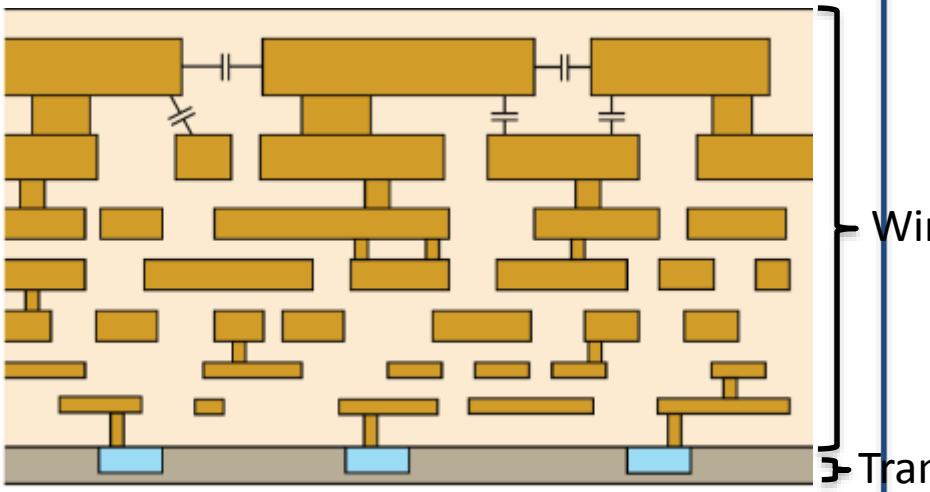
Large spontaneous emission rate enhancement in a III-V antenna-LED

Seth A. Fortuna[1], Christopher Heidelberger[2], Nicolas M. Andrade[1], Eugene A. Fitzgerald[2], Eli Yablonovitch[1], and Ming C. Wu[1]

[1]University of California, Berkeley; Dept. of Electrical Engineering and Computer Sciences
[2]Massachusetts Institute of Technology; Dept. of Materials Science and Engineering

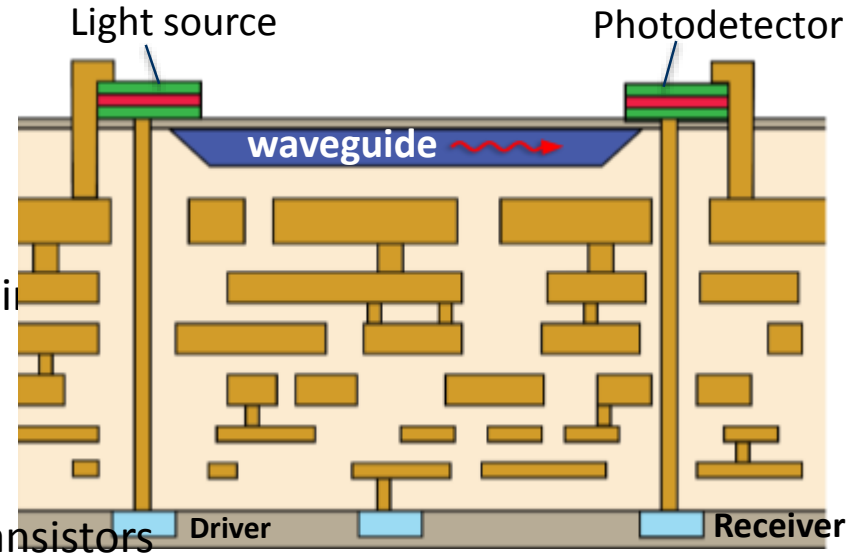
Energy efficient on-chip optical interconnect link

Electrical interconnect



- Minimum energy per bit:
  $\sim CV^2 \rightarrow$ **pJ/bit/cm**

Optical interconnect

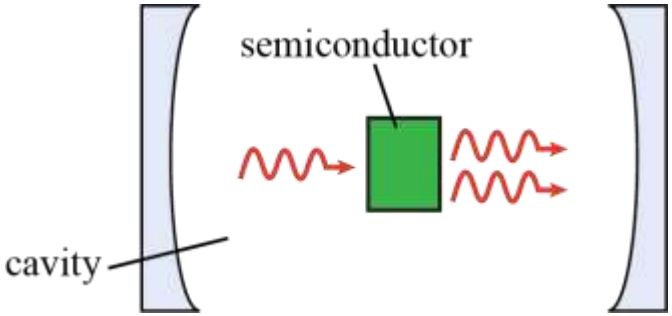


- Minimum energy per bit:
  ~aJ/bit

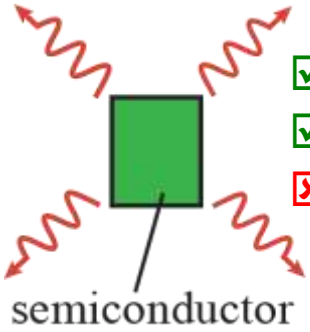
Drawing inspired by E. Macii,
Ultra Low-Power Electronics and Design.

Light sources for on-chip optical interconnect

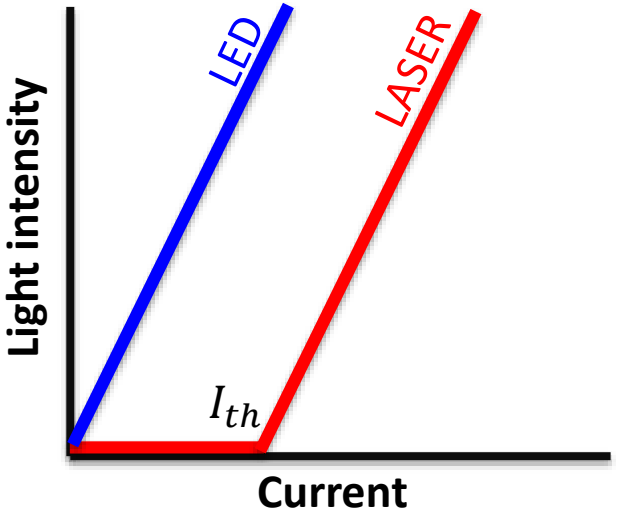
LASER

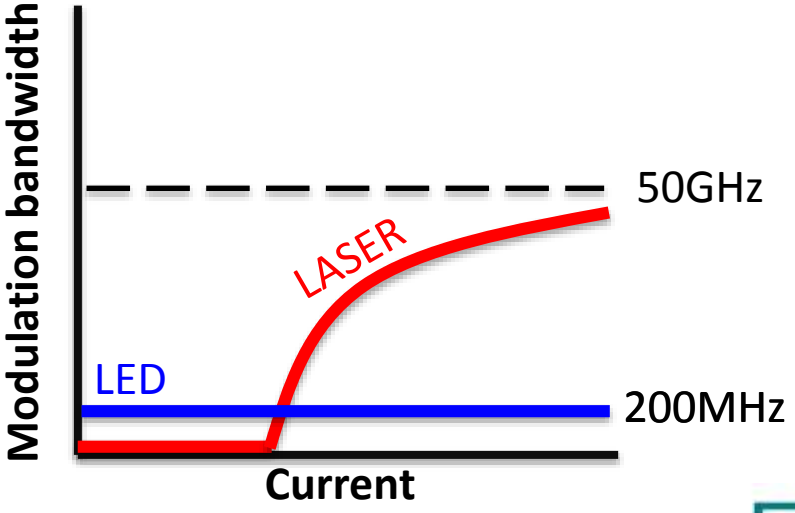


Light Emitting Diode (LED)



- ☑ Nanoscale
- ☑ Efficient
- ☒ Slow

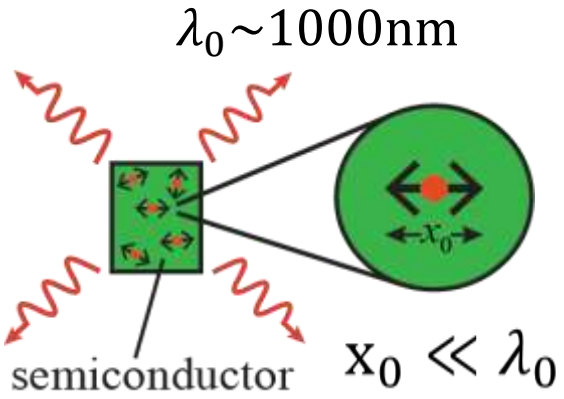




Spontaneous emission

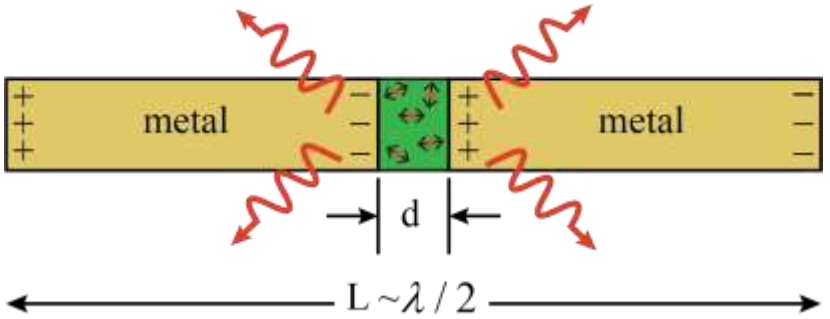
$$\text{Radiation rate} \propto \left(\frac{x_0}{\lambda_0}\right)^2$$

Spontaneous emission is **SLOW**



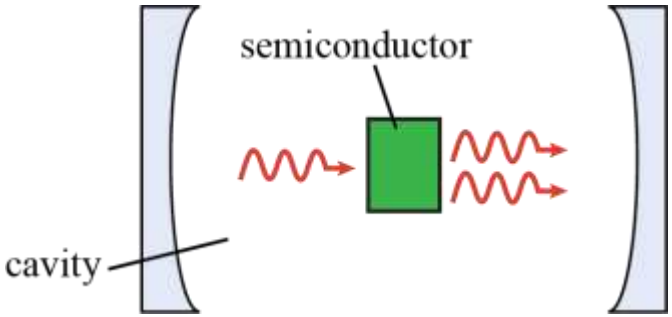
$$\text{Enhancement} \sim \left(\frac{L}{d}\right)^2$$

Spontaneous emission is **FAST**

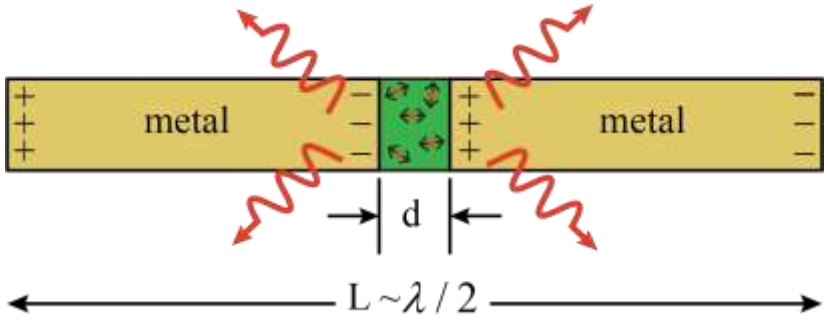


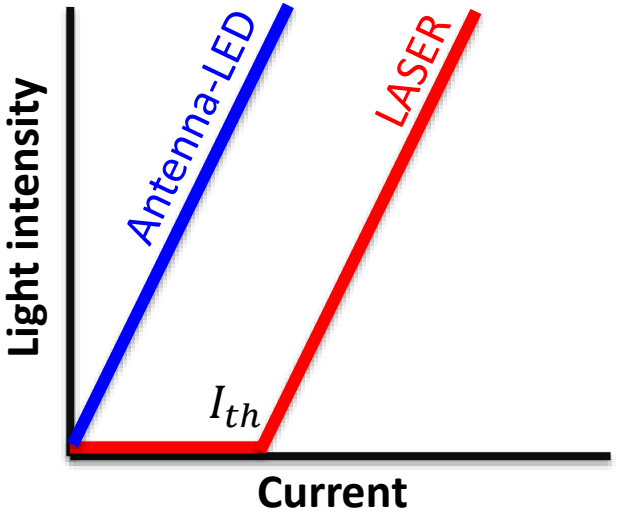
Antenna-LED for optical communication

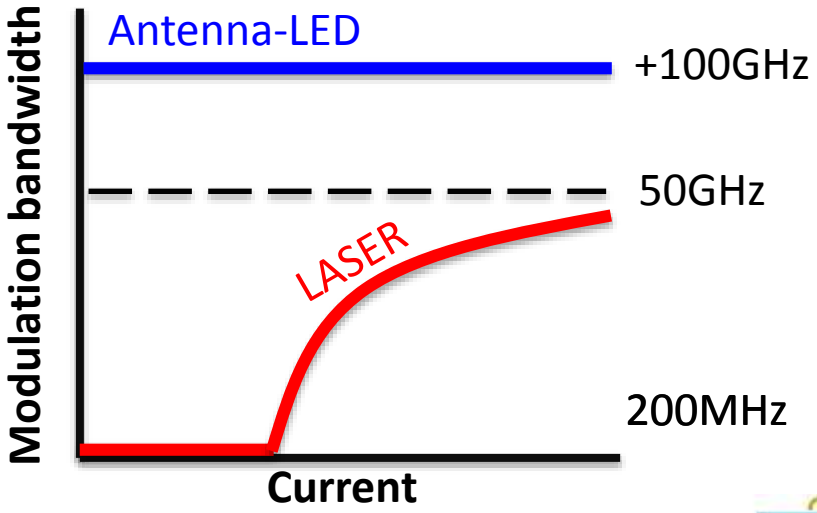
LASER



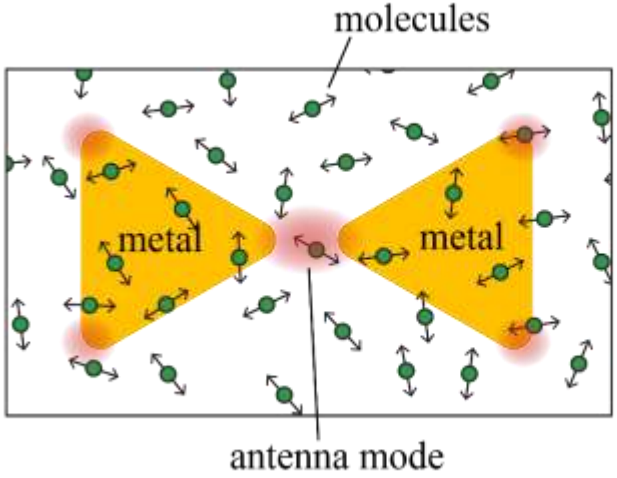
Antenna-LED



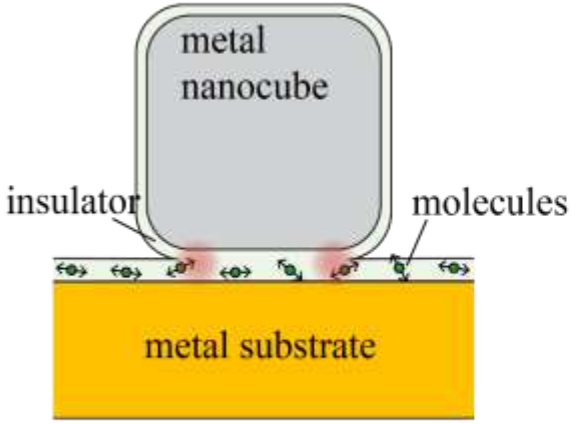




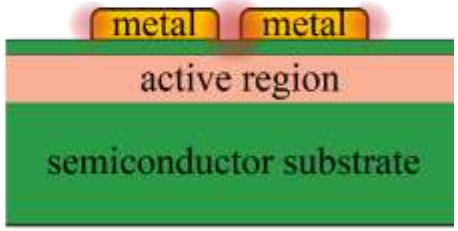
Examples of antenna-enhanced emitters



Kinkhabwala et al. Stanford.
Nat. Phot. 2009.

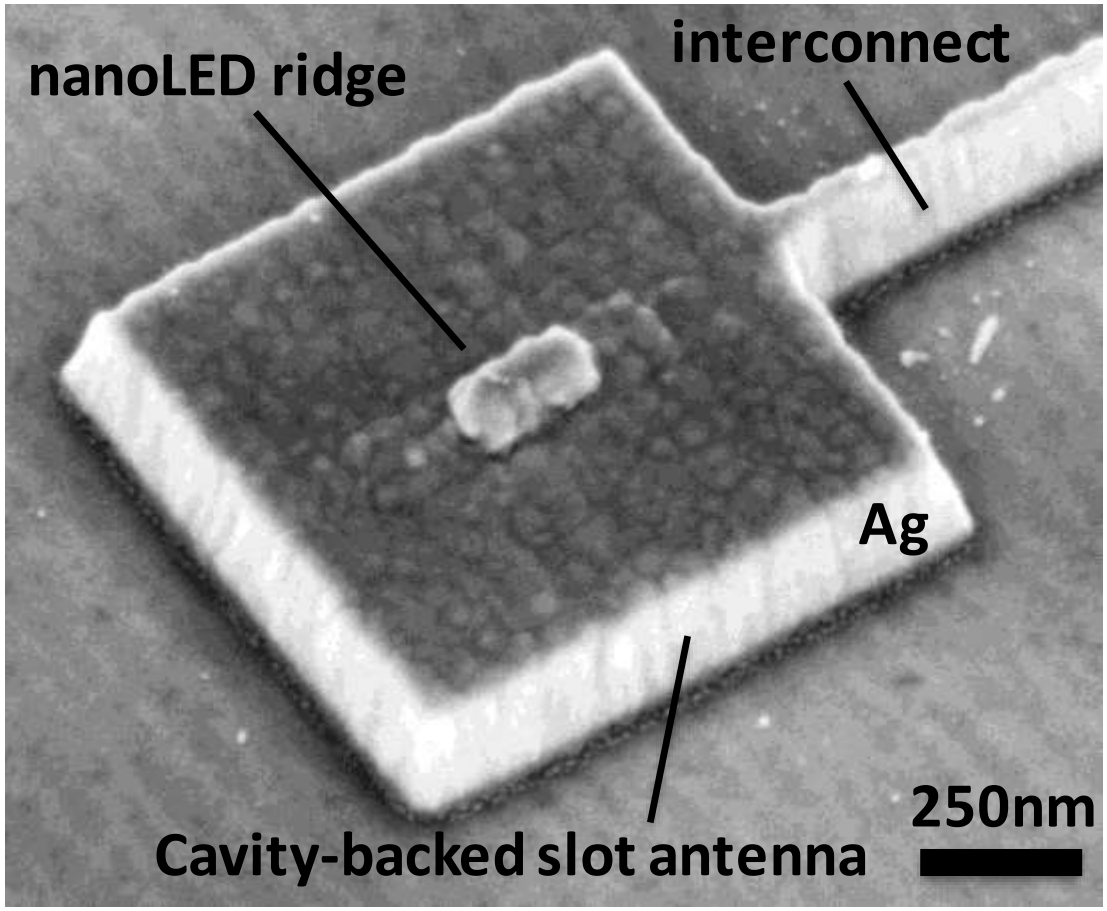


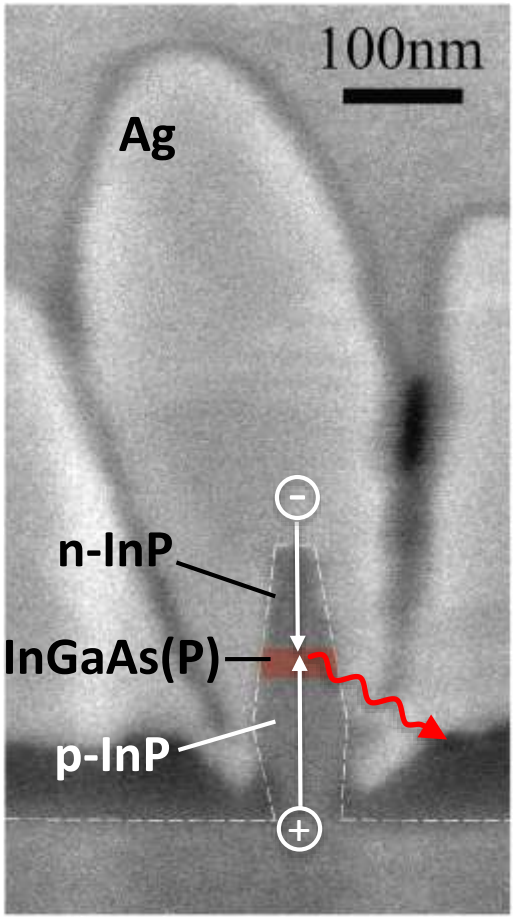
Hoang et al. Duke.
Nat. Comm. 2015.



Arbel et al. Technion.
Opt. Exp. 2011.

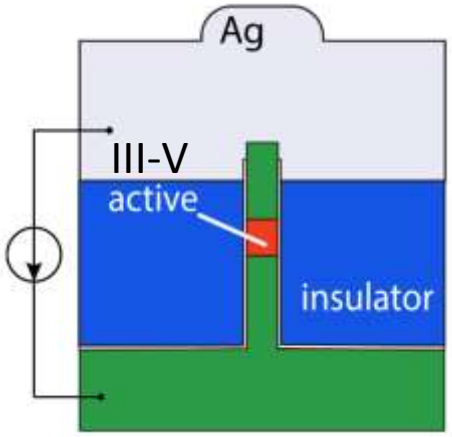
Electrically-injected III-V antenna-LED



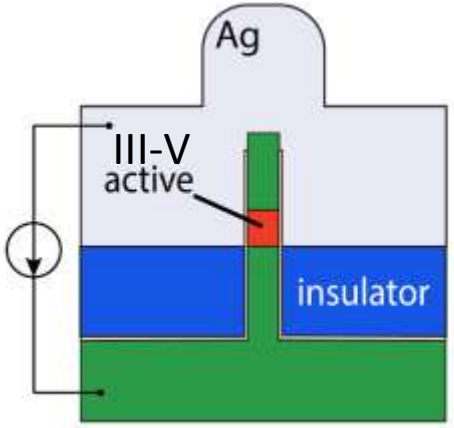


- Electrical injection is straight forward
- Directional light emission for coupling into waveguide
- > 100 GHz direct modulation rate

Antenna-enhanced electroluminescence

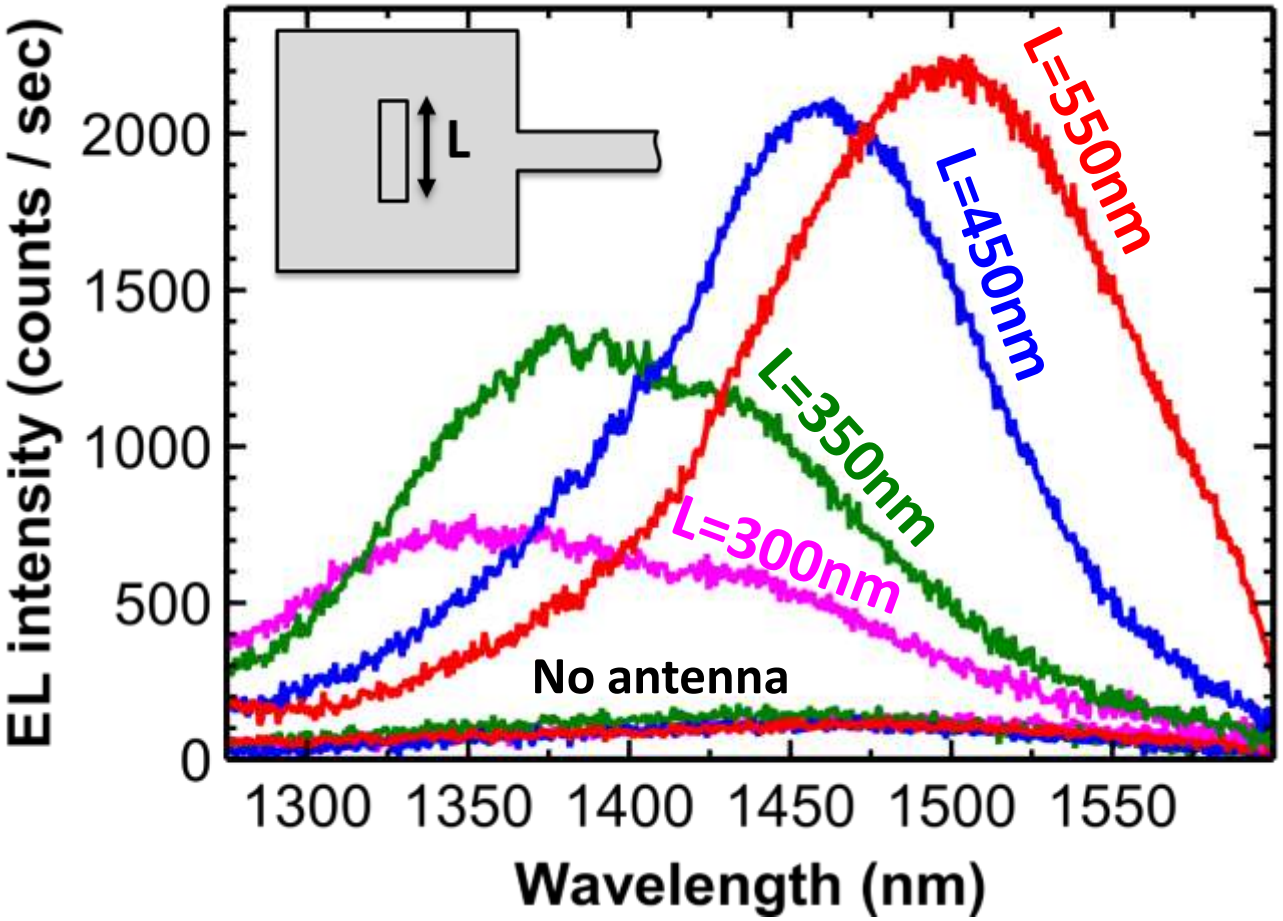


No antenna



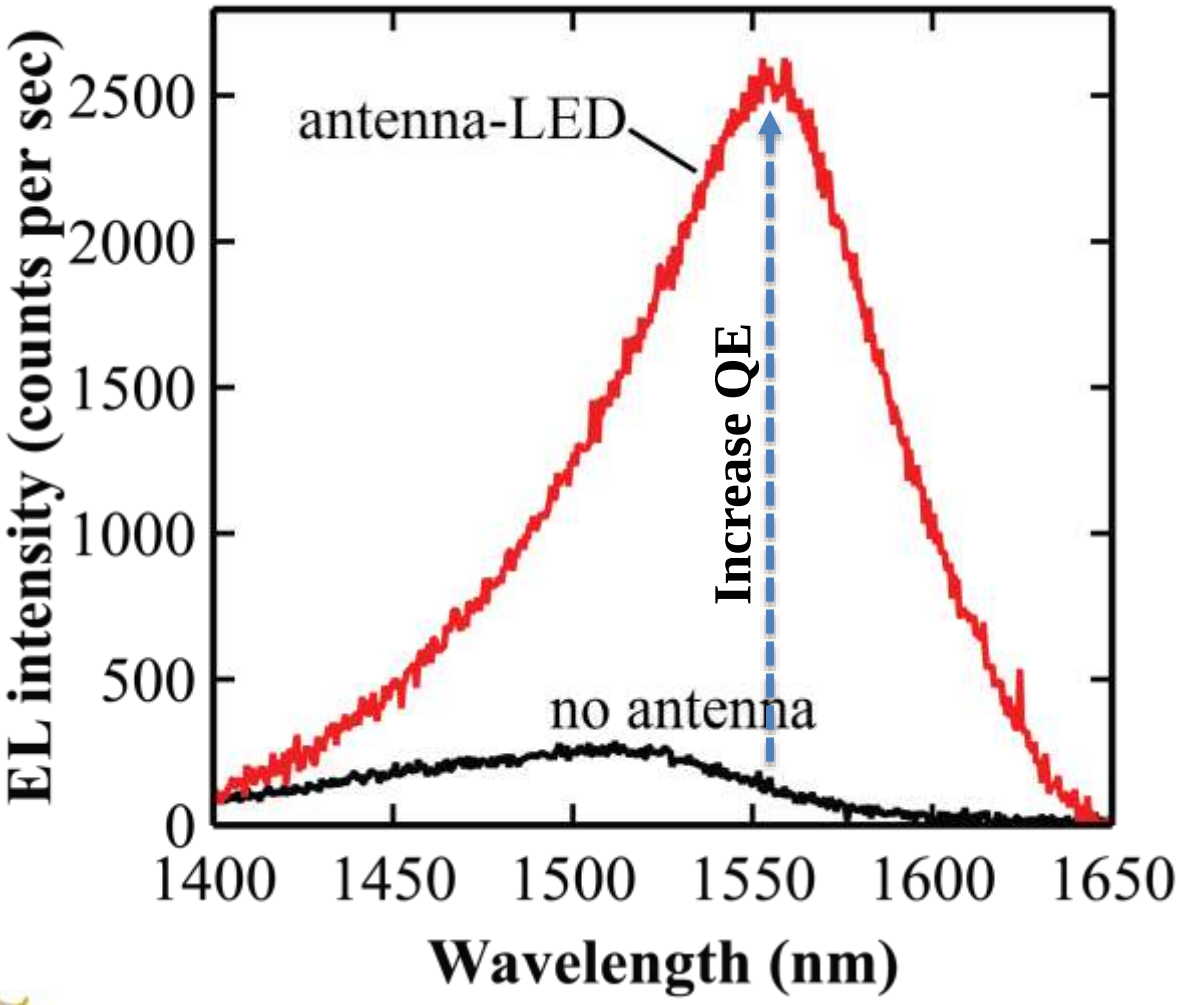
Antenna-LED

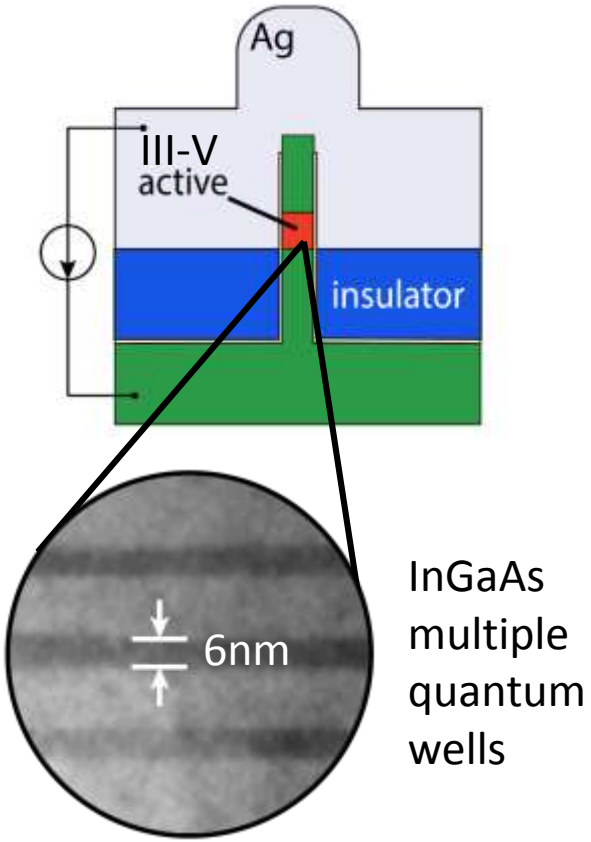
~100-fold increase in spontaneous emission rate



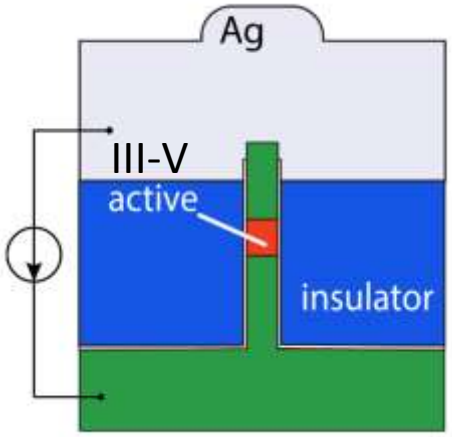
$$\text{Quantum efficiency} \approx \frac{\tau_{nr}}{\tau_{rad}}$$

200-fold enhancement of spontaneous emission rate

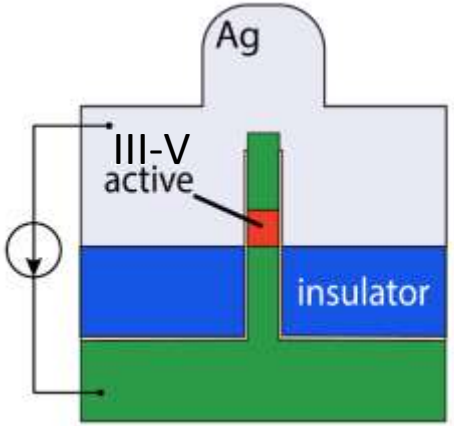




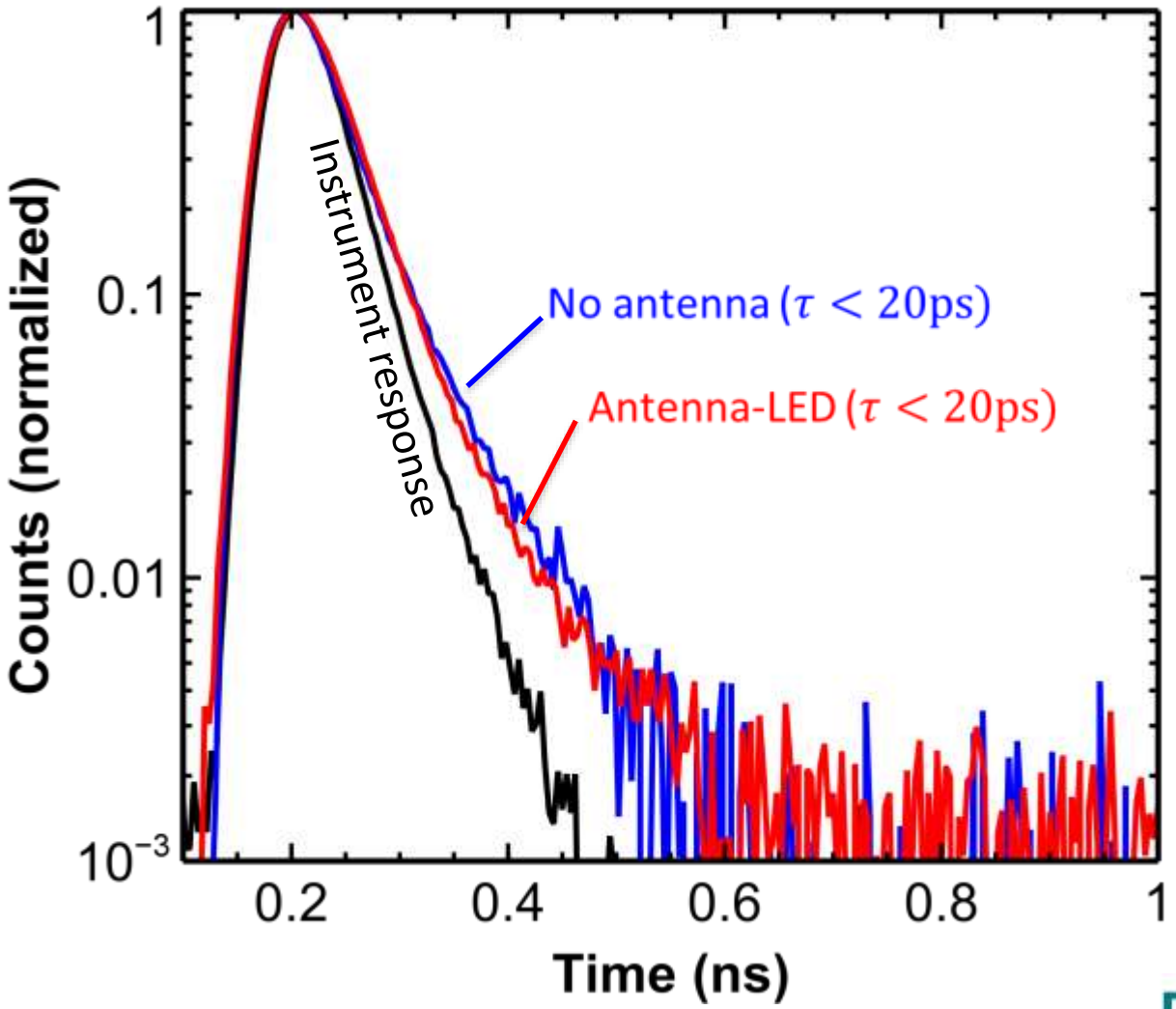
Time-resolved light emission



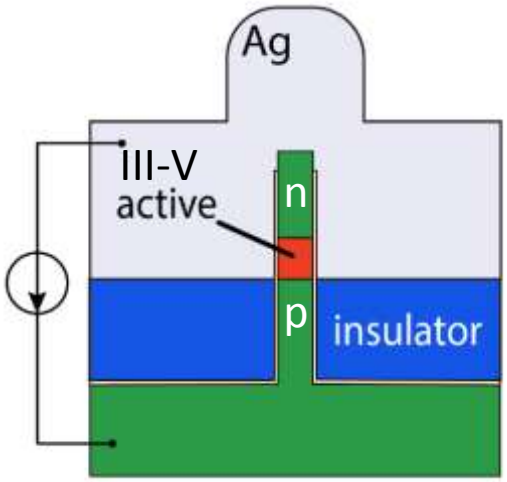
No antenna

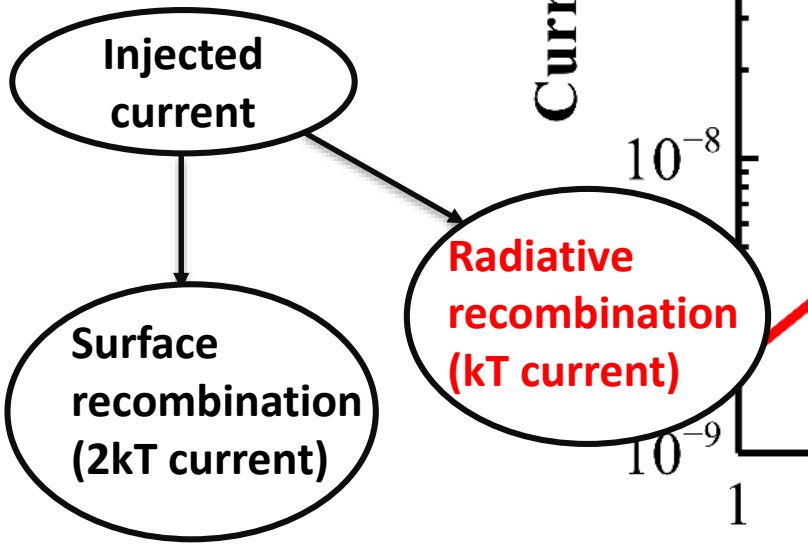


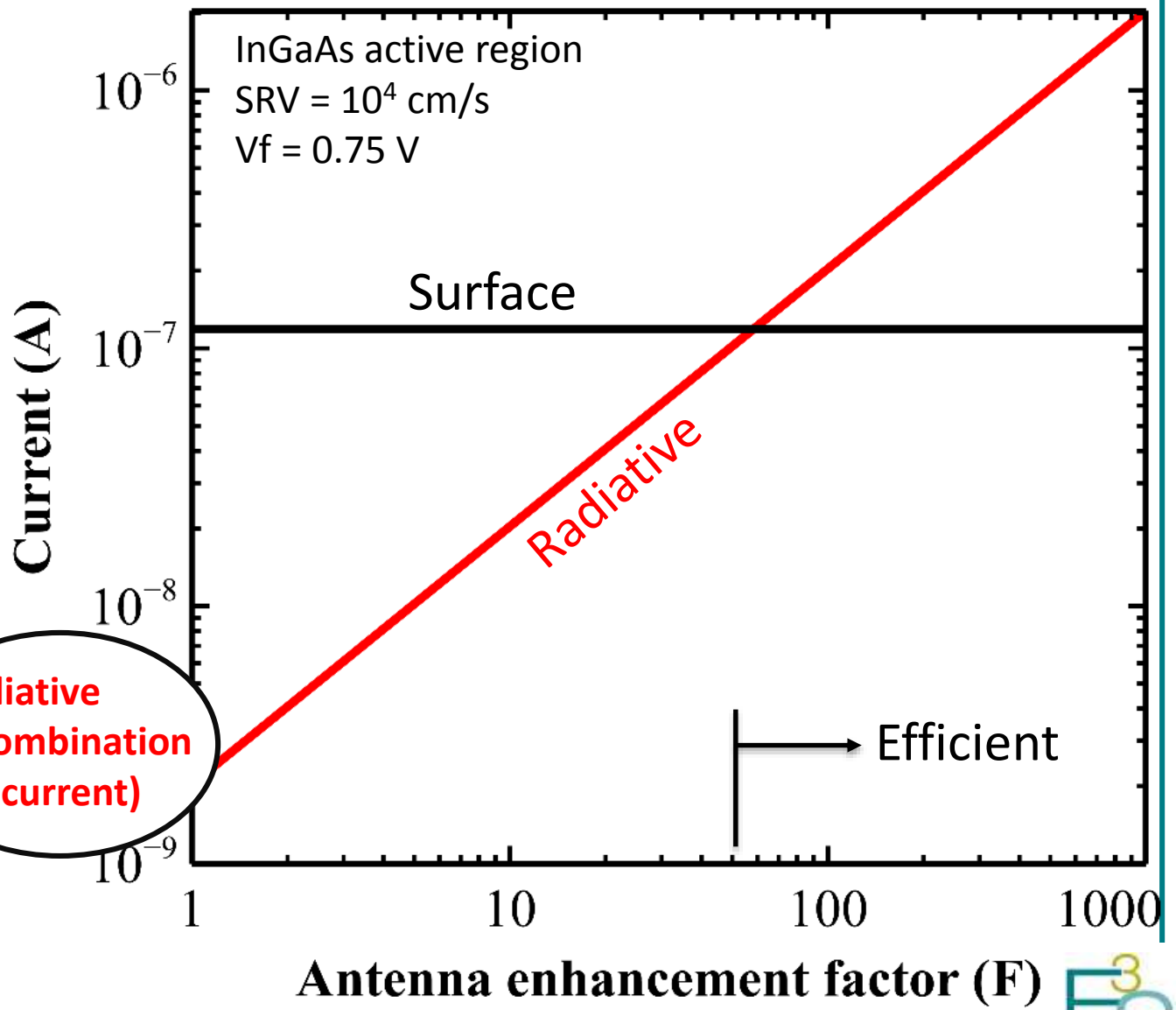
Antenna-LED



High efficiency despite high surface recomb. velocity

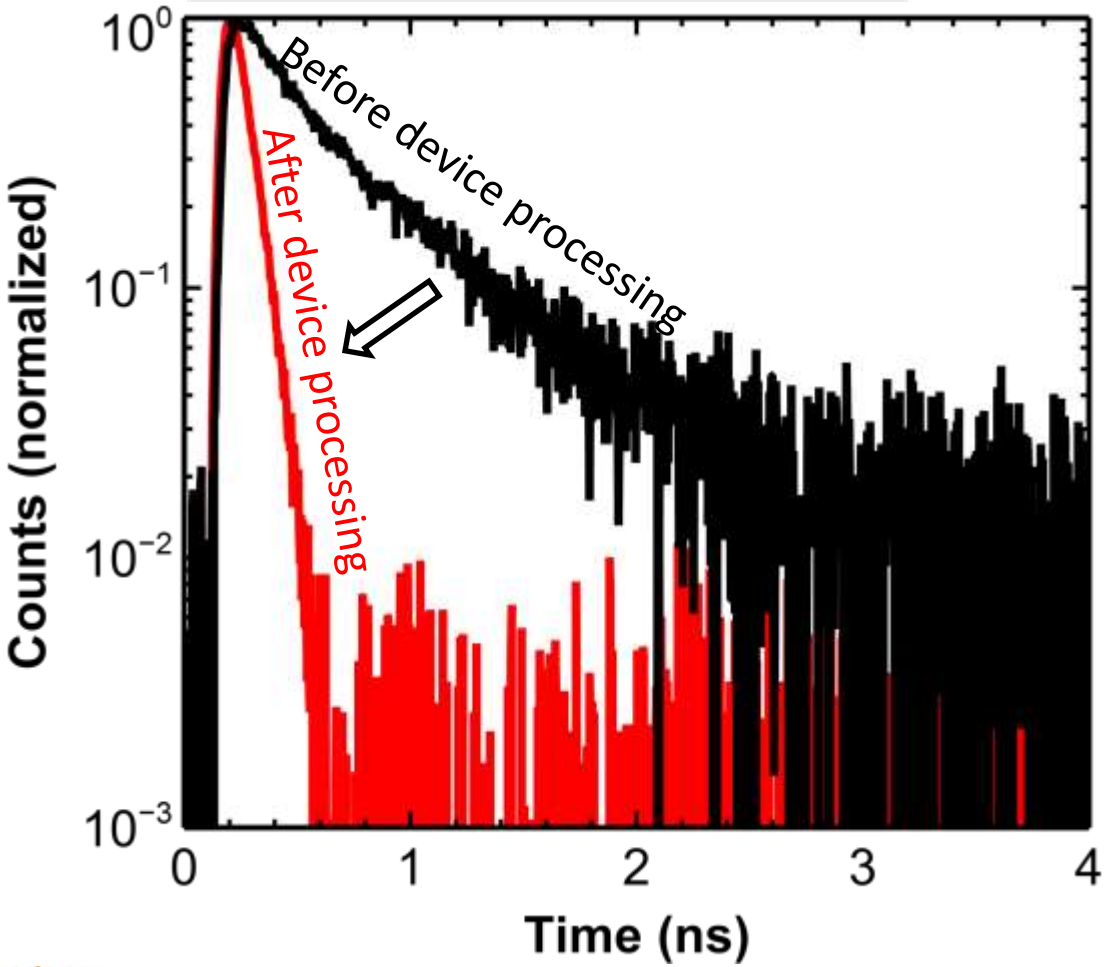






Process induced surface damage

Time-resolved photoluminescence



Before device processing:

$$\text{SRV} \cong 3 \times 10^4 \text{ cm/s}$$

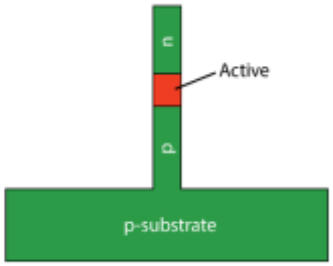
After device processing:

$$\text{SRV} > 10^5 \text{ cm/s}$$

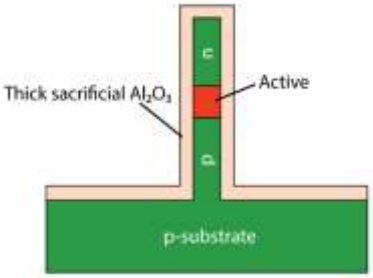
Surface needs to be protected during fabrication!

Improved process with ultra-clean surface

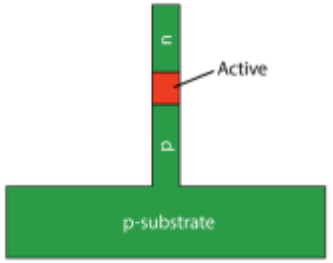
1. Dry etch ridge

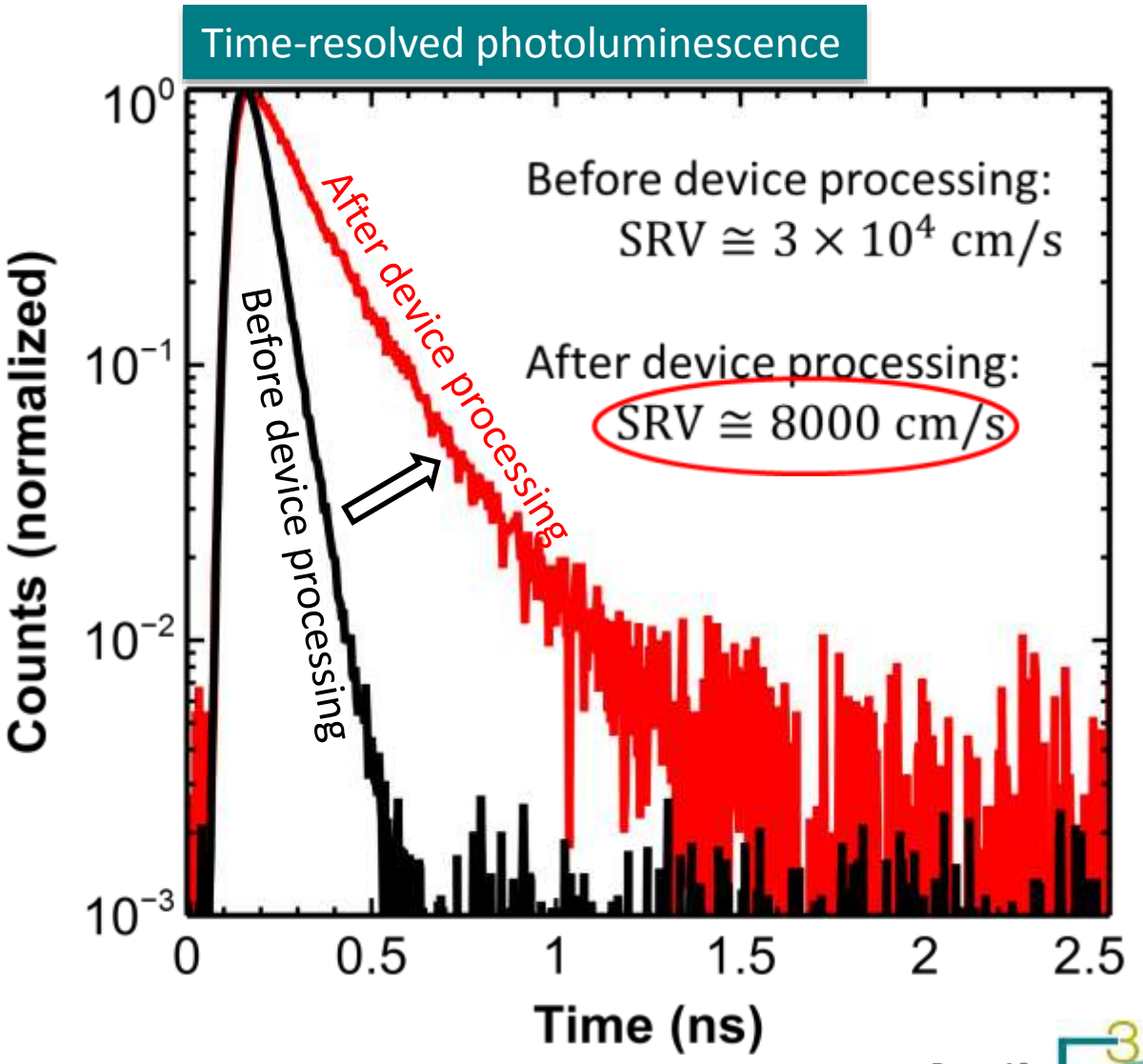


2. Deposit sacrificial Al_2O_3 (expose to plasma, anneal, etc.)

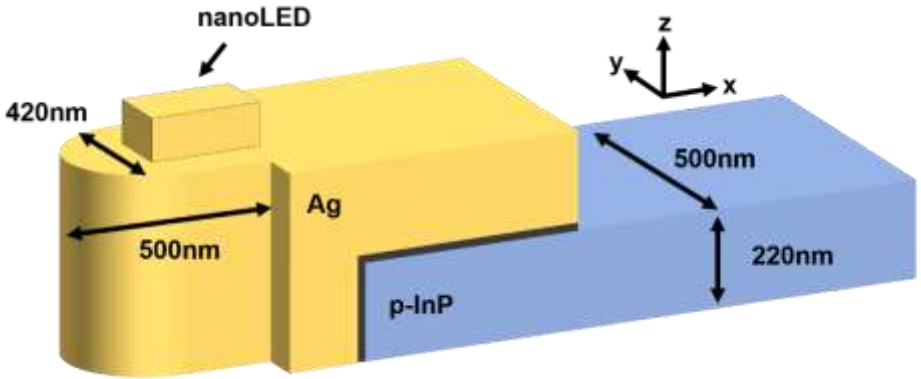


3. Strip sacrificial Al_2O_3 (TMAH)

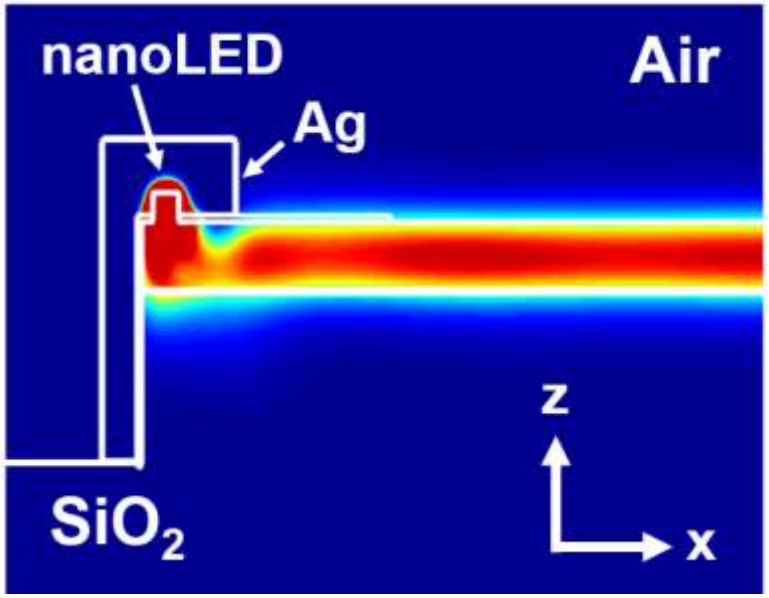




Efficient waveguide Coupling

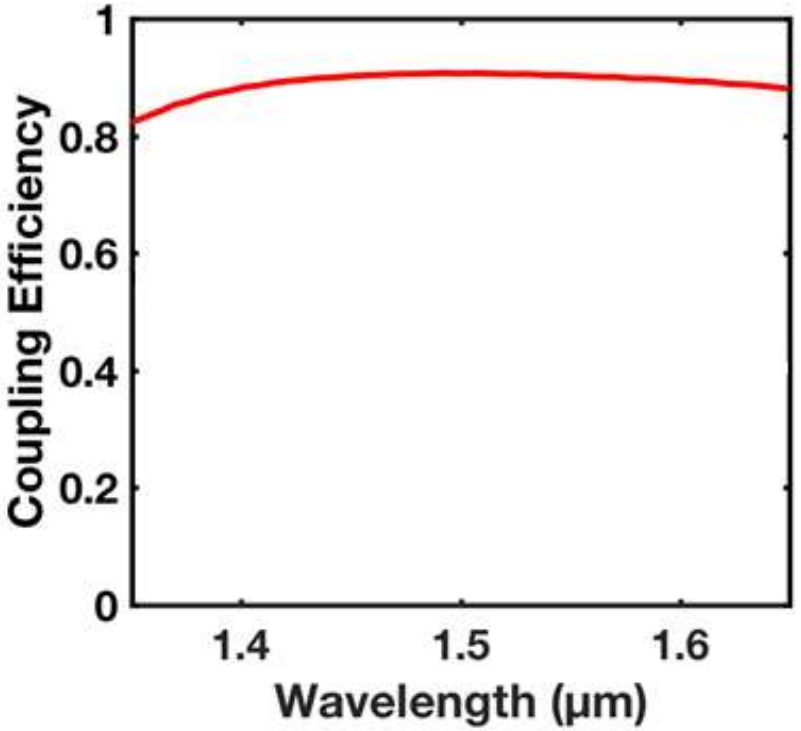


Perspective view of the parabolic reflector



Cross-section of simulated power flow

Waveguide coupling efficiency



Acknowledgement:
Nicolas Andrade (UC Berkeley)

Summary

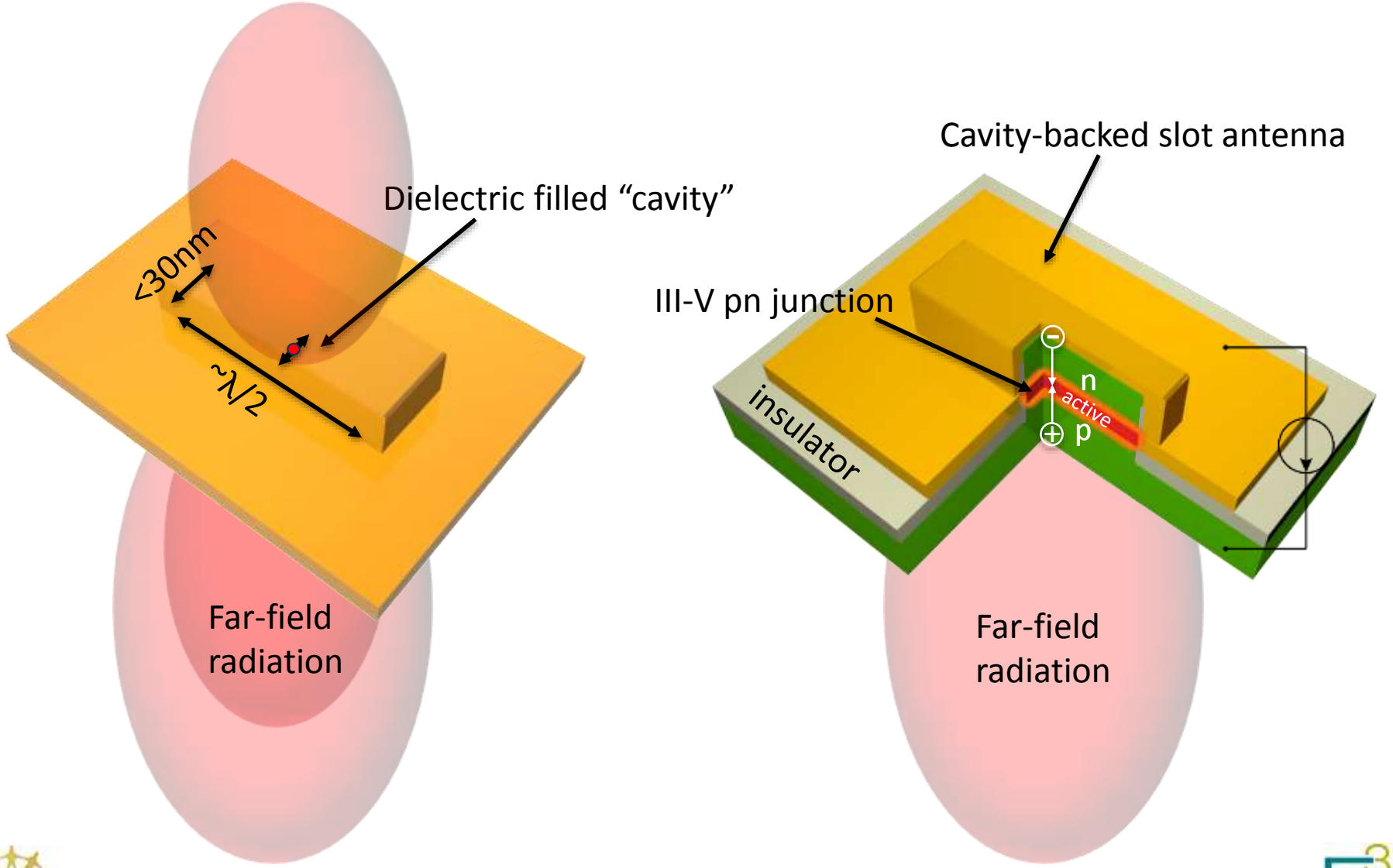
- Demonstrated 200-fold enhancement of spontaneous emission rate of electrically injected nanoscale III-V LED
- High efficiency possible despite large surface recombination velocity of III-V surface
- Ultra-clean InGaAs surface using sacrificial Al_2O_3
- Efficient and broadband coupling to single-mode on-chip waveguide is possible.

Acknowledgments

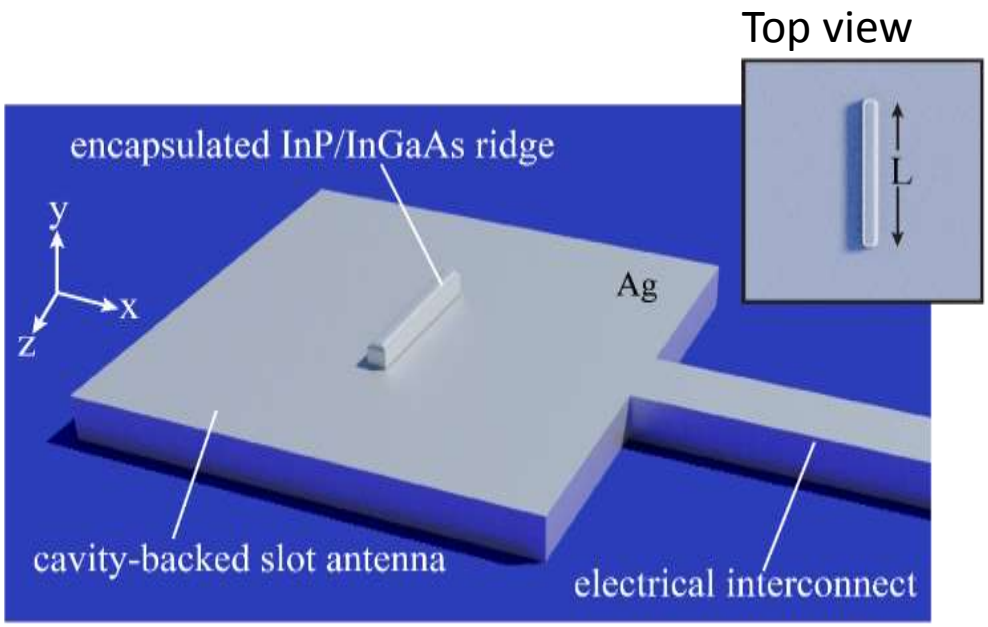
- **Financial support**
  - **NSF Science and Technology Center for Energy Efficient Electronics Science (E^3S)**
  - **Air Force Office of Scientific Research (AFOSR)**
  - **Berkeley Sensor & Actuator Center (BSAC)**
- **Technical support**
  - **UC Berkeley Marvell Nanolab staff**

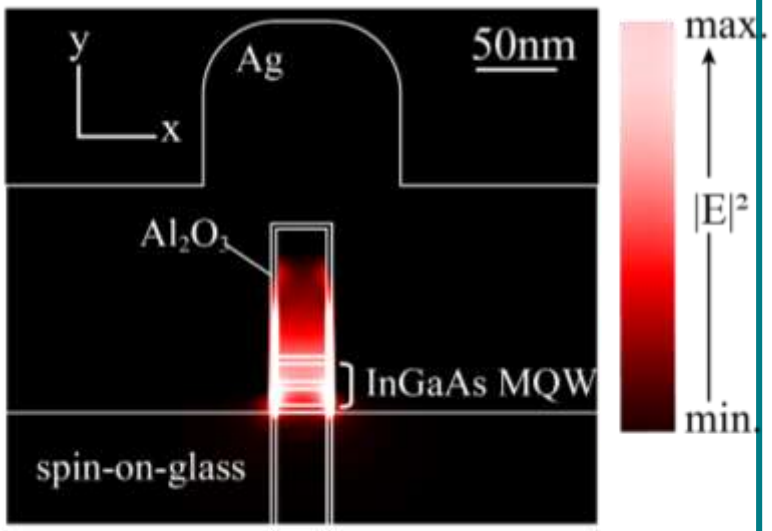
Backup

Electrically-injected III-V antenna-LED



Antenna mode



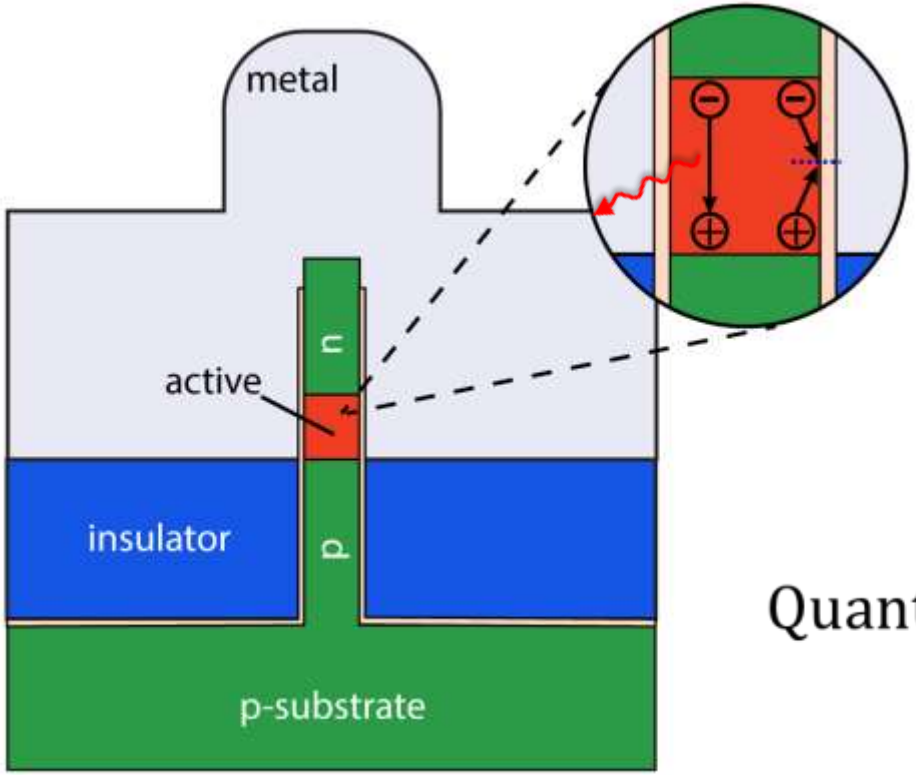


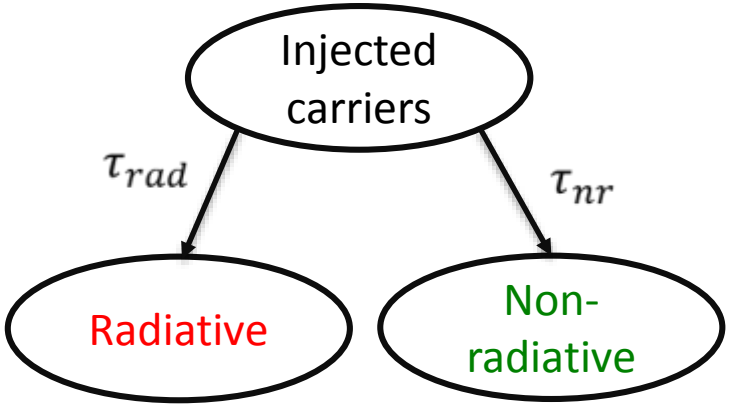
Advantages:

- Electrical injection is straight forward
- Self-aligned
- Directional light emission
- Thermal heat-sink

Spontaneous emission enhancement measurement

- **Antenna enhancement directly increases quantum efficiency**

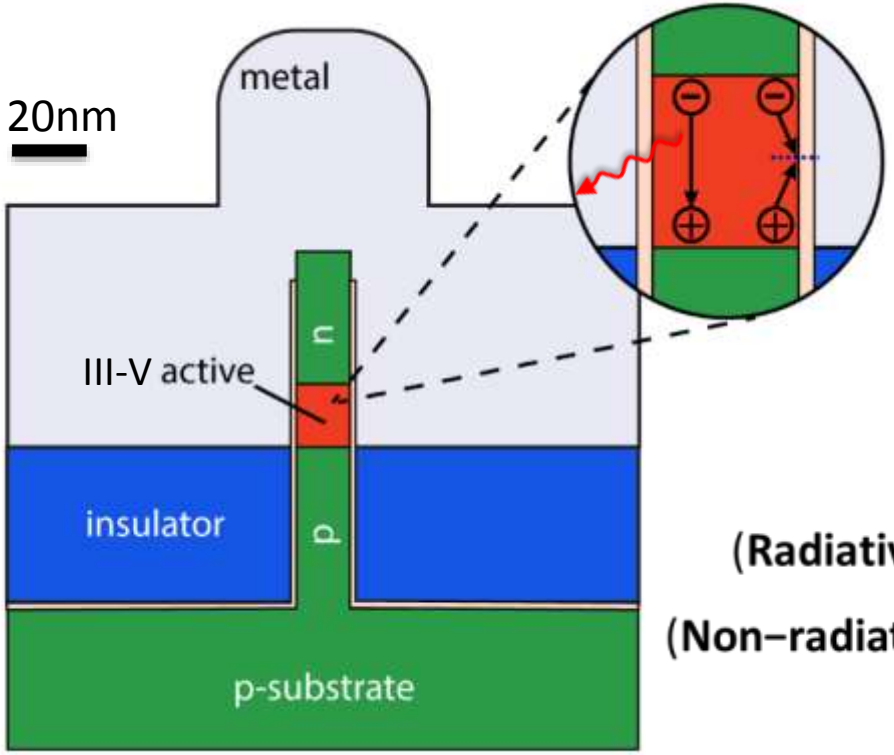


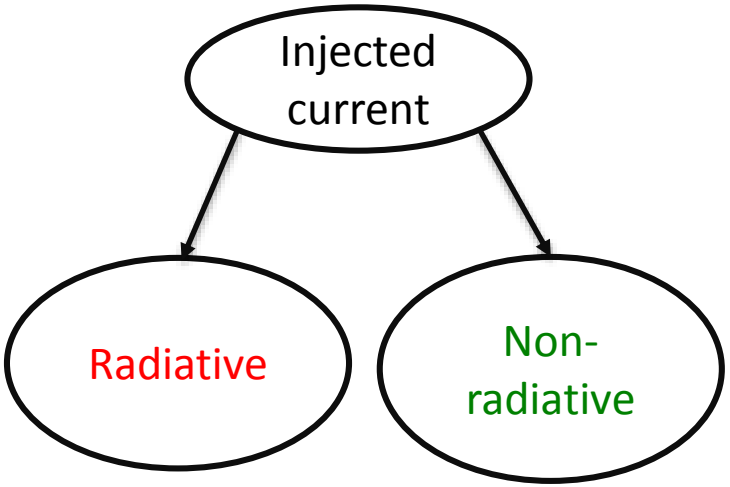


$$\tau_{nr} \ll \tau_{rad}$$

$$\text{Quantum efficiency } (\eta) = \frac{\tau_{rad}^{-1}}{\tau_{rad}^{-1} + \tau_{nr}^{-1}} \cong \frac{\tau_{nr}}{\tau_{rad}}$$

Can radiative recombination ever exceed non-radiative recombination?





(Radiative current) $I_{rad} = \text{Vol.} \times F \times B_0 \times n_i^2 e^{qV/k_B T}$

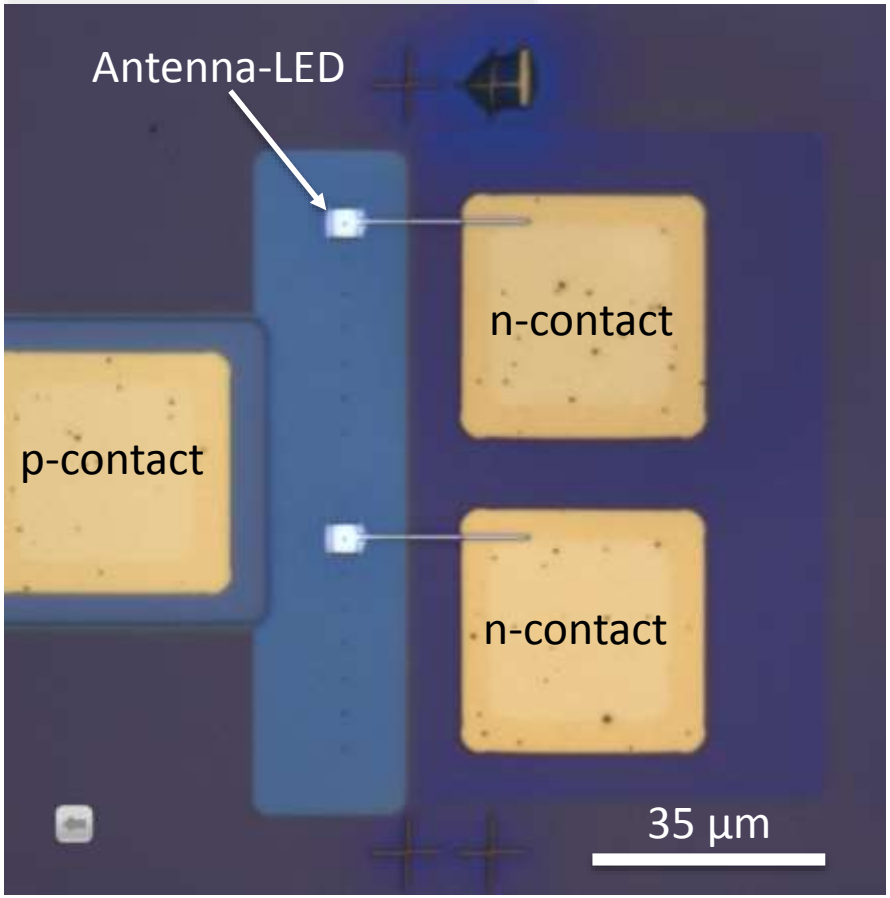
(Non–radiative current) $I_{nr} = \text{Area} \times SRV \times n_i e^{qV/2k_B T}$

F = antenna enhancement

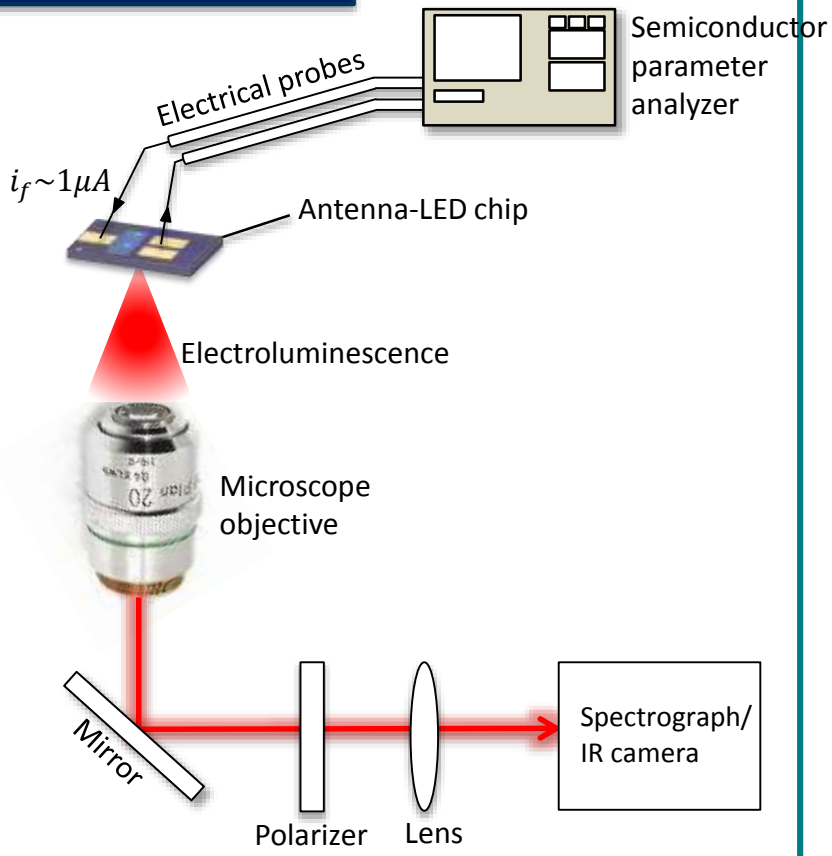
SRV = surface recombination velocity

Electroluminescence measurement

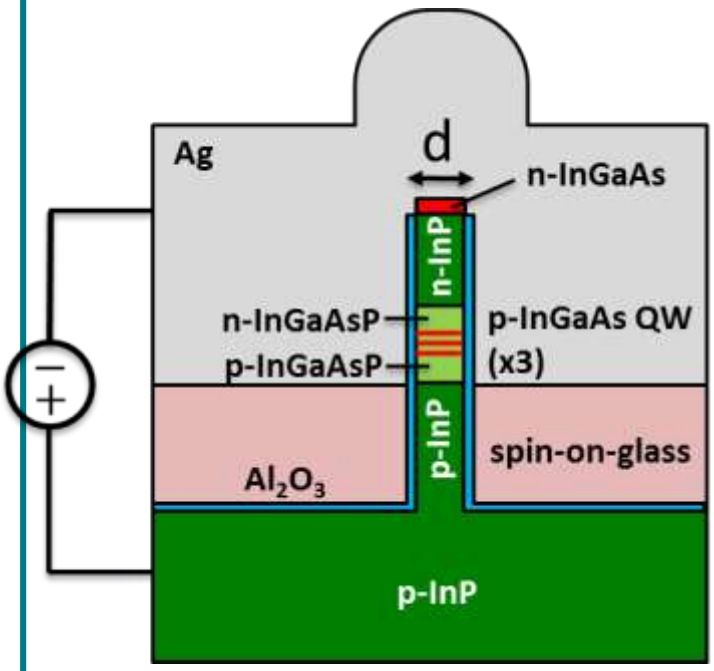
Optical image (frontside)



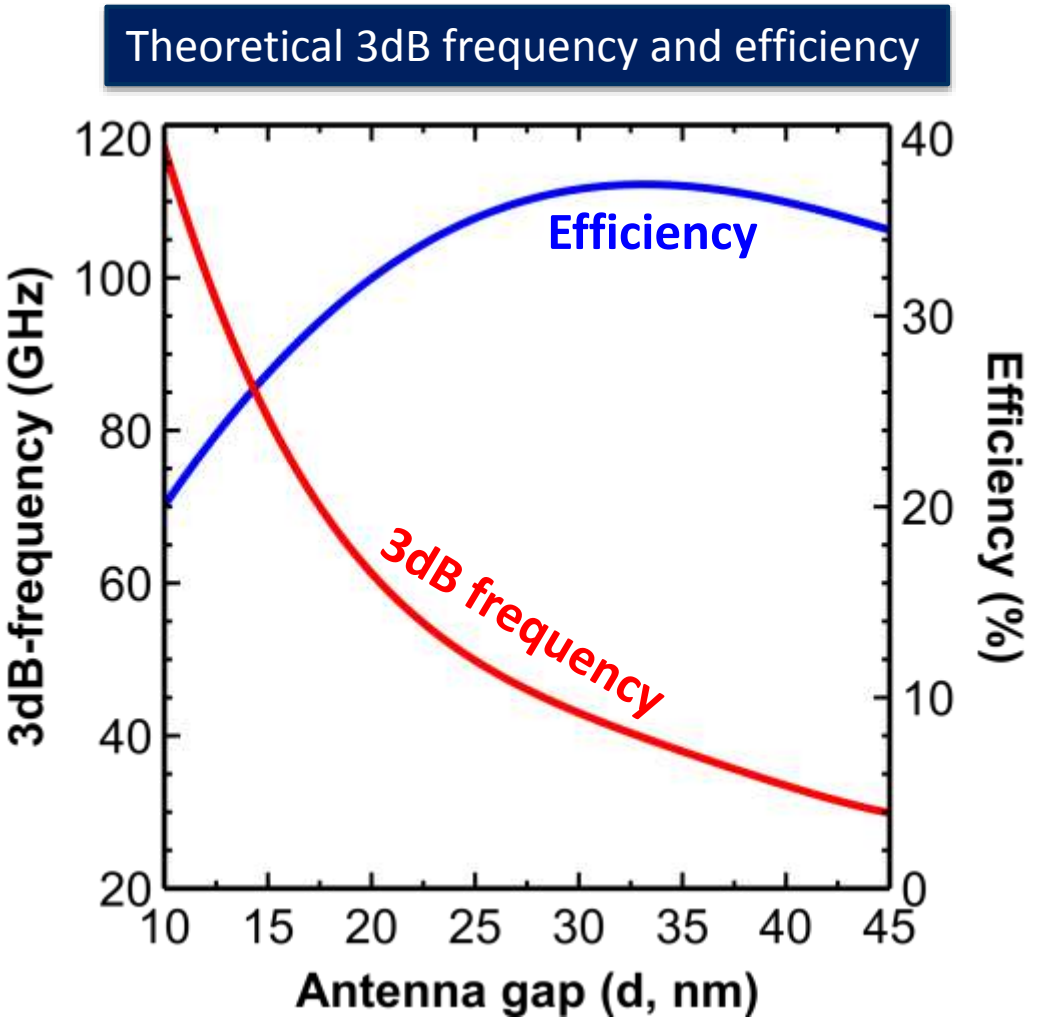
Measurement setup



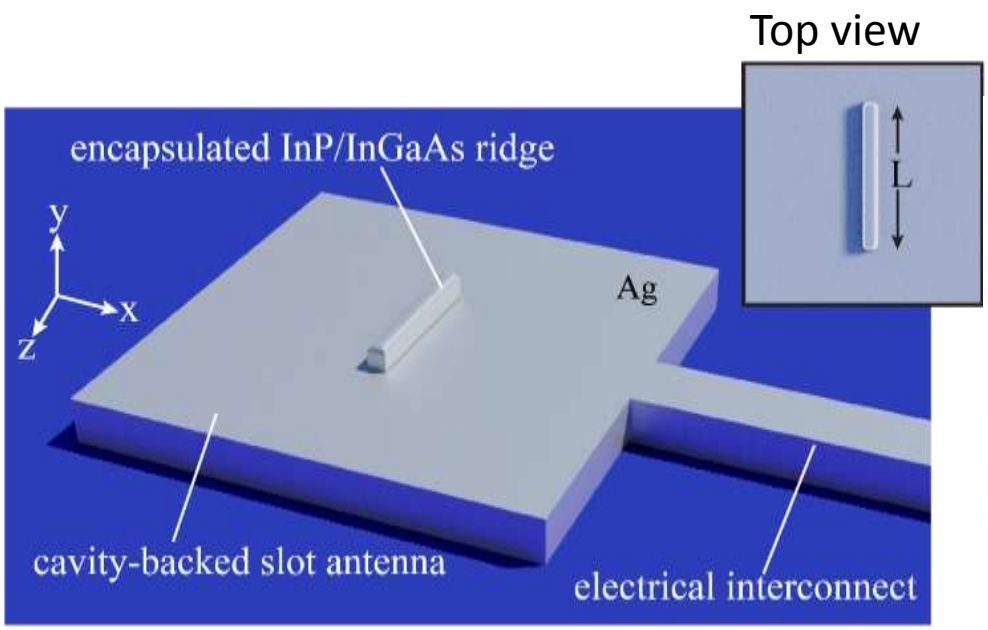
Toward >100 GHz direct modulation rate at high efficiency

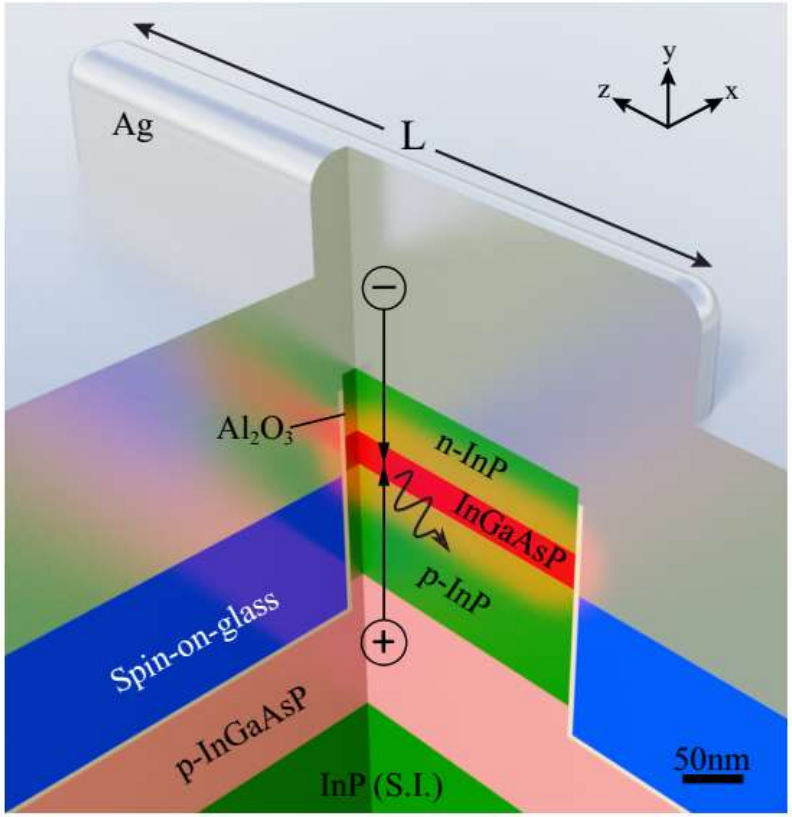


- MOCVD growth by Fitzgerald group (MIT)
- Multiple quantum well (MQW) active region
- Doped active region and cladding layers
- Highly doped n-contact layer



Electrically-injected III-V antenna-LED





Cut-away drawing

Advantages:

- Electrical injection is straight forward
- Self-aligned fabrication
- Directional light emission for coupling into waveguide
- > 100 GHz direct modulation rate