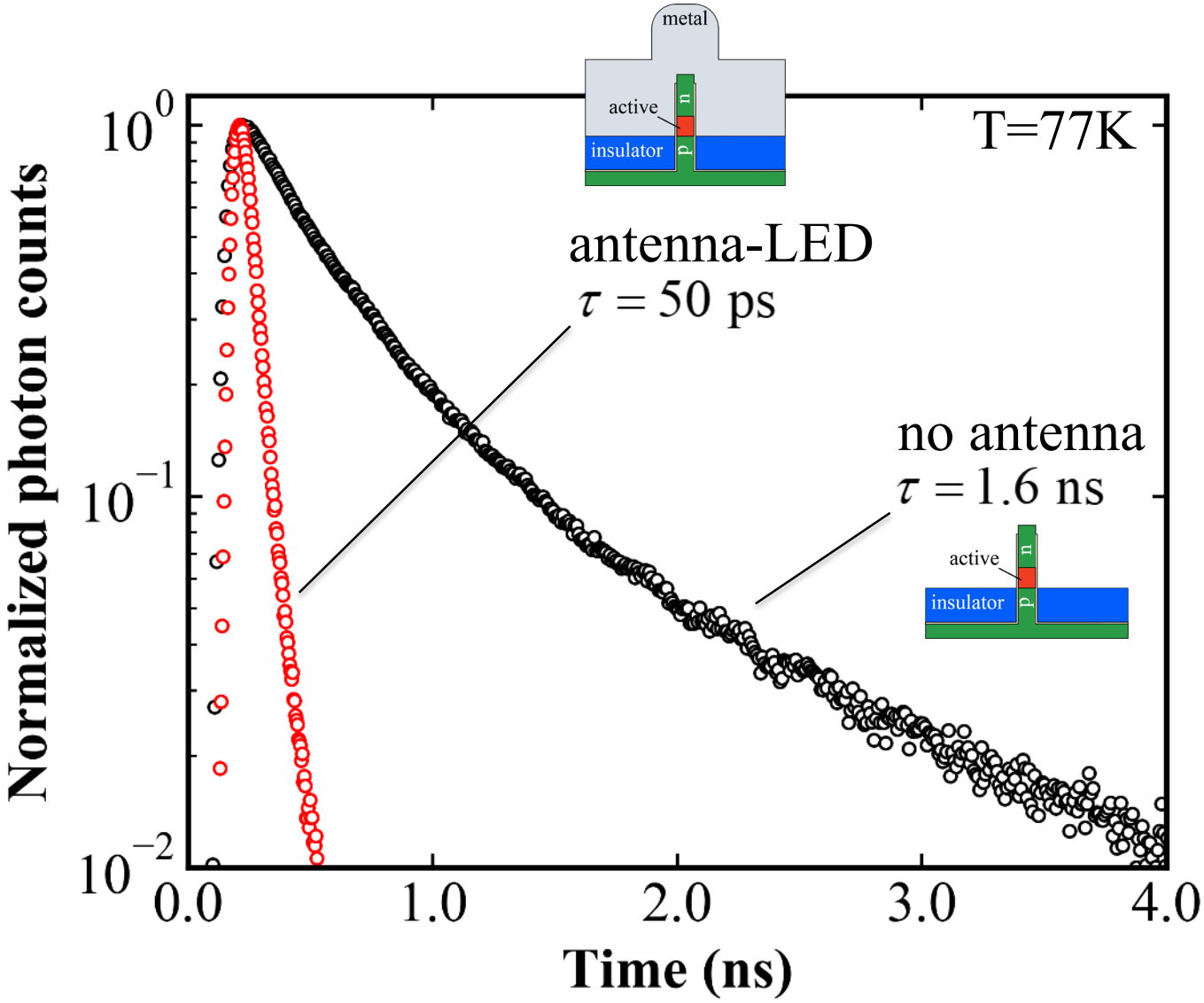
Further Enhancement with Device Scaling



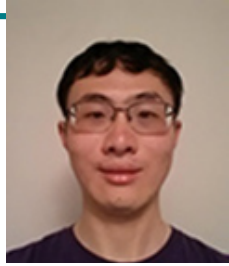


Oxide thickness on sidewall reduced from 3 nm to 1 nm

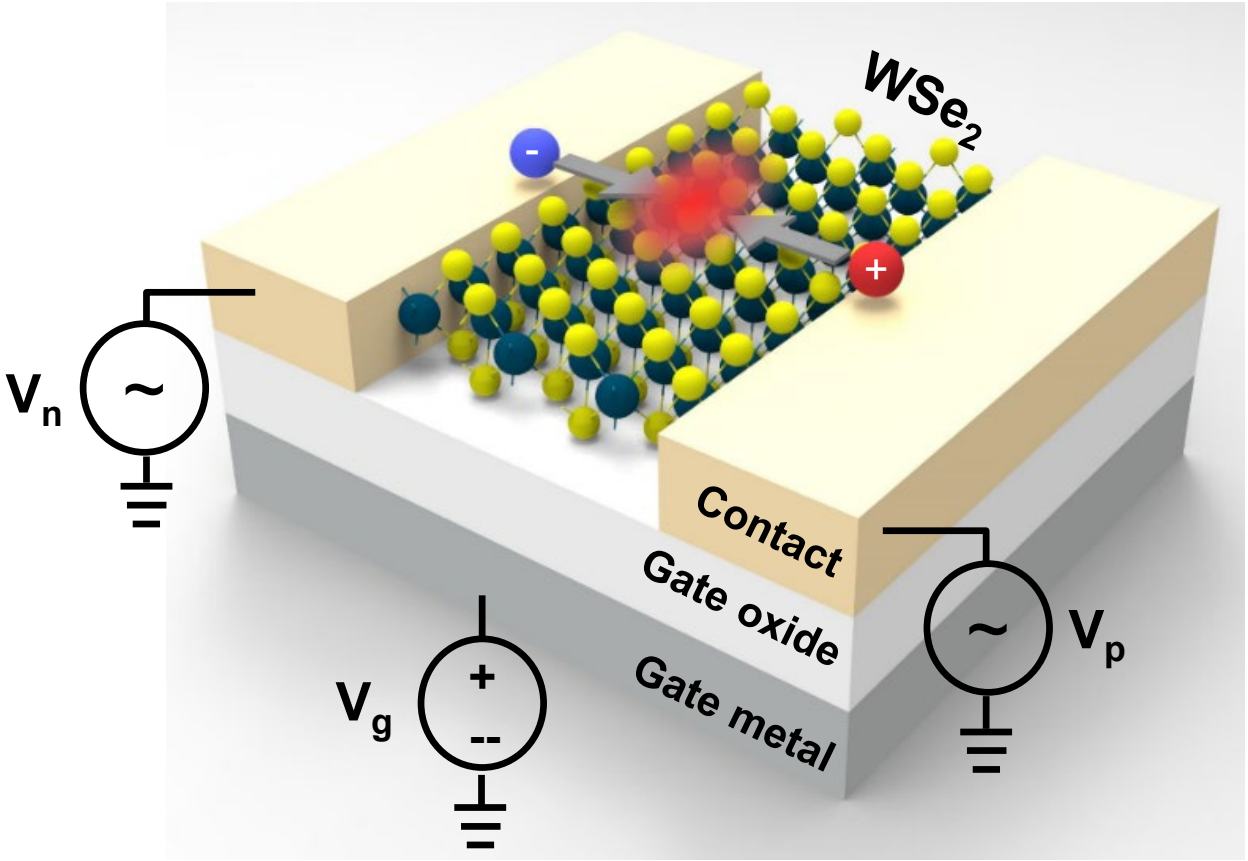
50 picosecond spontaneous emission lifetime
Aggressively-scaled 1nm oxide thickness



Electrical Injection LED with Monolayer WSe_2 Emitter



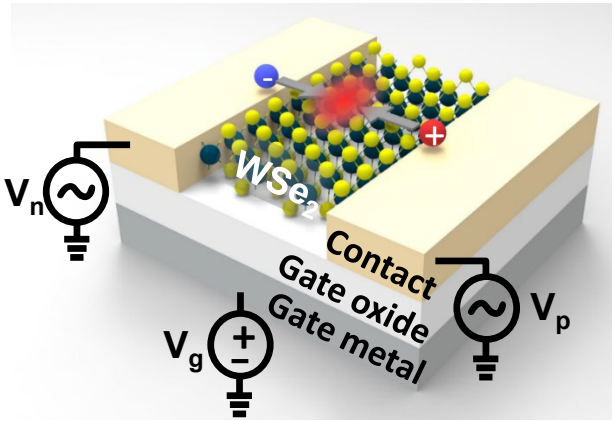
Kevin Han

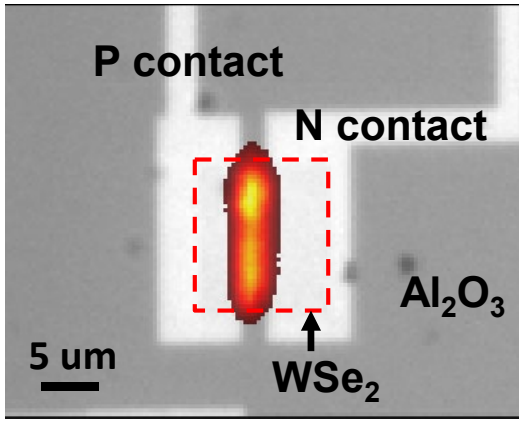


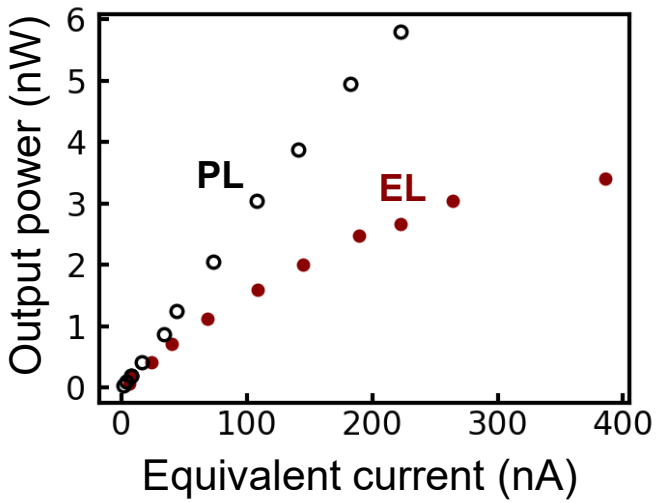
- Similar to back-gated field effect transistor structure
- Lateral p-n junction with electrostatic doping

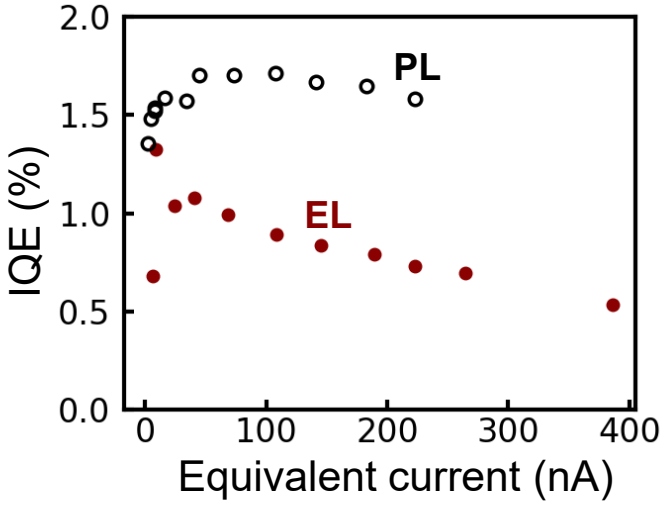
High efficiency Monolayer WSe_2 LEDs

Kevin Han



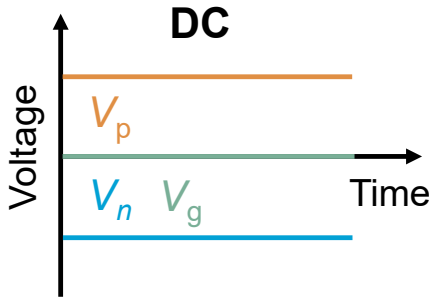


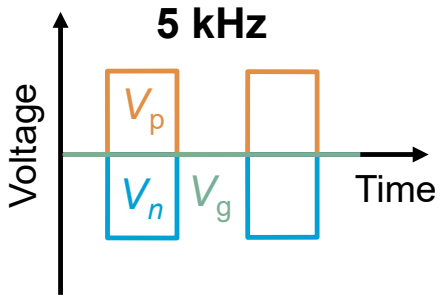


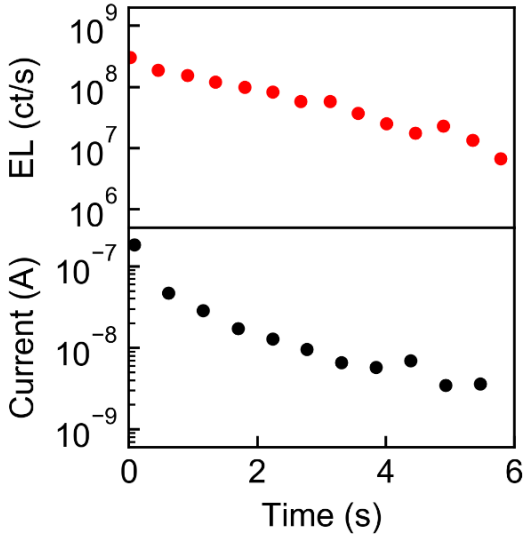


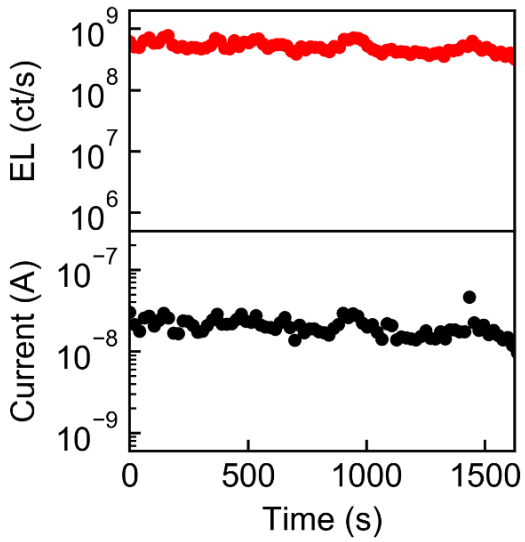
Process improvements yield EL efficiency close to PL (~1%), indicating material-limited efficiency

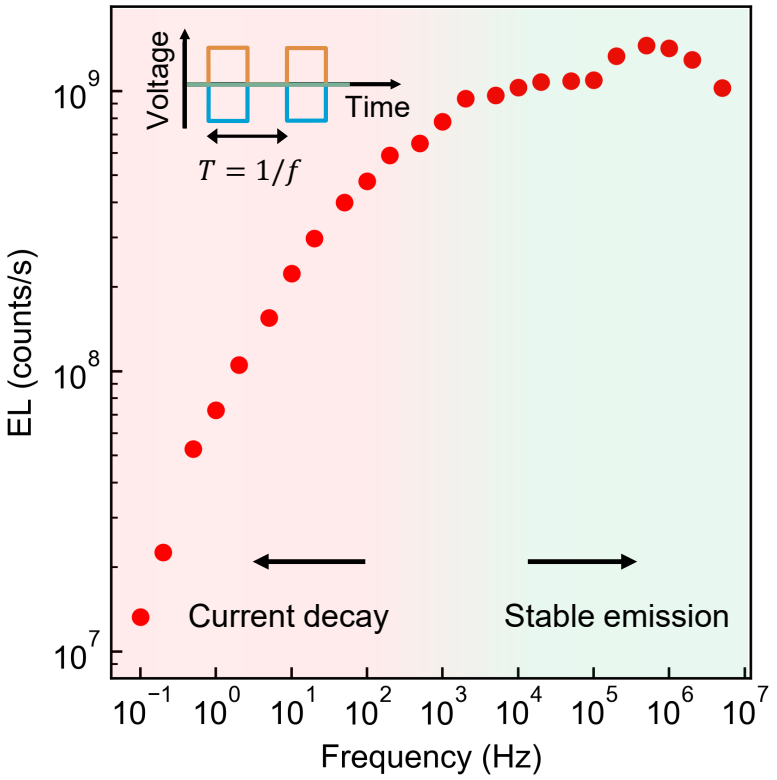
First Reliable LED Operation in Ambient







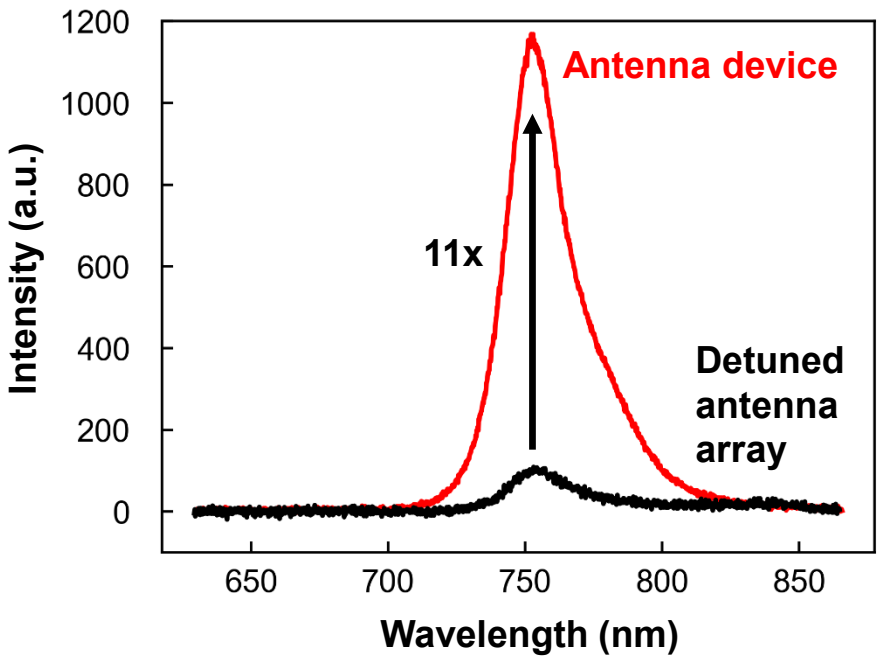




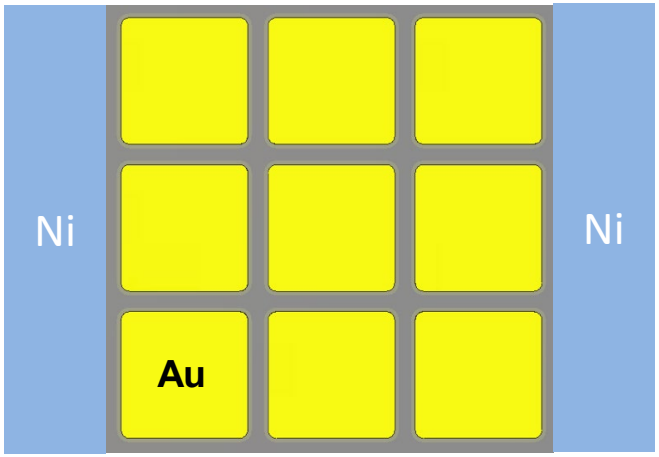
- Under DC bias, current and emission decay quickly in ambient conditions
- Pulsing greatly stabilizes light emission!

First Electrical Injection Antenna LED in Monolayer TMDC

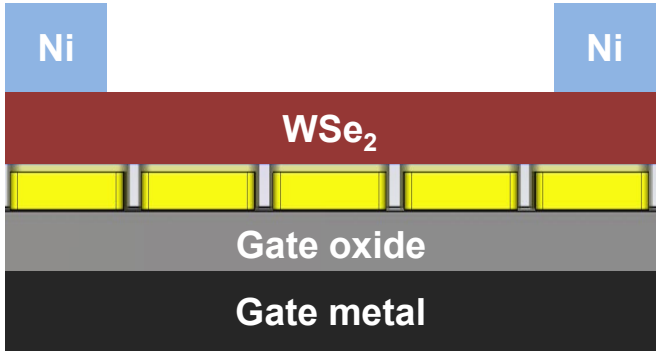
EL spectra normalized to current



Nanosquare antenna array



Top view



Side view

Major Accomplishments

- First temporal measurement of III-V antenna-LED
  - 50 ps spontaneous emission lifetime measured at 77K
  - Compared with 1.6 ns without antenna
- Electrical injection antenna LED with monolayer TMDC (WSe_2) emitter
  - Demonstrated first reliable LED operation in ambient condition
  - 11x enhancement demonstrated with optical antenna

- Plan for next period
  - III-V antenna-LED with p-doped emitter (for even faster response)
  - Experimental demonstration of waveguide coupling
  - Increase antenna enhancement in TMDC antenna-LED