Waveguide-Integrated Optical Antenna nanoLEDs for On-Chip Communication

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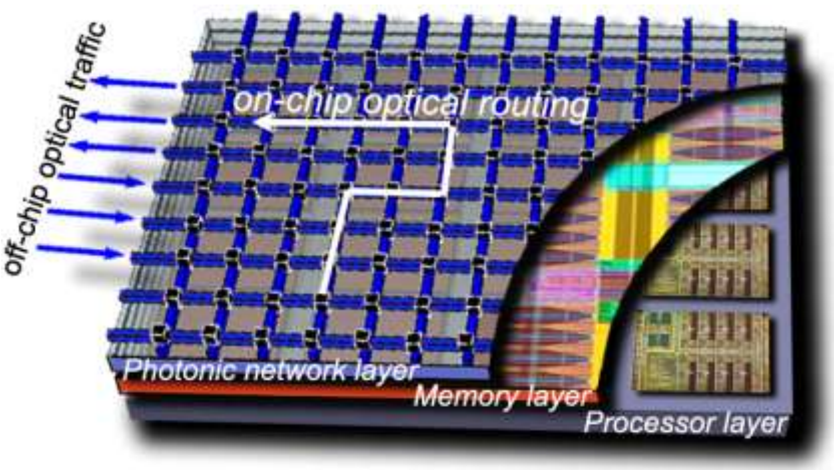
Power Consumption in Modern CPUs

- ***50% - 80%* of CPU power dissipation is in wire interconnects**
- **Energy Required to charge a wire ~CV^2**
- **Minimum energy to send one bit across a chip:**

Intel's 45nm Process Interconnect Layers
(Source: Intel)



Concept Drawing of 3D Integrated Processor with Optical Interconnects
(Source: IBM)

$$CV^2 \approx 2\frac{\text{pF}}{\text{cm}} * 1\text{cm} * (1\text{V})^{\ 2}$$
$$= \mathbf{2pJ}$$

$$17 \text{ photons @ } 0.8\text{eV/photon} \approx$$
$$= \mathbf{2aJ}$$

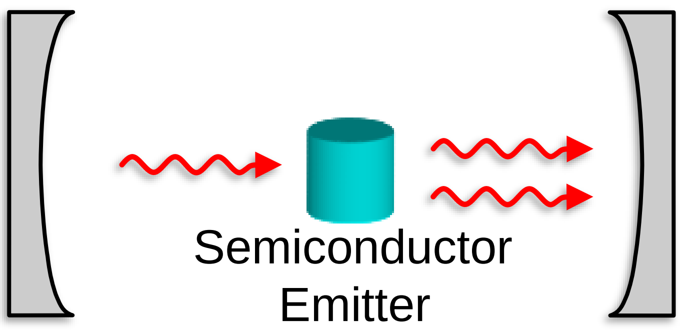
Optical Source for Energy-Efficiency Interconnect

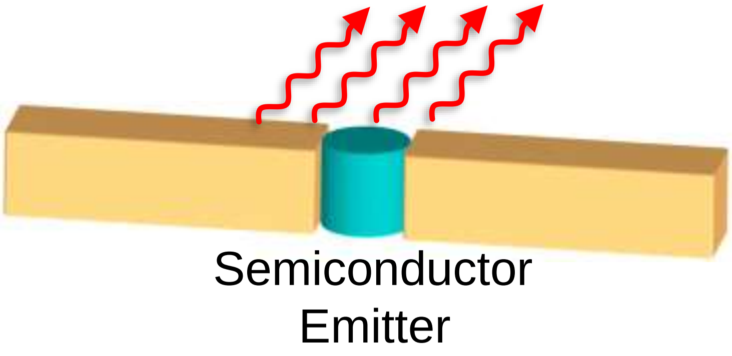
Semiconductor Laser:

- Excessive energy consumption due to bias current
  - e.g., for lasers with 1µA threshold, and bias at 5x threshold, E ~ 400 aJ/bit at 10Gbps

Optical antenna-enhanced nanoLED:

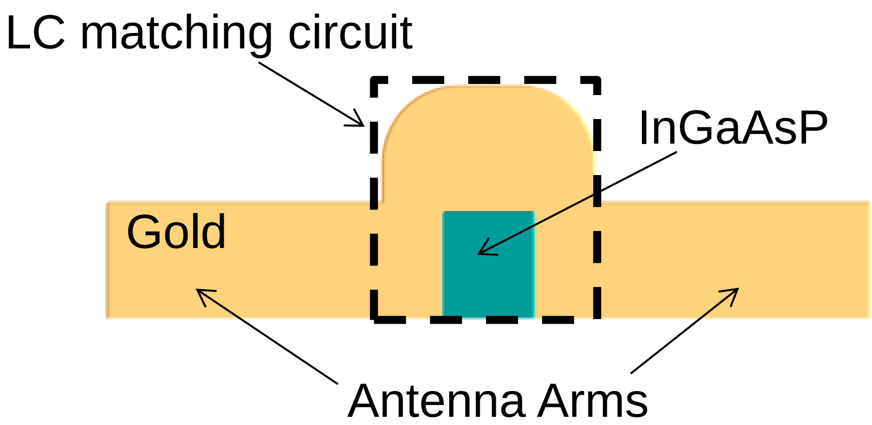
- No bias current
- Optical antenna enhance bandwidth by up to 1000x (10 to 100 Gbps possible)
- Energy consumption ~2x photon energy





Arch-Dipole Antenna Based nanoLED

Optical Antenna



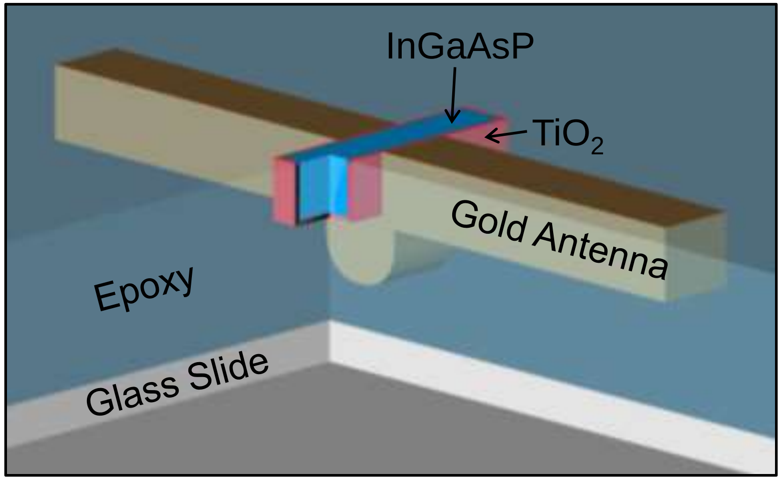
Expected Enhancement:

Gap Spacing (d) = 35nm
Length (L) = 400nm

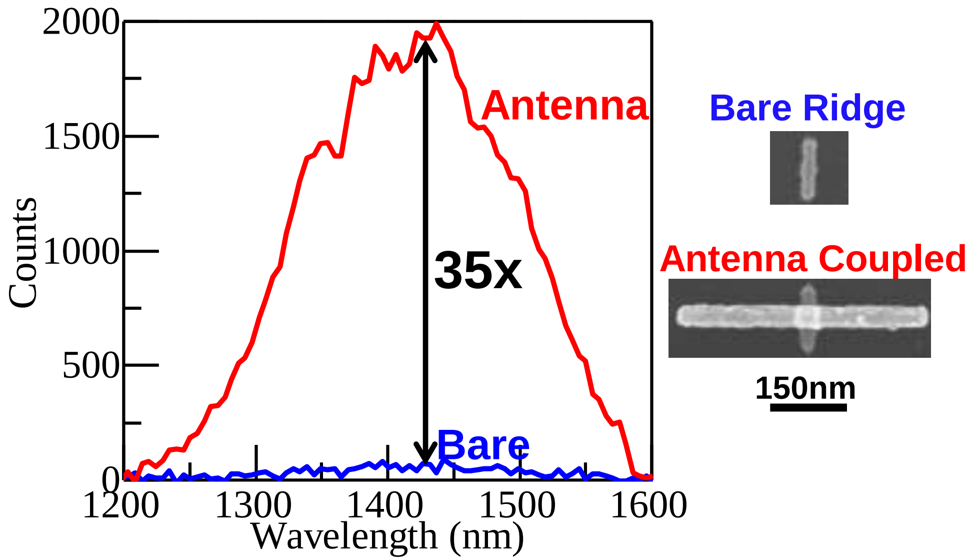
$$\frac{\tau_o}{\tau} = \frac{1}{4}\left(\frac{L}{d}\right)^2 \approx 33x$$

Eggleston, et. al, IEEE 23rd ISLC (2012).

Free-Standing Structure

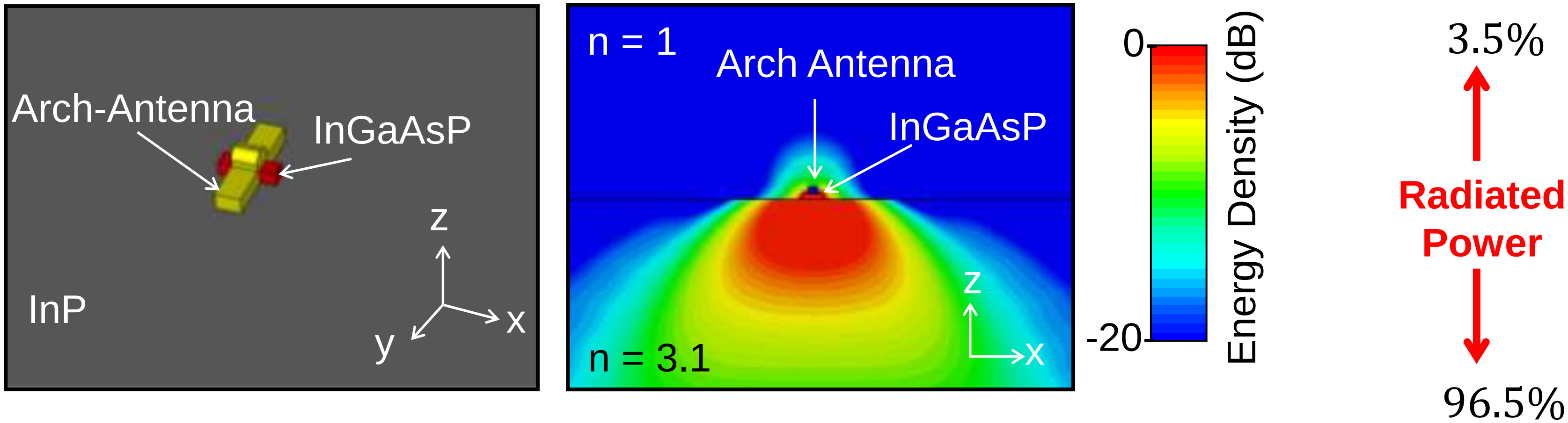


Optical Emission Spectra

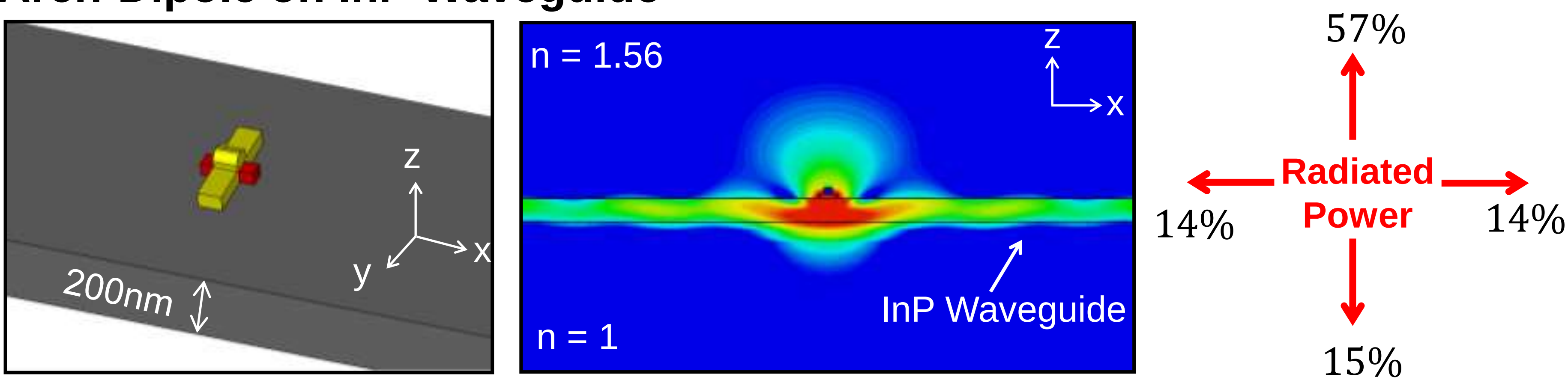


InP Waveguide Design

Arch-Dipole on InP Substrate

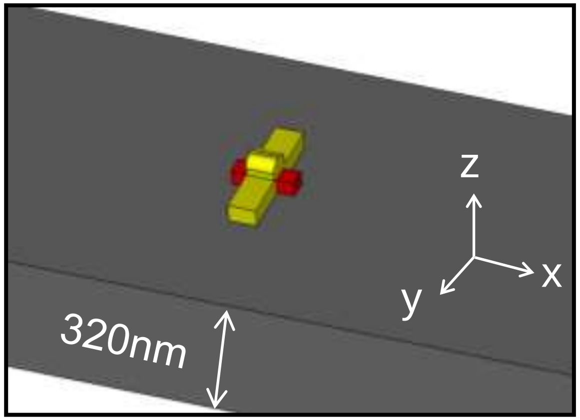


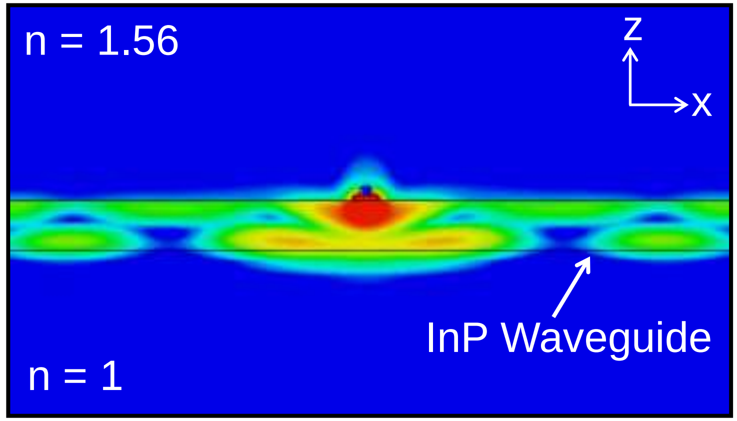
Arch-Dipole on InP Waveguide

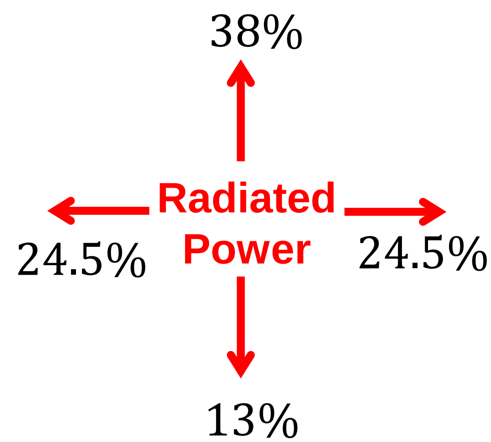


InP Waveguide Design

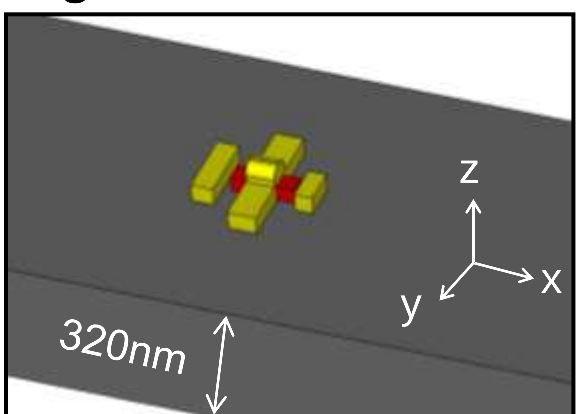
Thicker InP Substrate

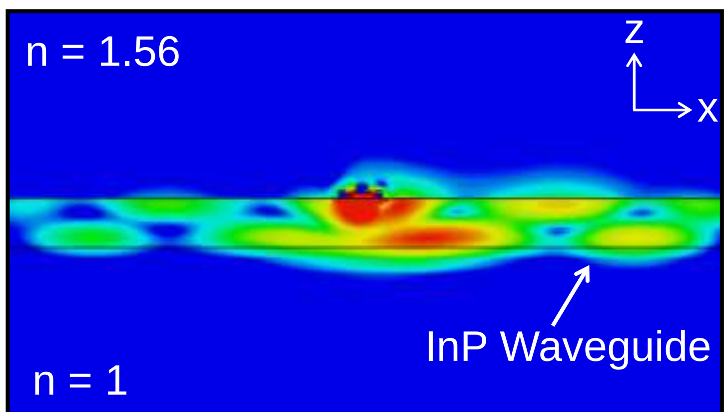


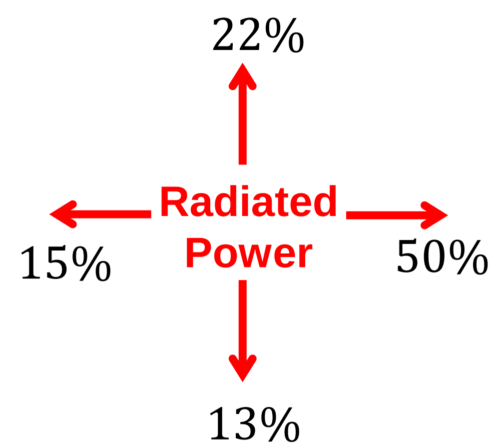




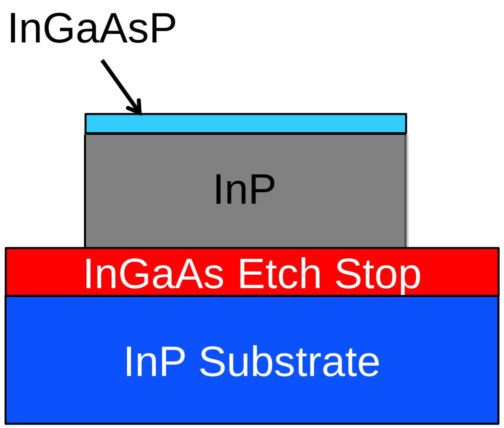
Yagi-Uda Structure



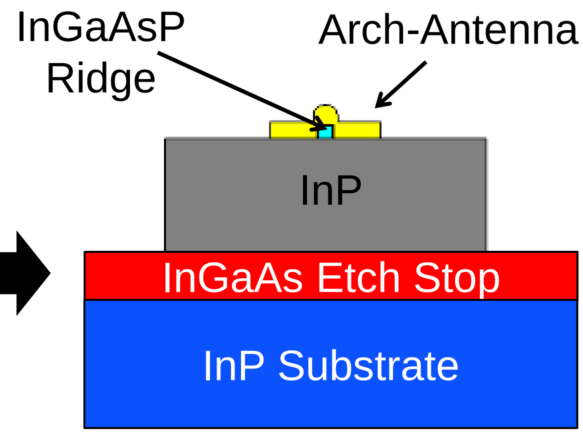




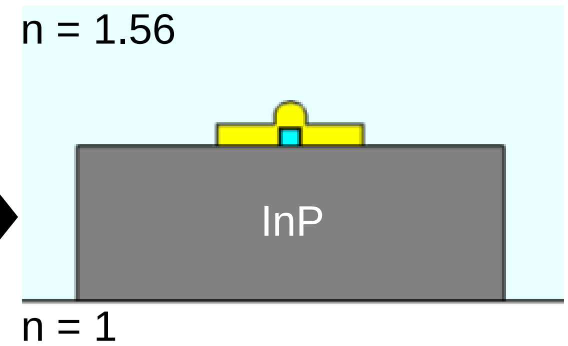
Waveguide Fabrication



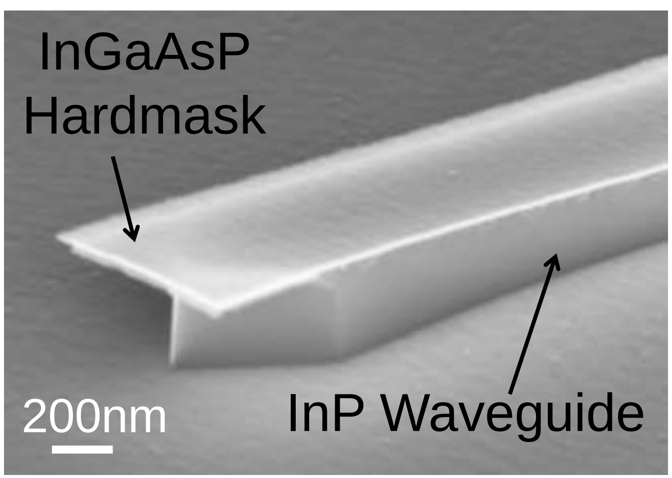
Wet-etch InP Waveguide

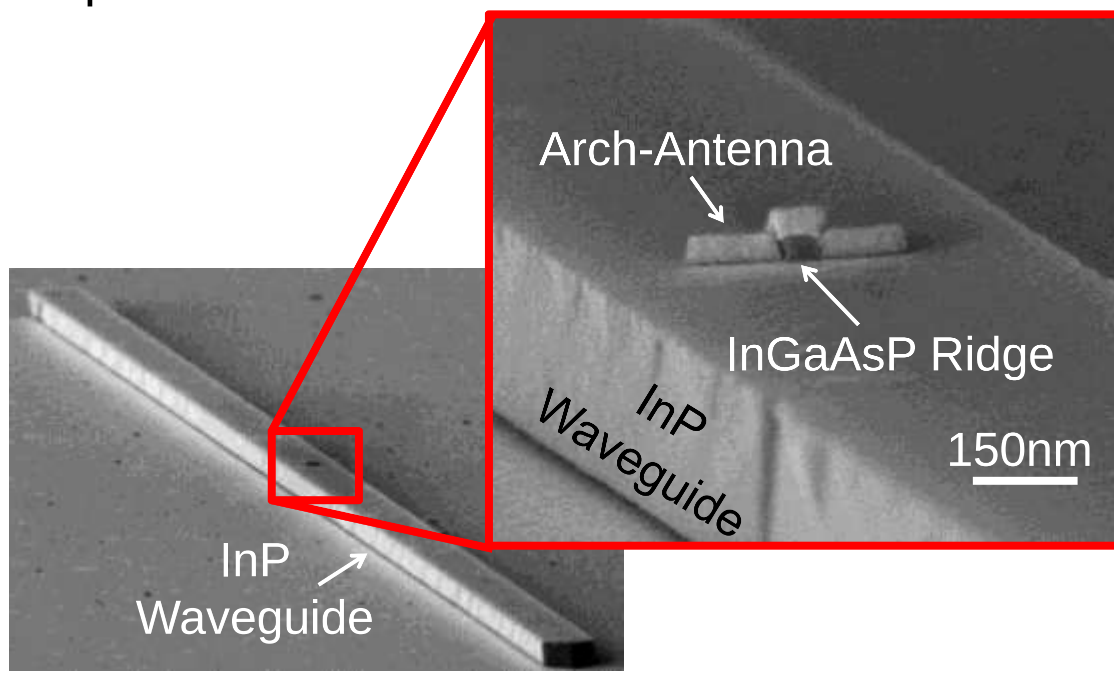


Etch InGaAsP ridge and deposit antenna



Bond to carrier wafer and remove substrate

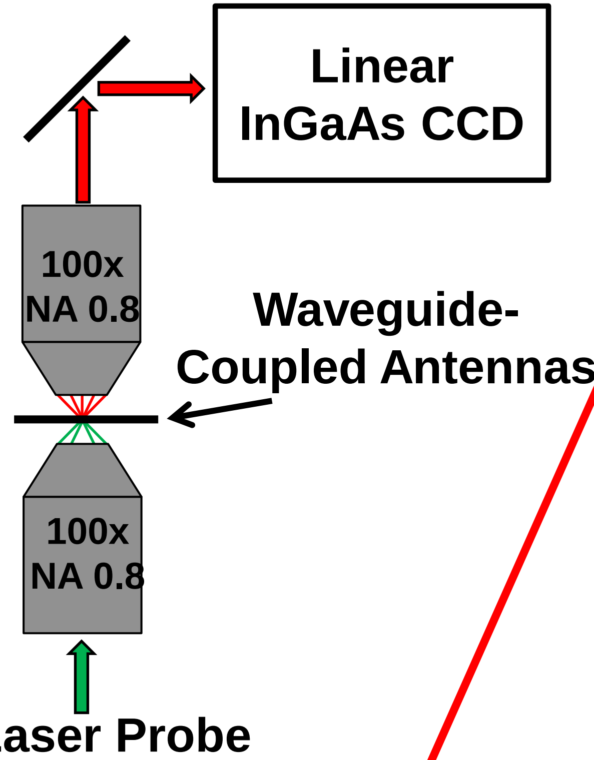


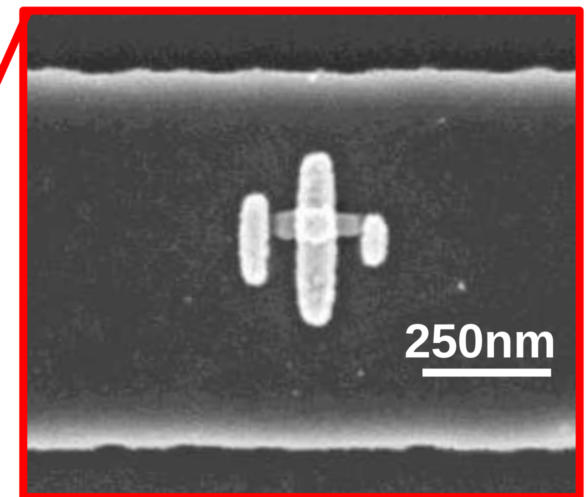


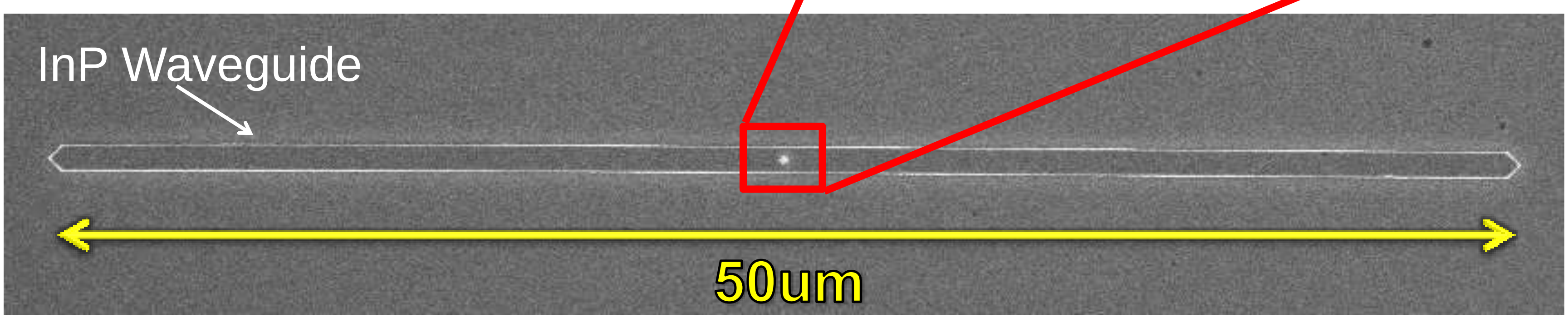
Optical Emission Measurements

Optical emission is collected with a front-side 0.8NA objective and imaged on a LN-cooled CCD.

Sample probed with a 720nm Ti:Sapphire fs-pulsed laser from the back-side.



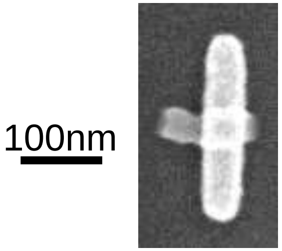




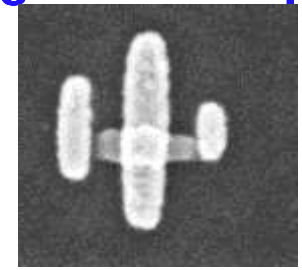
Total Light Emitted From Waveguide Coupled nanoLED

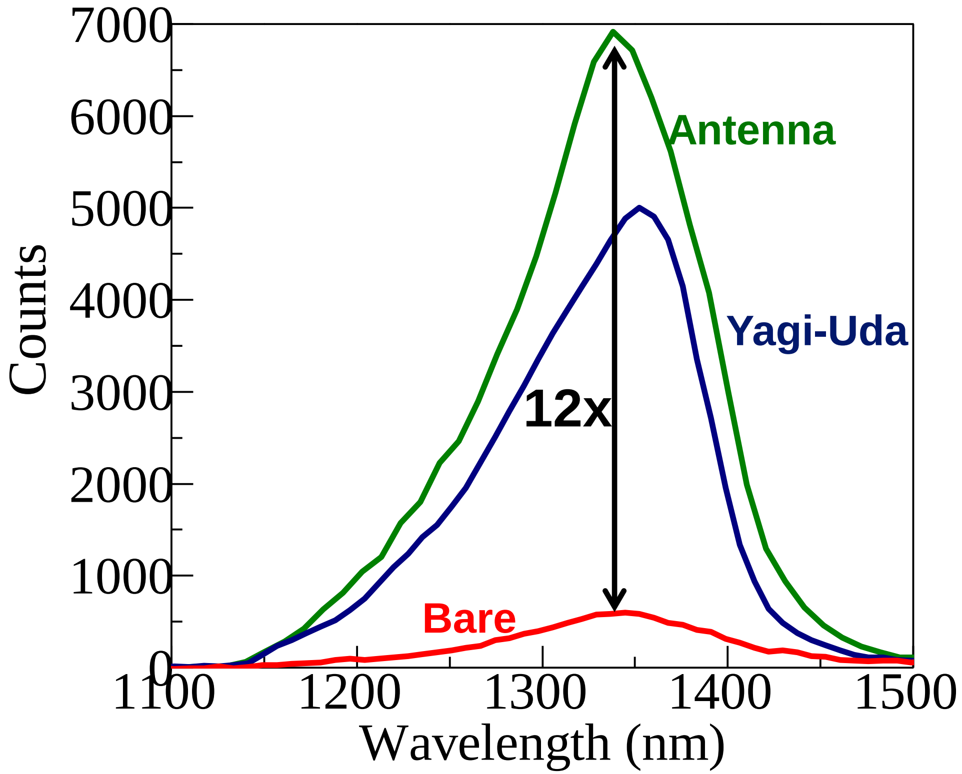
Bare InGaAsP

Antenna Coupled



Yagi-Uda Coupled





Expected Enhancement:

Gap (d) = 40nm, Length (L) = 300nm

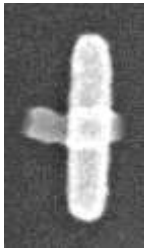
$$\frac{\tau_o}{\tau} = \frac{1}{4}\left(\frac{L}{d}\right)^2 \approx \mathbf{14x}$$

Optical Emission Spatial Map

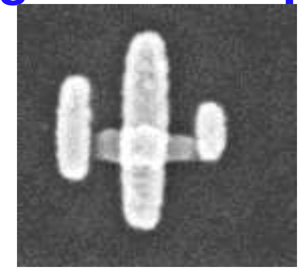
Bare InGaAsP

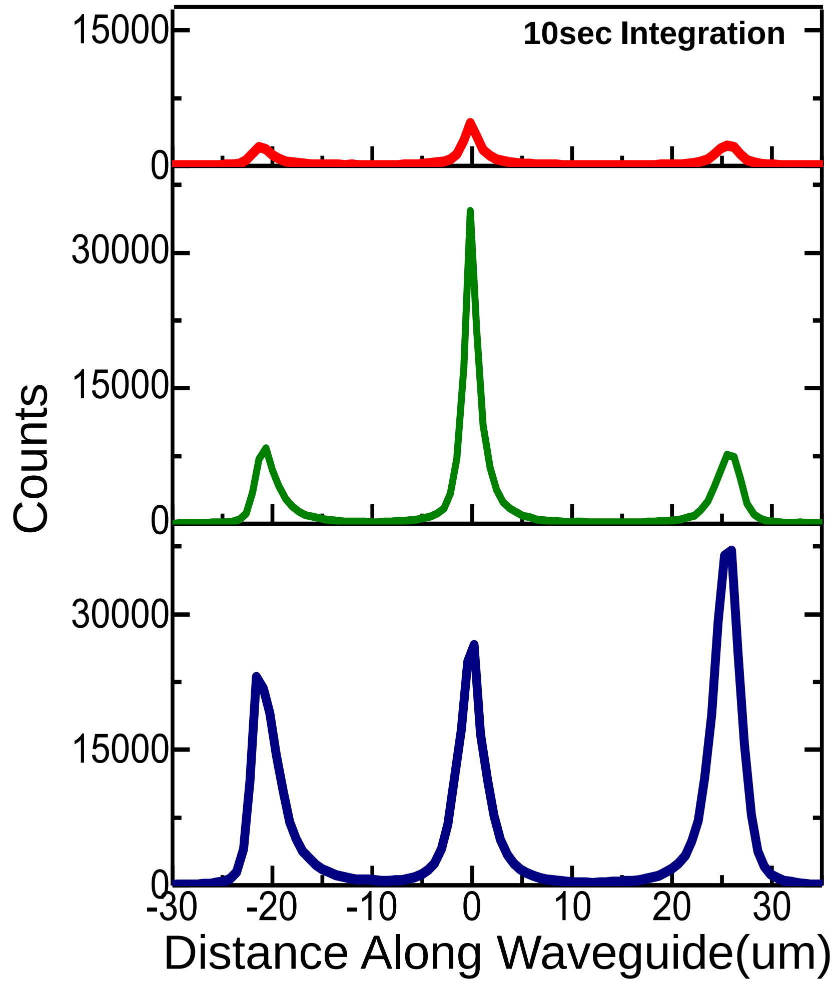
Antenna Coupled

100nm



Yagi-Uda Coupled





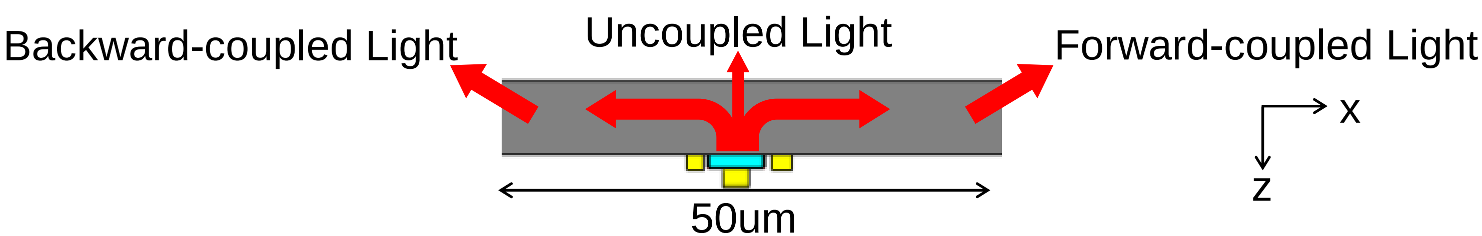
$\eta_{coupling} \approx 50\%$

$\eta_{coupling} \approx 50\%$

$\boldsymbol{\eta_{coupling} \approx 70\%}$

$Front/_{Back} = 1.6 : 1$ *

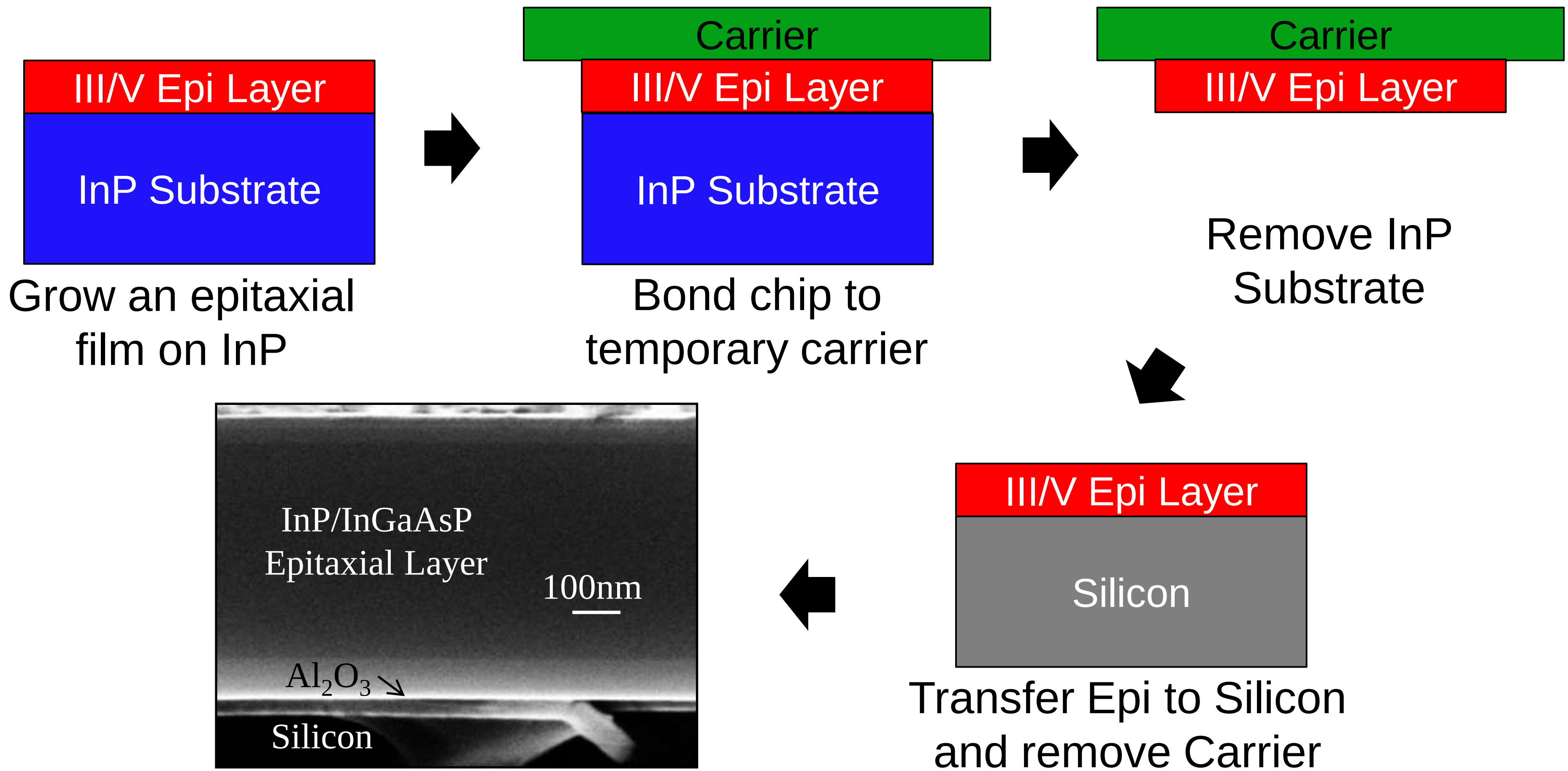
***3:1** *with narrower waveguides*



Eggleston 10

Integration with Silicon Photonics

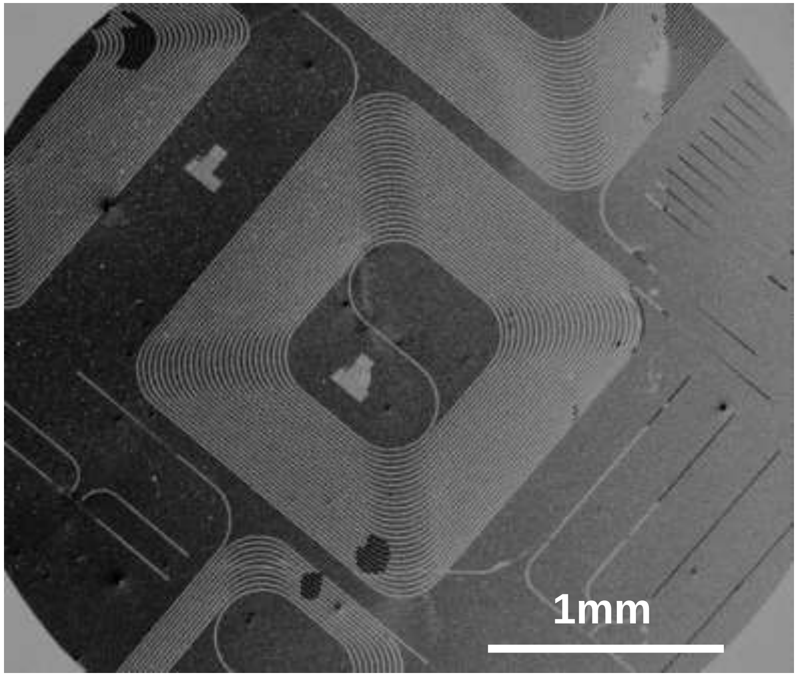
- **Epitaxial Lift-off is used to transfer III-V chips to Silicon substrates**



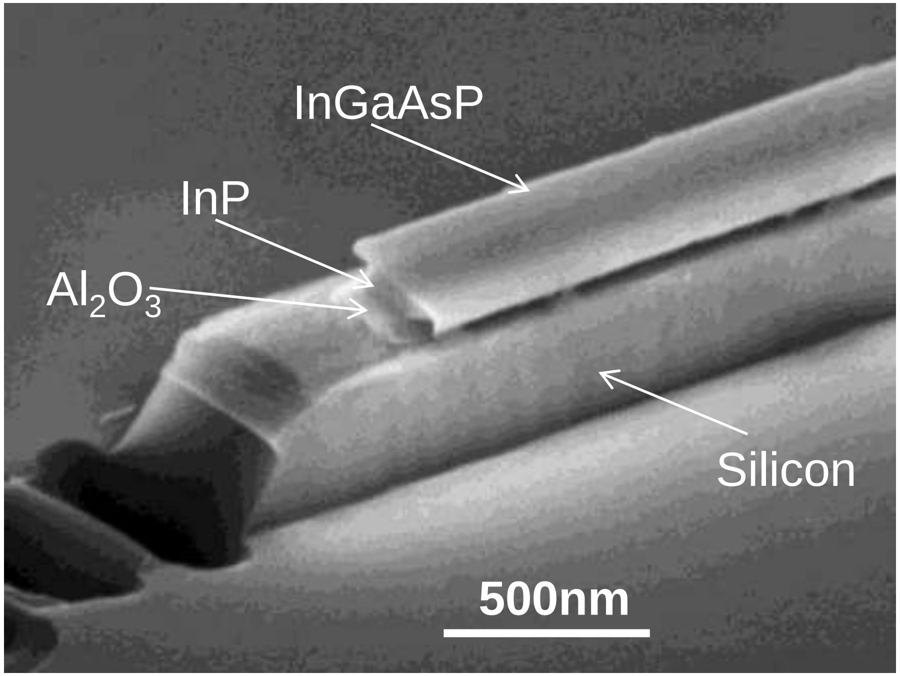
Cross-sectional SEM

Silicon Photonics with Active III/V Material

- **Silicon wafers and Silicon processing technology can be used to make large-area photonics chips with active III/V Matieral**



Top View SEM of Fabricated III/V on Silicon Waveguides



Perspecive SEM of III/V on a Silicon Waveguide

Summary

- **Demonstrated a nanoLED with enhanced spontaneous emission coupled to a multi-mode InP Waveguide**
  - **70% Coupling Efficiency**
  - 50% Forward coupling
  - Directional emission of 3:1

- **Future Work**
  - Integrate nanoLED with single mode waveguide on Silicon Photonics platform

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