Theme III:
Progress on Antenna-Enhanced LEDs

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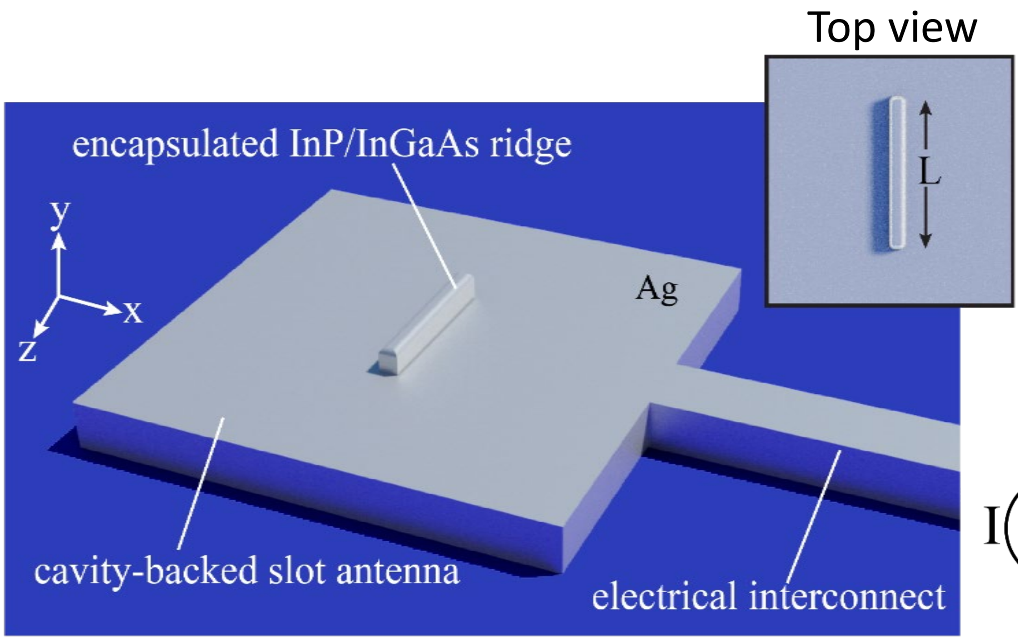
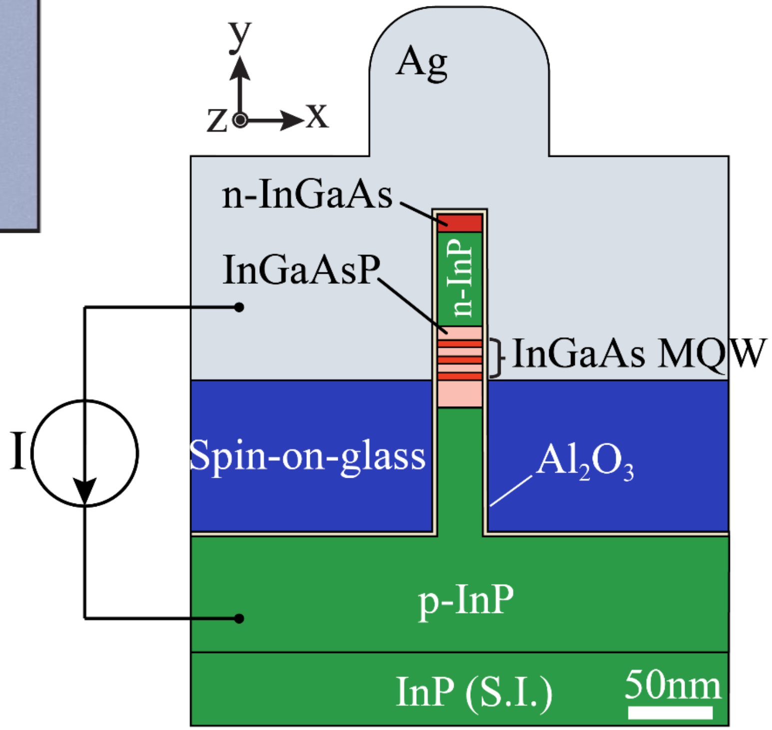
Outline

- Review of electrically-injected III-V antenna-LED
- Can the III-V antenna-LED ever be efficient?
  - Controlling surface recombination velocity
  - Novel technique for cleaning III-V surface
- Progress in doping active region

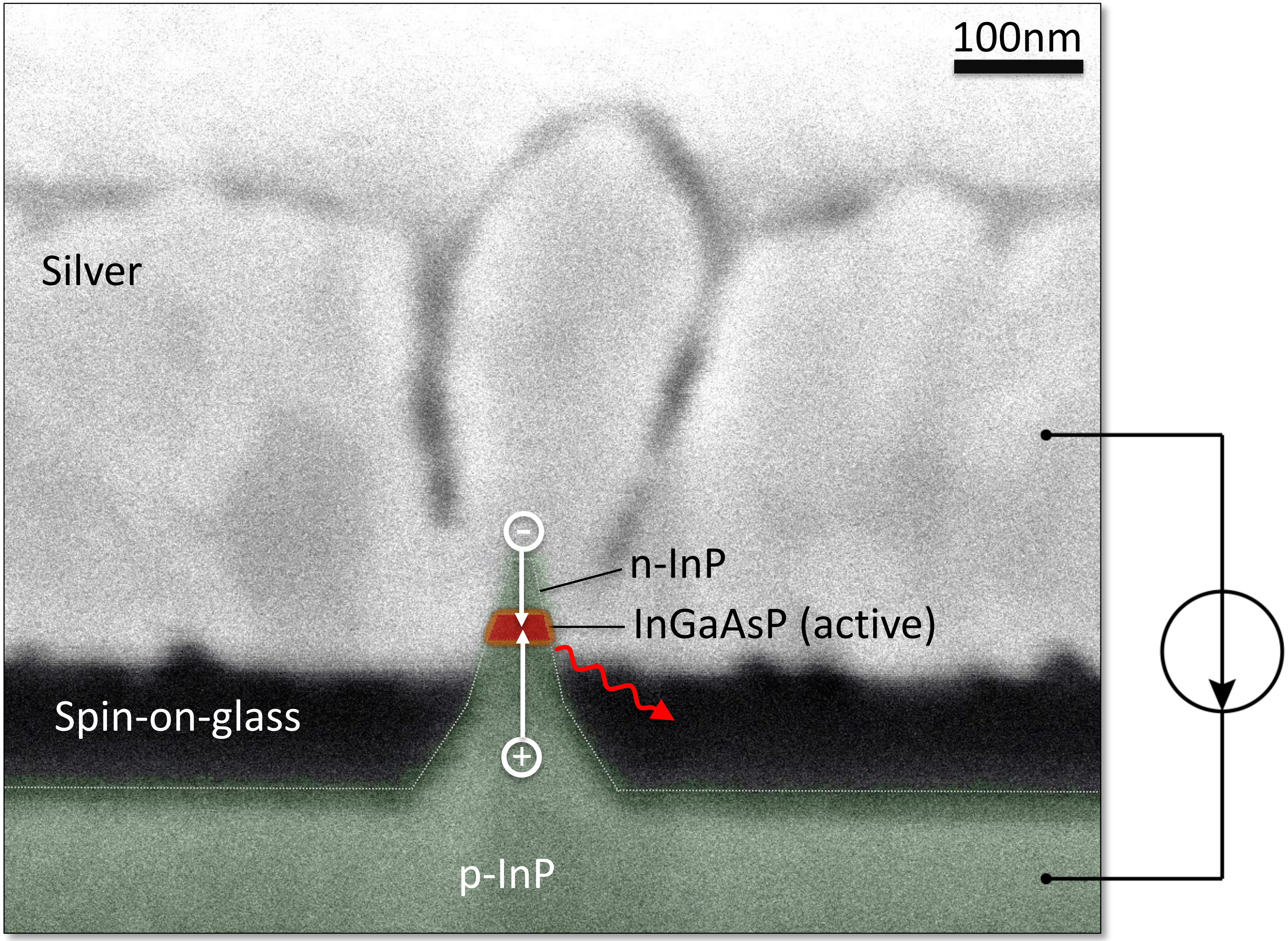
Electrically-injected III-V antenna-LED





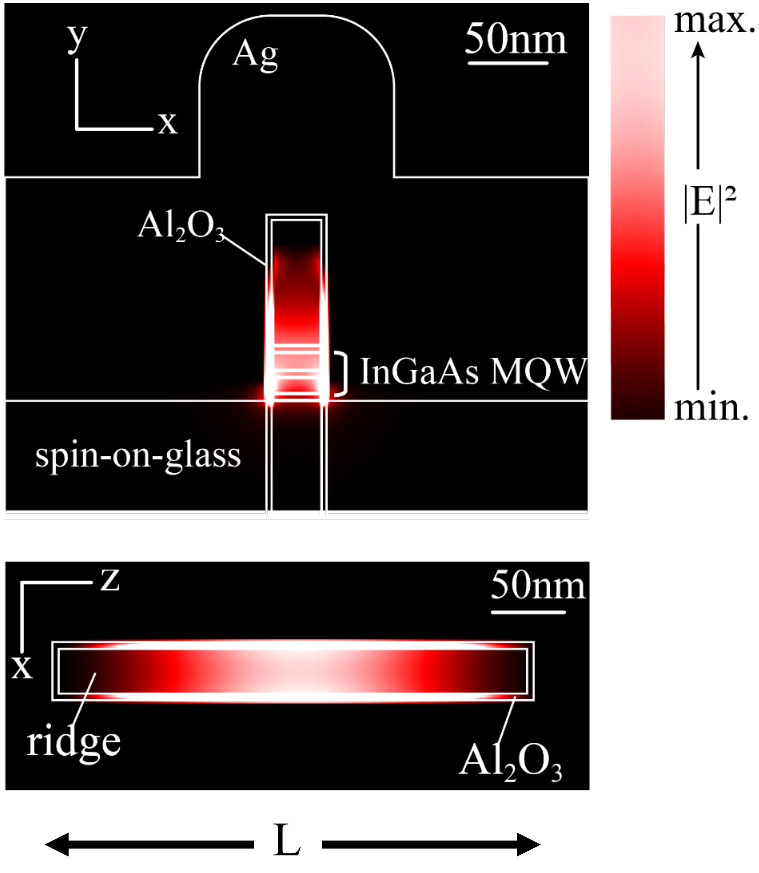
Advantages:

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

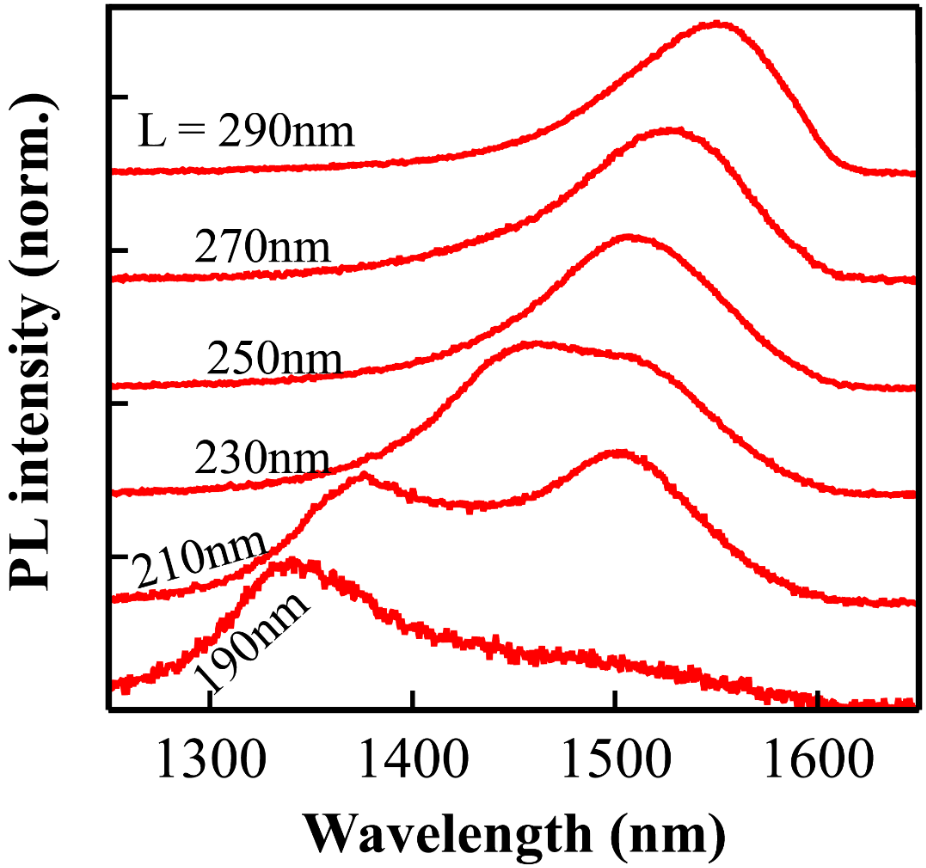


100nm
Silver
n-InP
InGaAsP (active)
Spin-on-glass
p-InP

Engineering the antenna mode

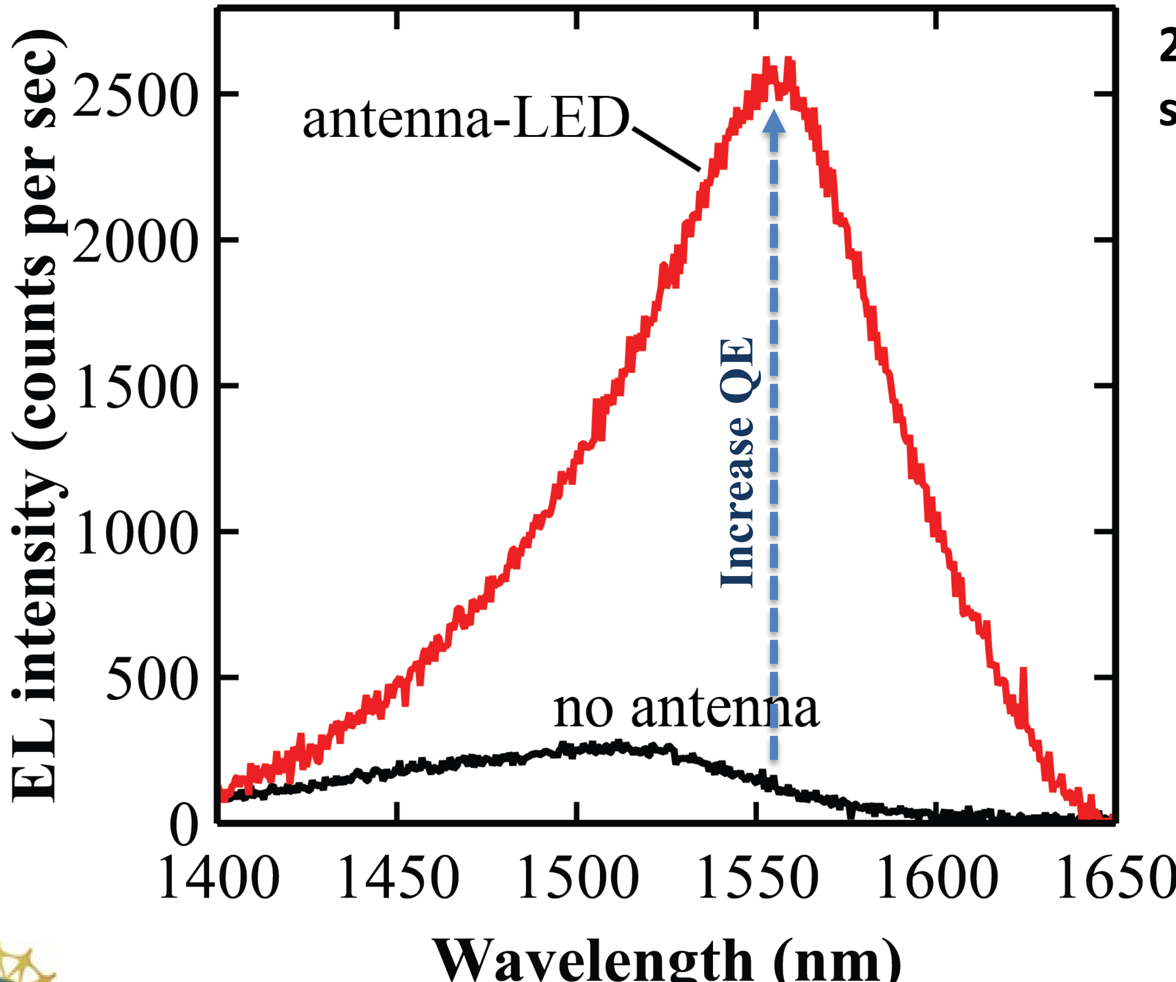


Photoluminescence



Enhancement of spontaneous emission rate

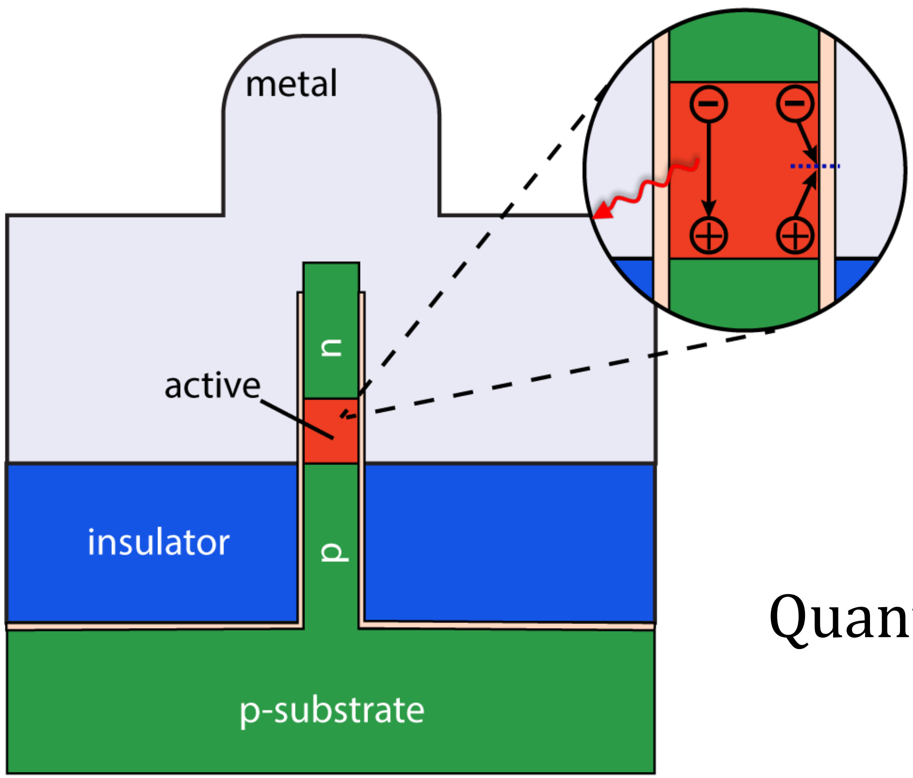
Electroluminescence

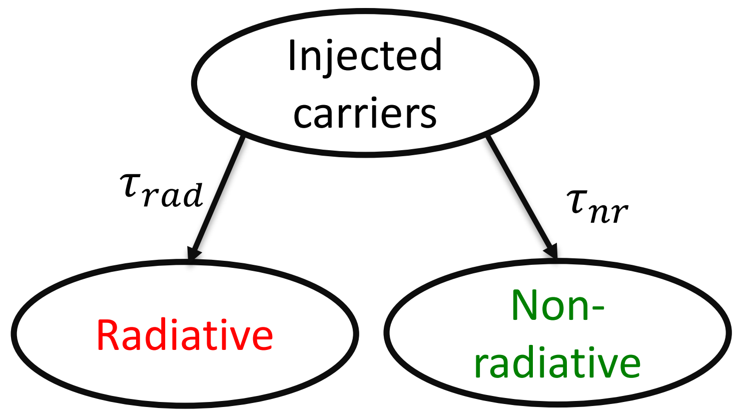


200-fold increase in spontaneous emission rate

Spontaneous emission enhancement measurement

- **Antenna enhancement directly increases quantum efficiency**

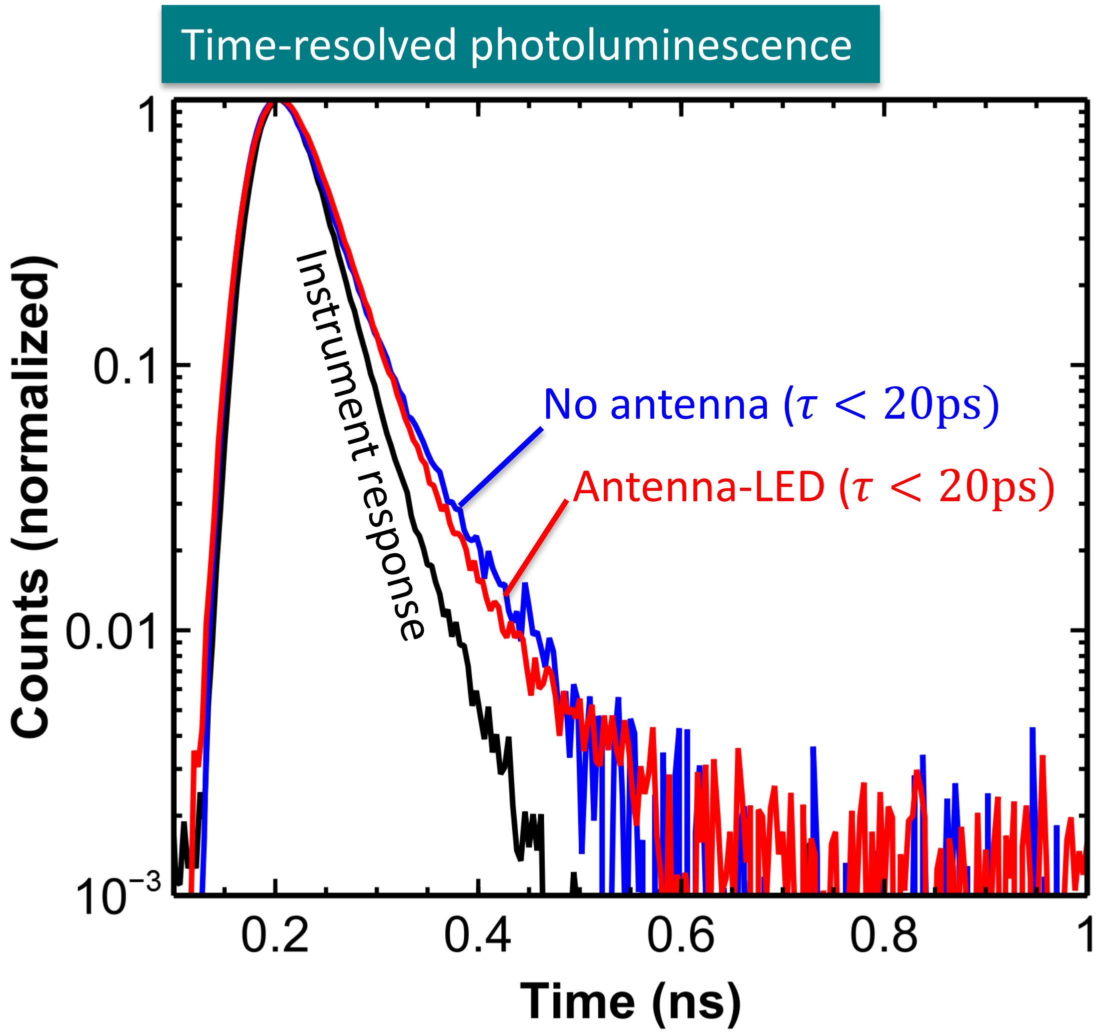




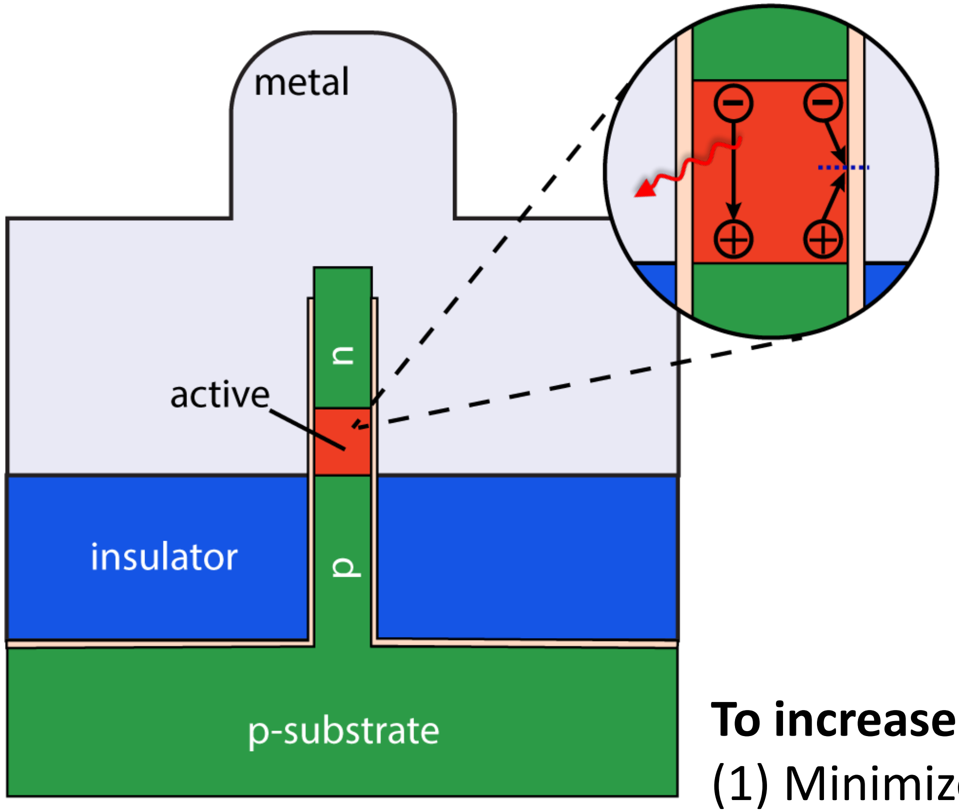
$$\tau_{nr} \ll \tau_{rad}$$

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

Device is fast but not yet efficient



Can radiative recombination ever exceed non-radiative recombination?



$$I_{tot} = \underbrace{AN}_{I_{nr}} + \underbrace{BN^2}_{I_{rad}} + \underbrace{CN^3}_{I_{Auger}}$$

$$\mathrm{I_{rad}} = \mathrm{Vol.} \times \mathrm{F} \times \mathrm{B_0} \times \mathrm{n_i^2} \mathrm{e}^{qV/k_BT}$$

$$\mathrm{I_{nr}} = \mathrm{Area} \times v_s \times \mathrm{n_i} \mathrm{e}^{qV/2k_BT}$$

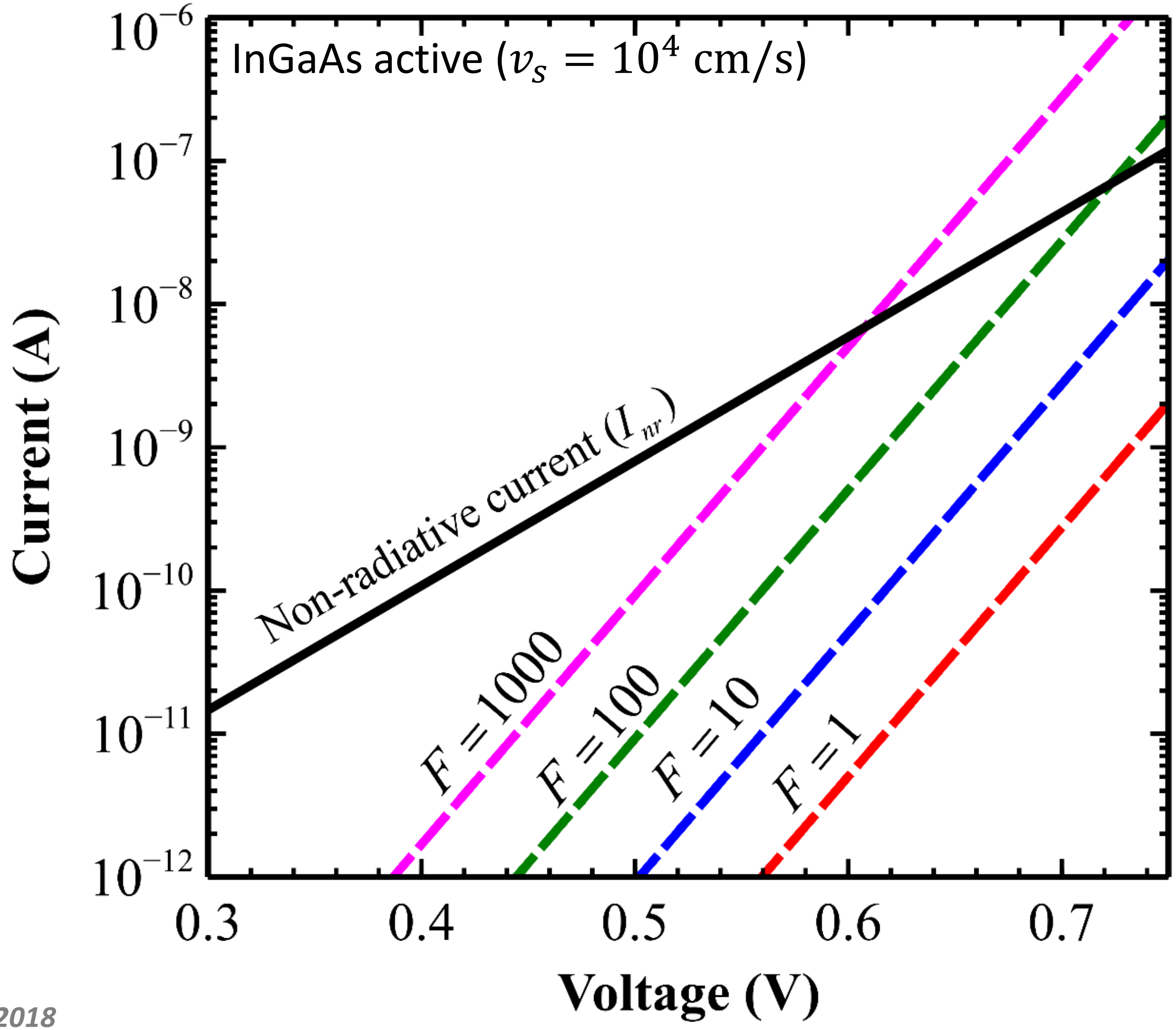
To increase efficiency:

(1) Minimize surface recombination velocity (v_s)

(2) Maximize carrier density

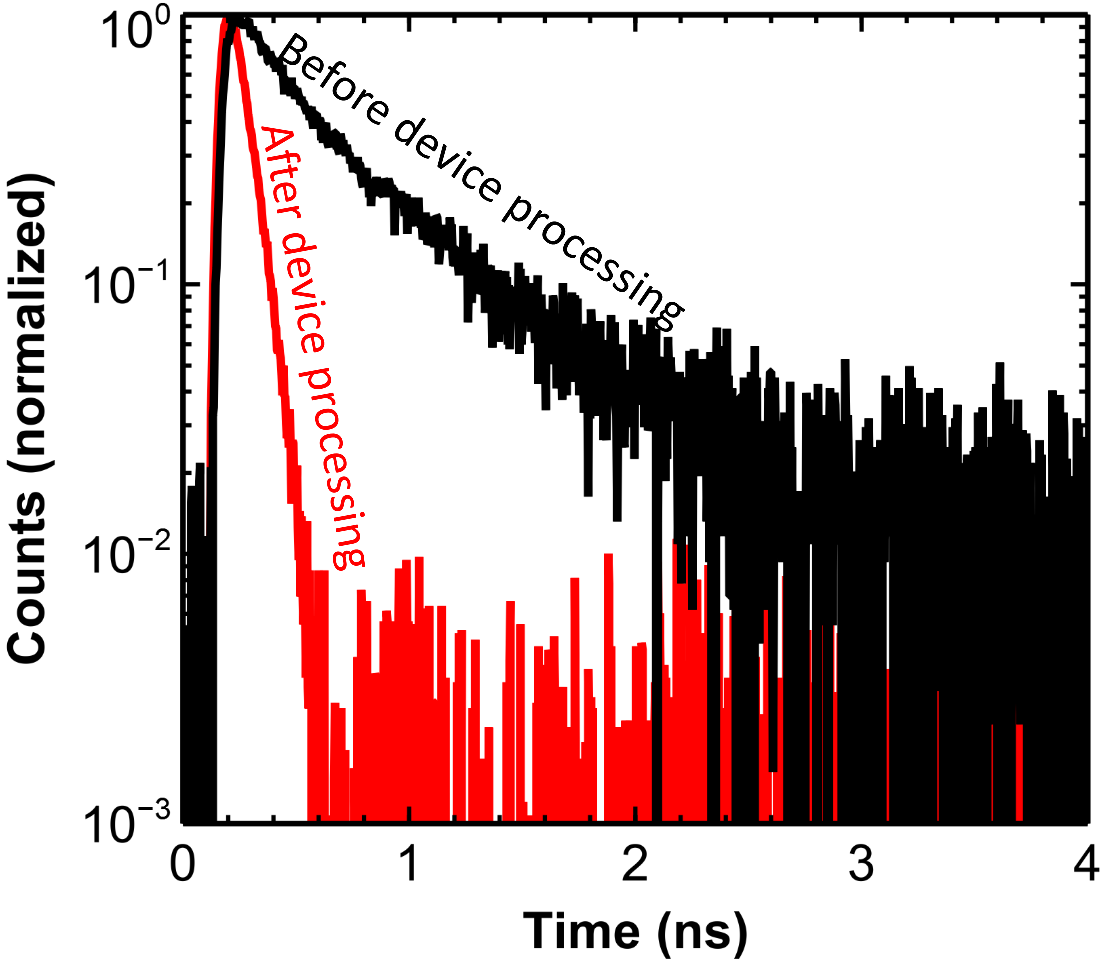
(3) Maximize antenna enhancement (F)

Can radiative recombination ever exceed non-radiative recombination? <u>YES</u>



Process induced surface damage

Time-resolved photoluminescence



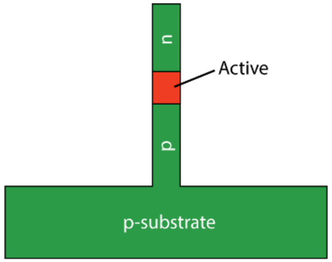
Before device processing:
$$v_s \cong 3 \times 10^4 \text{ cm/s}$$

After device processing:
$$v_s > 10^5 \text{ cm/s}$$

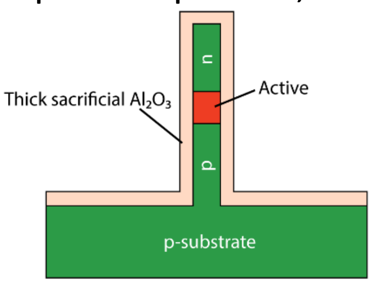
Surface needs to be protected during fabrication!

Improved process with sacrificial Al_2O_3

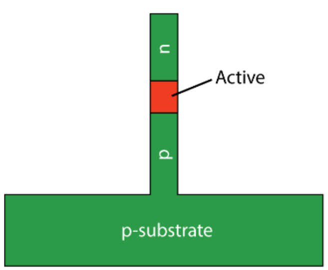
1 Dry etch ridge



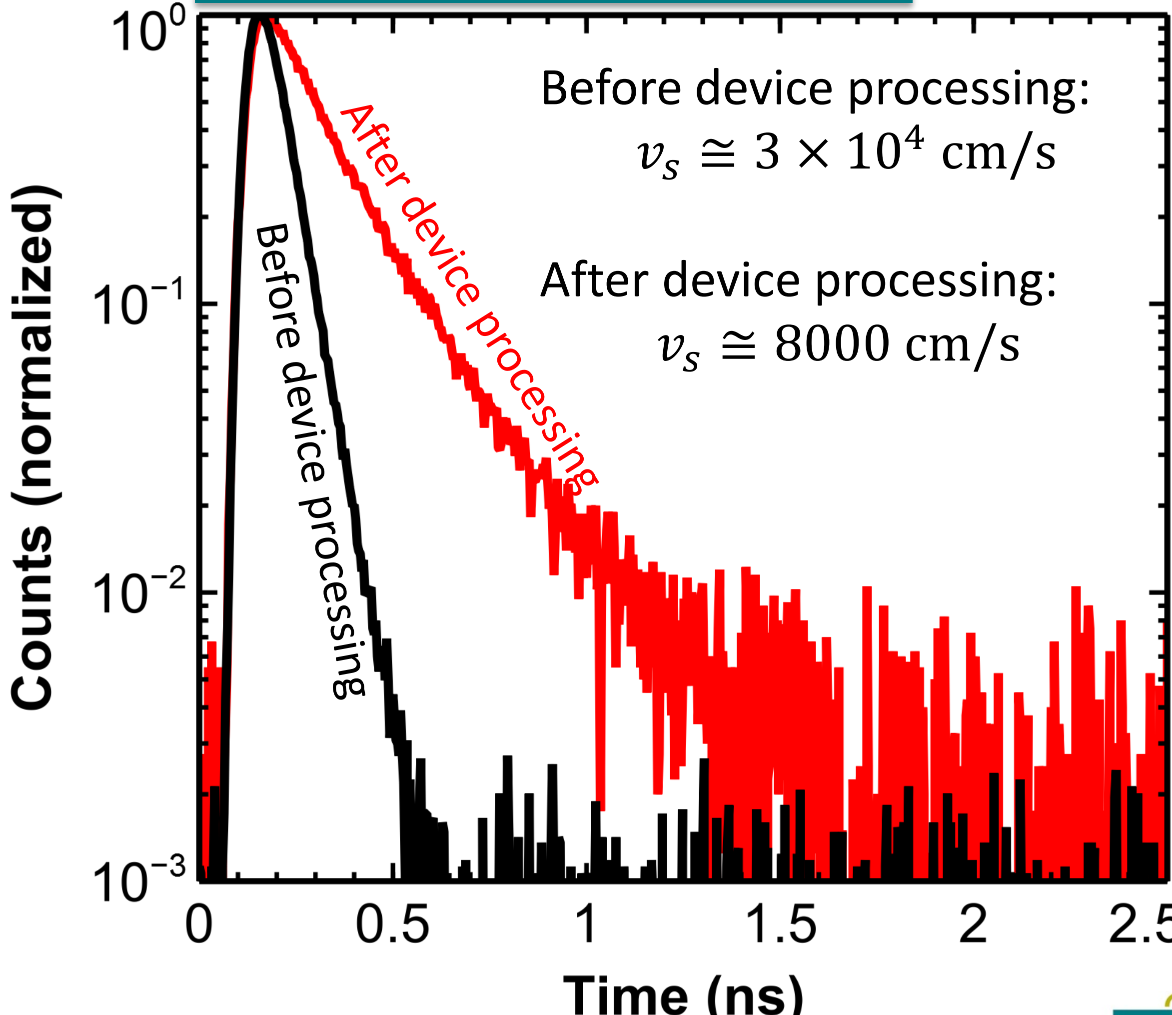
2 Deposit sacrificial Al_2O_3
(expose to plasma, anneal, etc.)



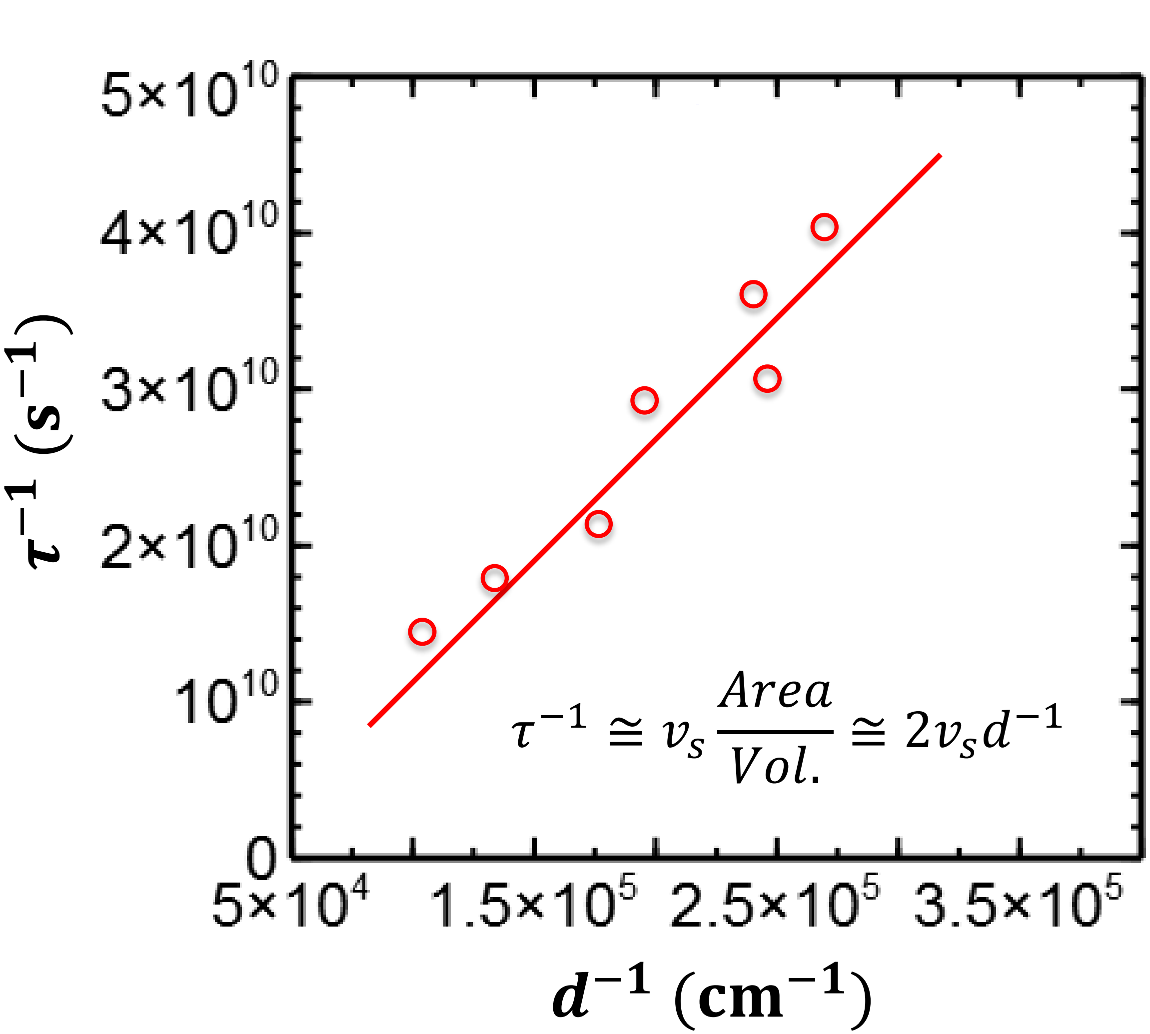
3 Strip sacrificial Al_2O_3 (TMAH)

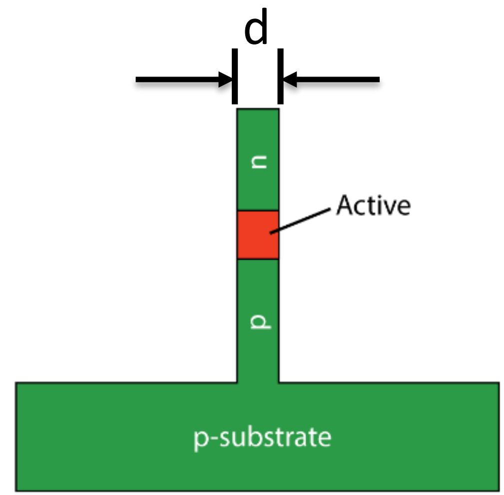


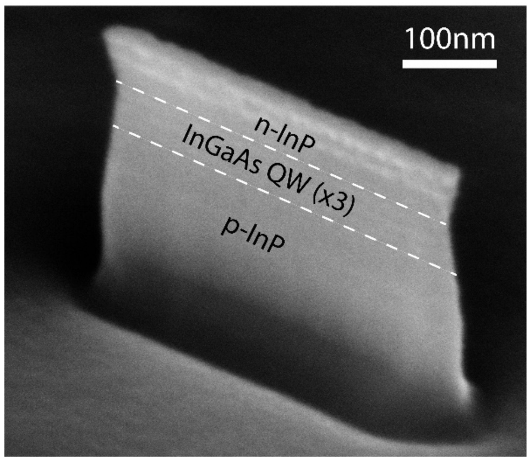
Time-resolved photoluminescence



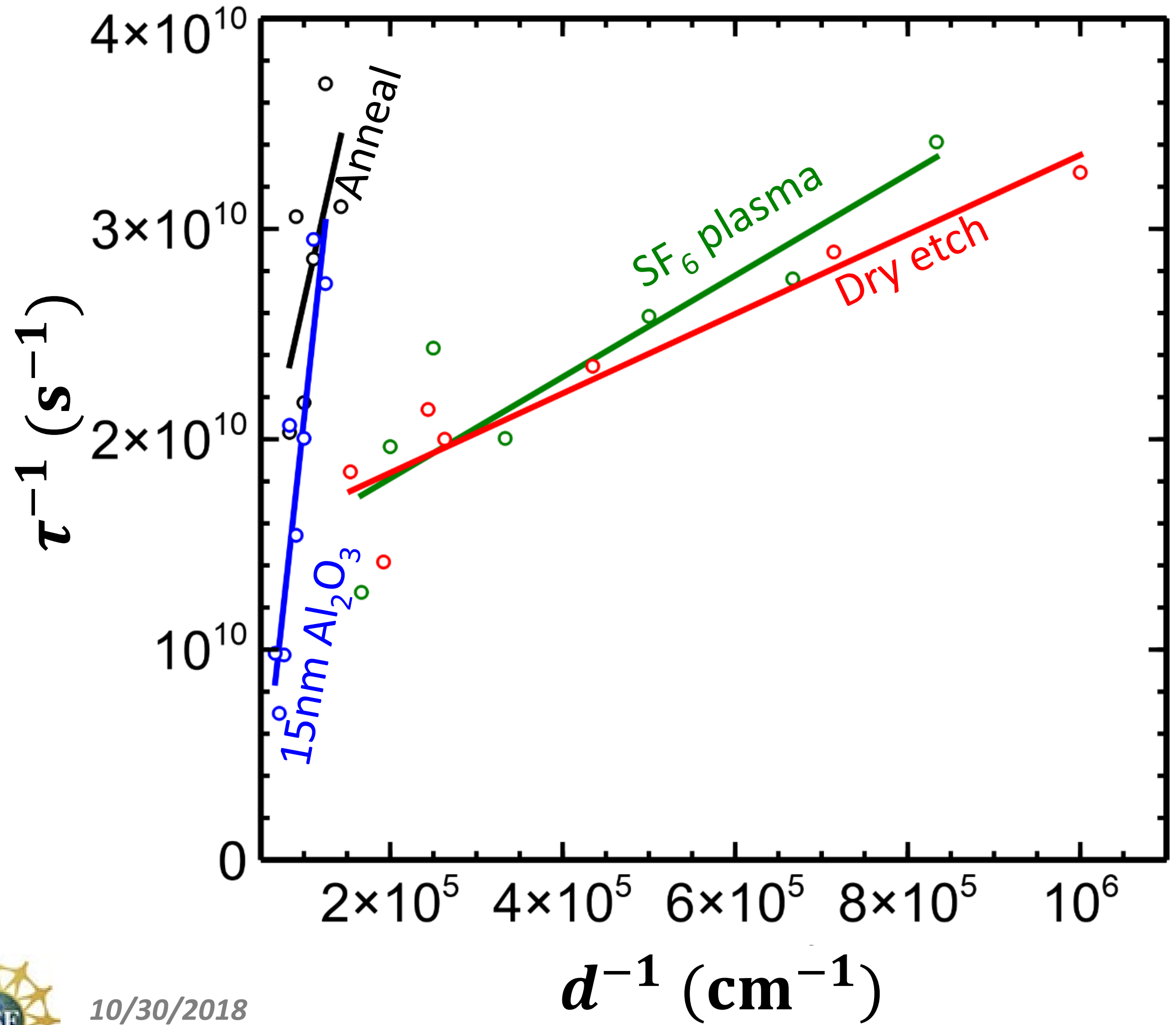
Extraction of surface recombination velocity



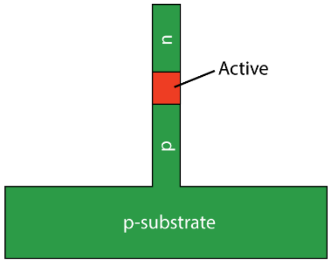




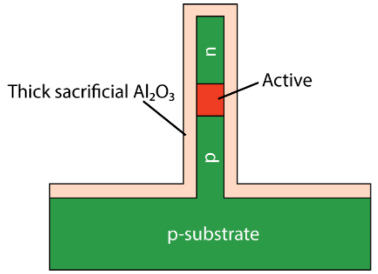
Monitoring surface recombination velocity throughout antenna-LED fabrication



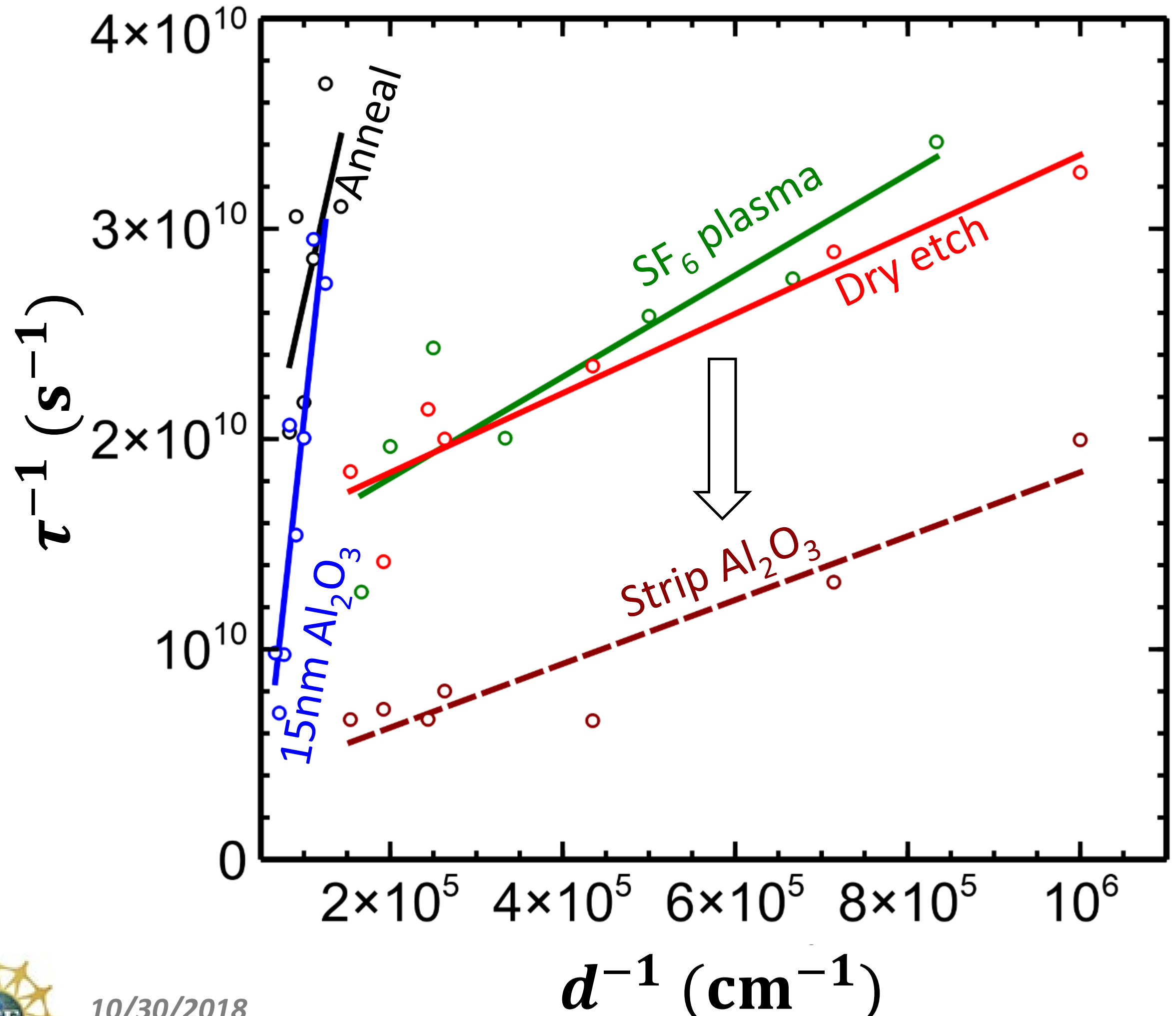
1 Dry etch ridge

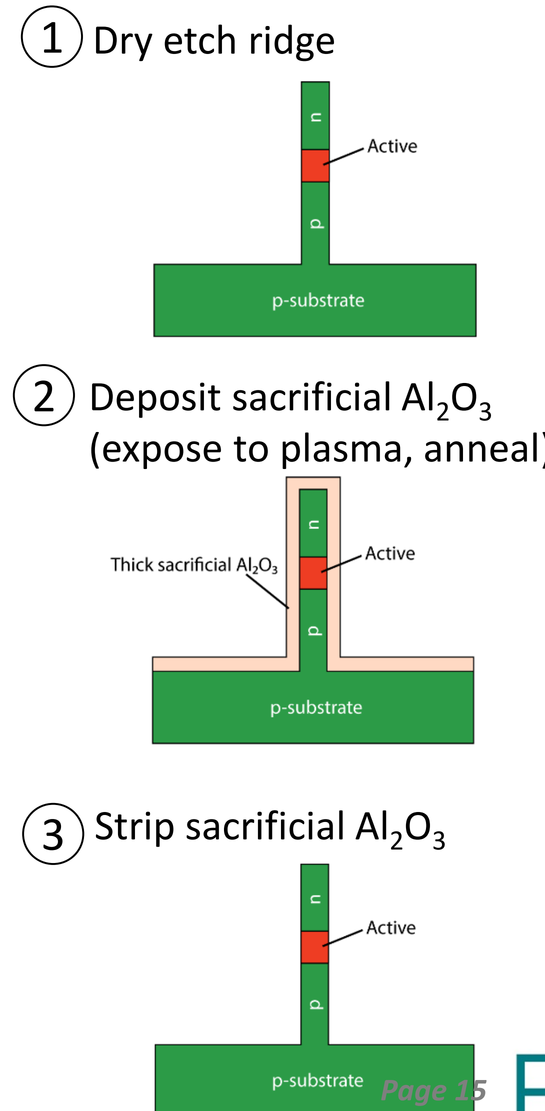


2 Deposit sacrificial Al_2O_3 (expose to plasma, anneal)

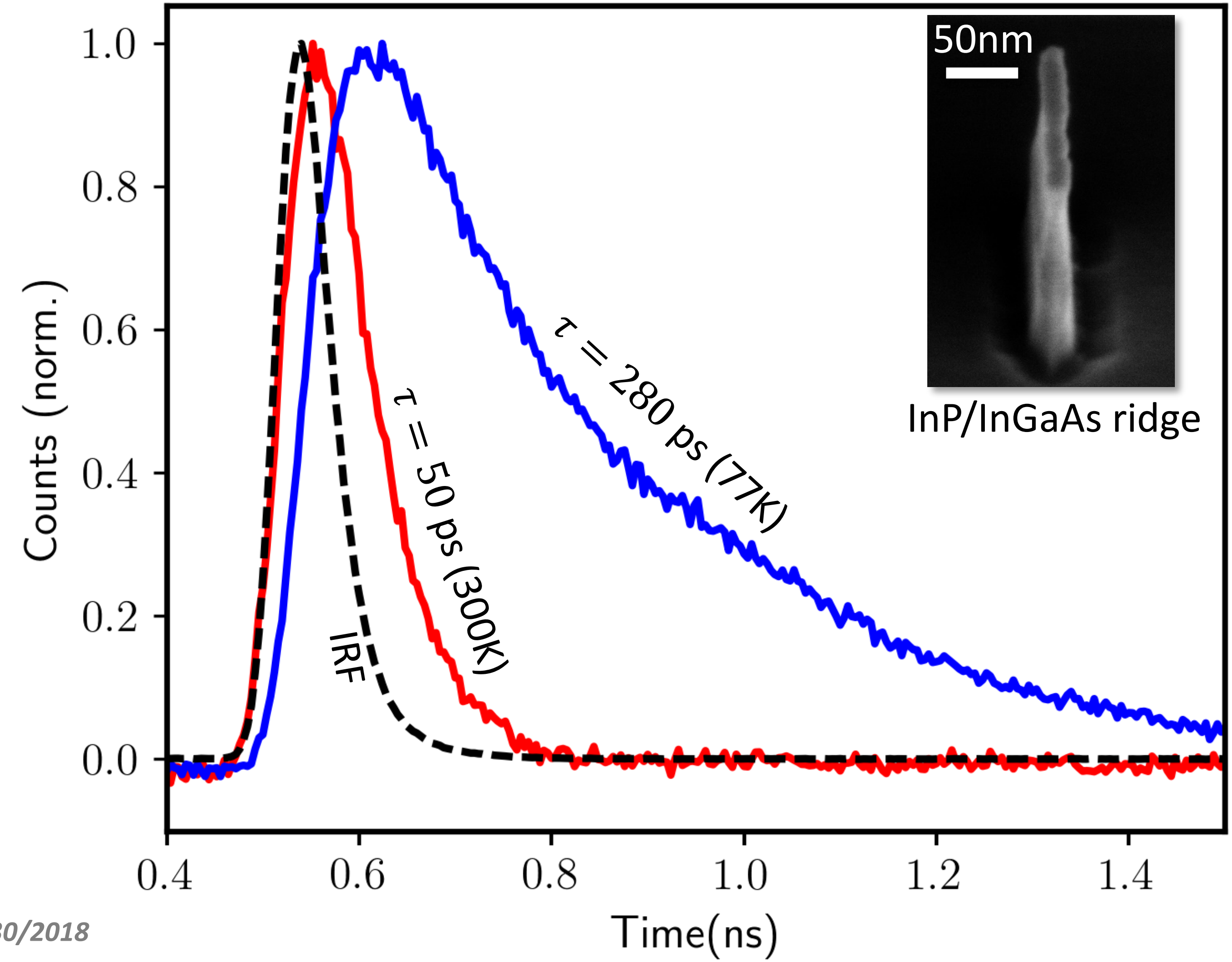


Sacrificial Al_2O_3 process protects and cleans III-V surface





Low-temperature (77K) time-resolved photoluminescence measurement



Increasing carrier concentration with p-doping active region

(undoped) $R_{rad} \cong FB_0 np$

- B_0: Antenna enhancement
- p: Carrier density

- High current density needed for high radiative rate (R_{rad})
- Injected carrier density $> 5 \times 10^{18} \mathrm{cm}^{-3}$ is not feasible

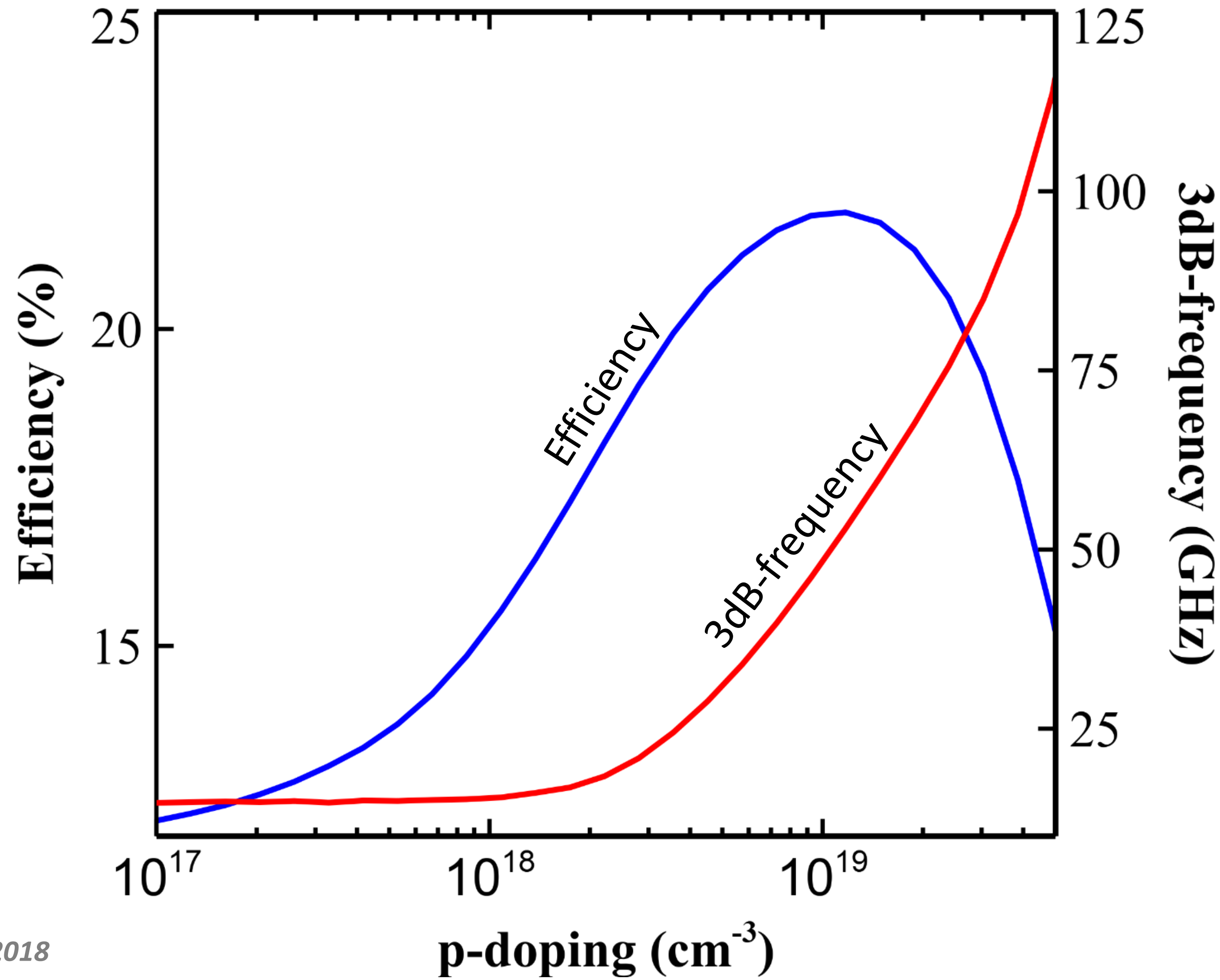
(doped) $R_{rad} \cong FB_0 np_0$

- B_0: Antenna enhancement
- p_0: p-type doping

- High current density **not** needed for high radiative rate (R_{rad})
- p-type doping $> 10^{19} \mathrm{cm}^{-3}$ is feasible

Increased modulation speed with doped active region

Predicted 3dB frequency and efficiency



p-doping III-V materials in MOCVD

Zinc
(precursor: DEZn)

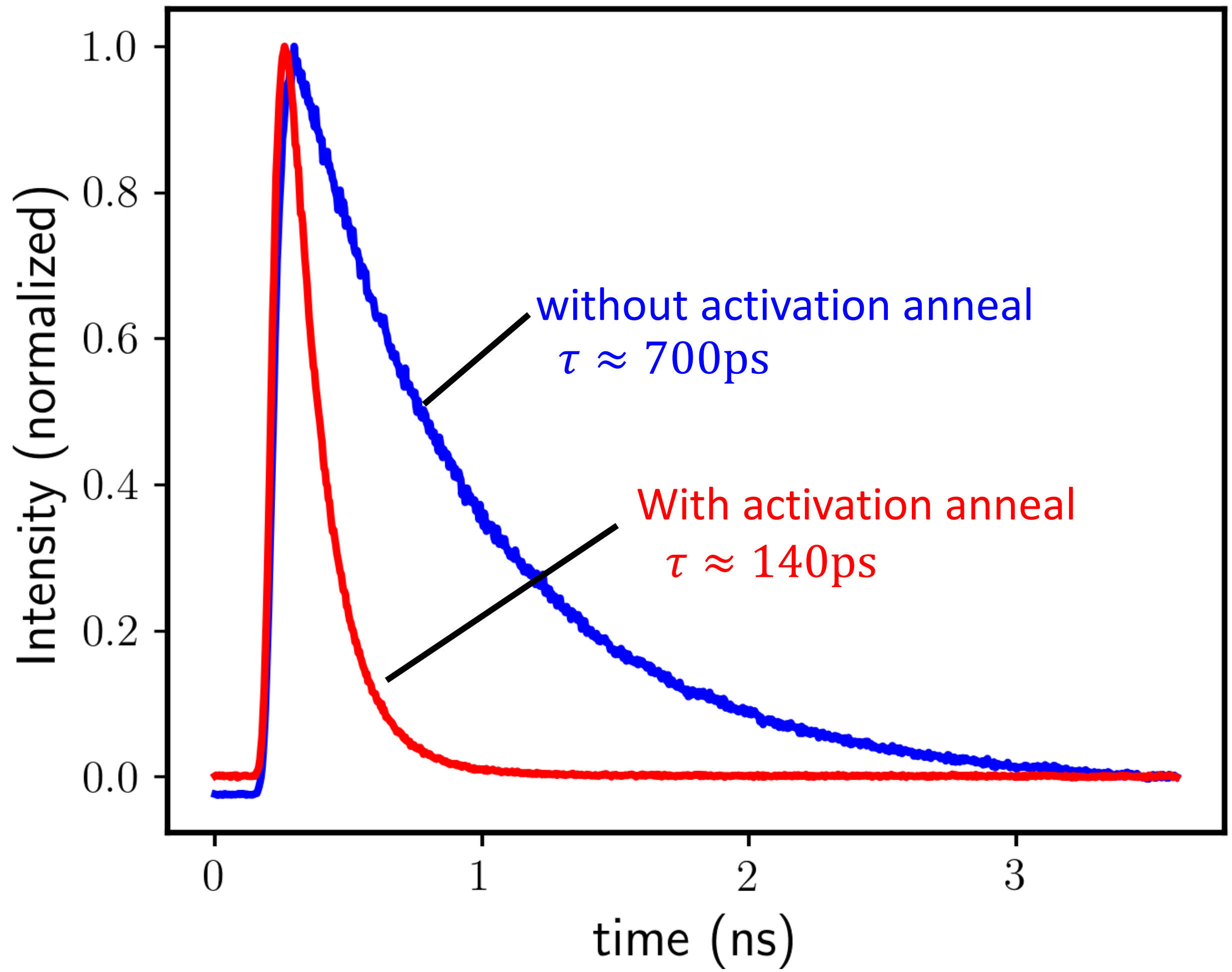
- Most common
- High growth quality
- High diffusion coefficient

Carbon
(precursor: $CBrCl_3$,CCl_4)

- High doping (>10^{19} cm^{-3}) is possible
- Low diffusion coefficient
- Amphoteric
  (both p and n-type dopant)
- Low growth temperature

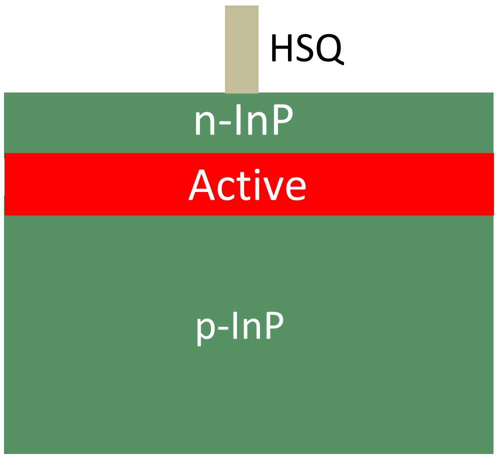
High carbon p-type doping of InGaAs ($N_A = 10^{19}$ cm^{-3})

Time-resolved photoluminescence

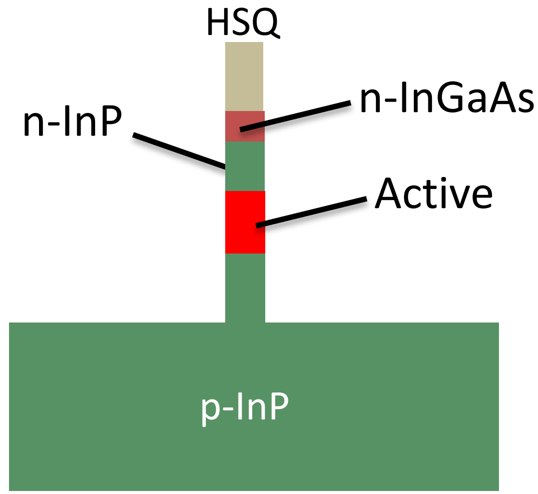


Summary

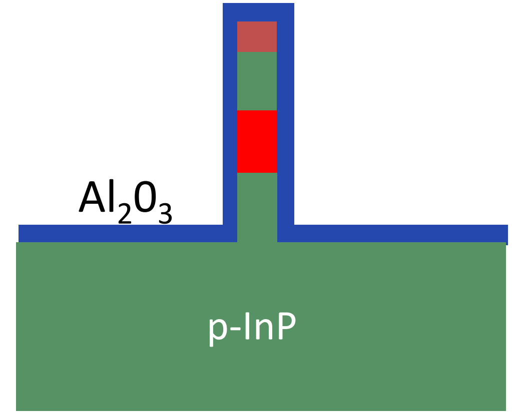
- High efficiency antenna-LED is possible despite high III-V surface recombination velocity.
- Developed a technique to protect and clean the III-V surface using sacrificial Al_2O_3 layer.
- Demonstrated high carbon p-type doping of InGaAs ($10^{19}\mathrm{cm}^{-3}$).



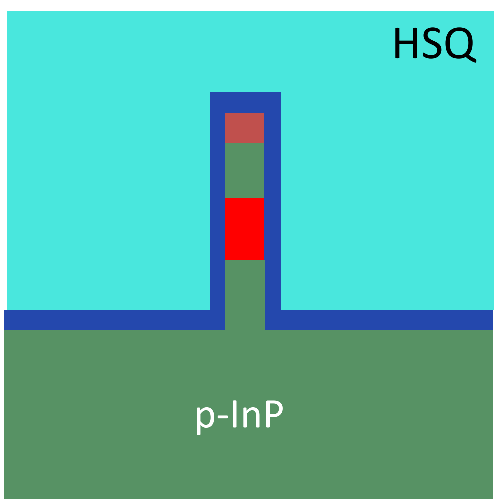
1) Pattern dry etch hard mask (HSQ)



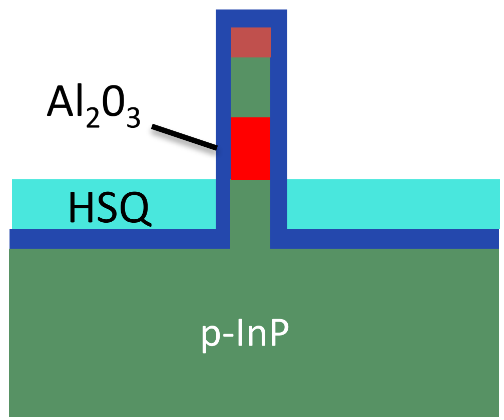
2) Dry etch



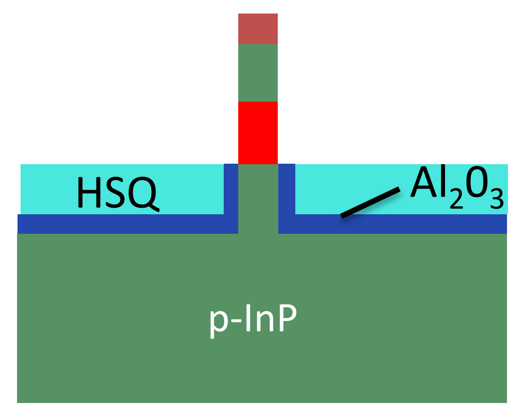
3) Al_2O_3 deposition **SACRIFICIAL** (~15nm) ALD



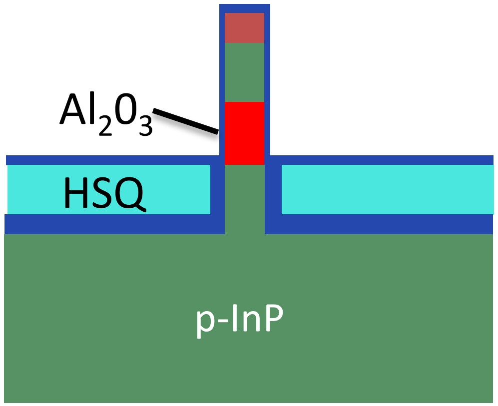
4) HSQ planarization



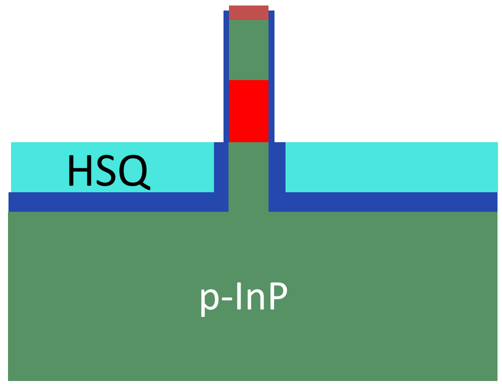
5) Etch back HSQ



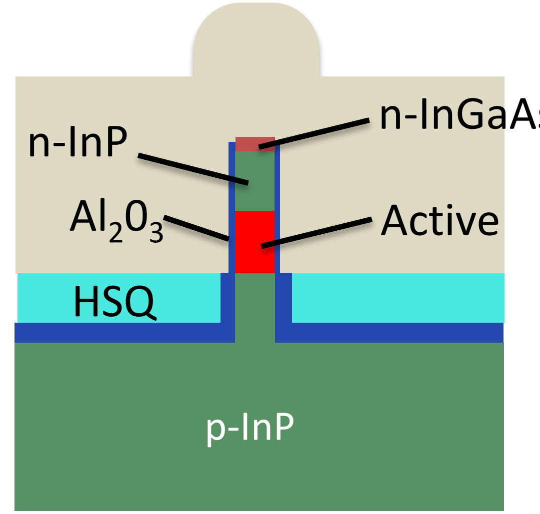
6) Remove thick Al_2O_3



7) Al_2O_3 dep.
THIN (~1nm) ALD



8) Etch back Al_2O_3



9) Pattern antenna