Prototype Photonic Integrated Circuit (ProtoPIC):

A Flexible Platform for Hybrid Integration

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Outline

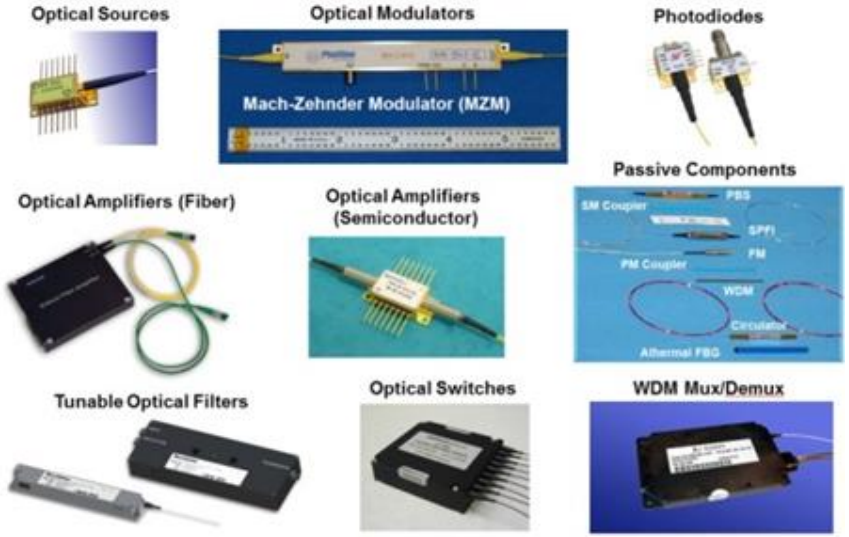
- **Motivation**
- **Integrated photonics platforms at Lincoln Laboratory**
- **Hybrid integration ProtoPIC**
- **ProtoPIC extended cavity laser**
- **Summary**

Photonic Integration in the Commercial Space

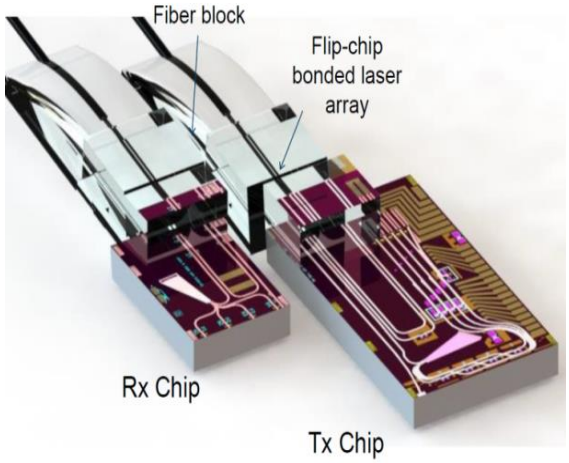
- **Light enables higher data speeds with less power consumption**

- **Photonic integrated circuits (PICs) enable manipulation of light on a chip**
  - Commercial driver: Internet/Telecom
  - Silicon photonics incorporate on-chip modulators and photodetectors, but no native light sources!
  - Challenge: Hybrid integration of III-V lasers

Discrete Optical Components

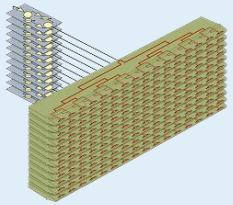


Chip-Scale Integration

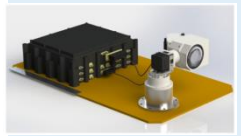


Photonic Integration in Other Domains

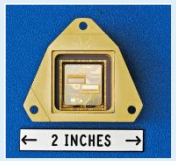
Microwave Systems



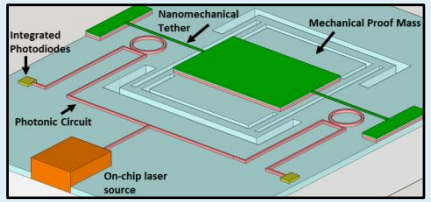
Free-Space Lasercom



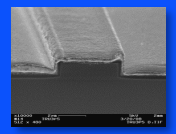
Laser Radar

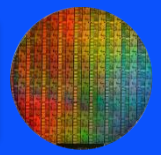


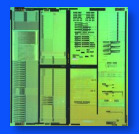
Inertial Sensors



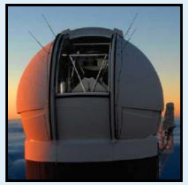
Electronic-Photonic Integration Technology

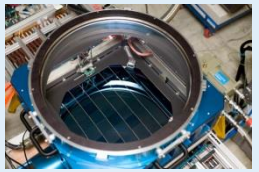




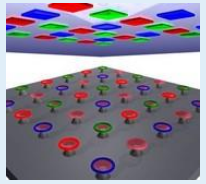


Optical Imaging

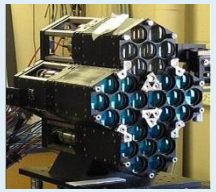


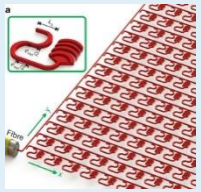


Chem/Bio Sensors

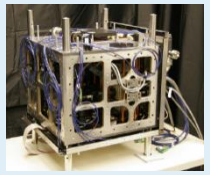


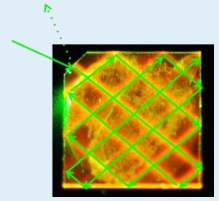
High-Energy Lasers





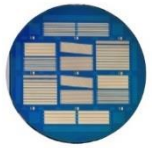
Quantum Information





Electronic-Photonic Integration Development Resources at Lincoln Laboratory

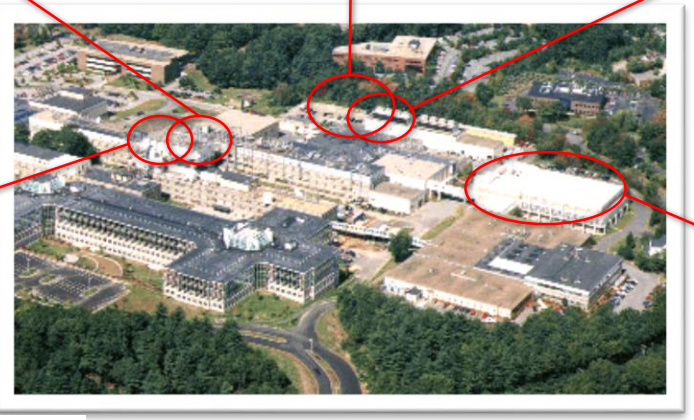
InP Laser Wafer 50 mm Diameter



Materials Growth (III-V, Diamond)

III-V Fabrication Cleanroom

Electronic-Photonic Packaging



Back-end Processing Cleanroom

Microelectronics Laboratory

Silicon PIC Wafer 200 mm Diameter

- InP, GaAs, GaN, Diamond
- Optoelectronic Components
- Emitter and Detector Arrays
- III-V Photonic Integration

- Precision Flip-Chip Packaging
- Laser-Welded Fiber Pigtailing
- Reliability and Lifetime Testing
- Heterogeneous Hybrid Integration

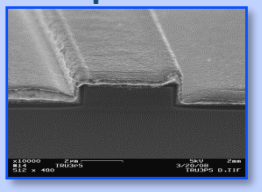
- 200 mm Silicon Fab Toolset
- 90 nm CMOS
- Silicon and Silicon Nitride Photonics
- Wafer-Scale 3D Integration

Photonic Components at Lincoln Laboratory

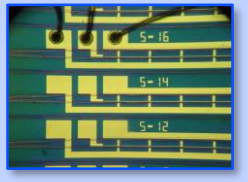
Compound Semiconductor (III-V) Photonic Integration

Materials: InP, GaAs, GaN, Diamond

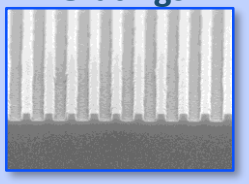
Lasers and Optical Amplifiers



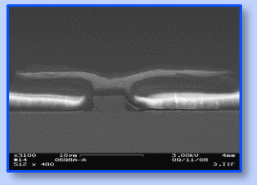
Modulators



Gratings



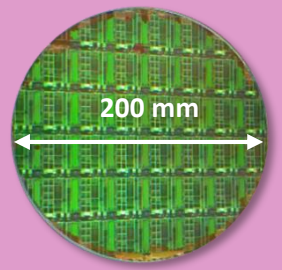
Photodiodes



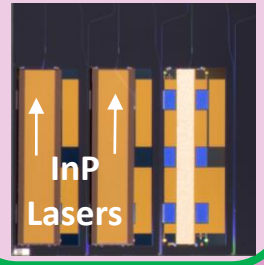
Monolithic III-V PICs

III-V to Si Hybrid Integration and Electronic-Photonic Integration

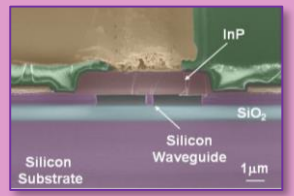
Si Photonics + CMOS



SiN Photonics + III-V Laser



Hybrid Si/III-V Wafer Bonding

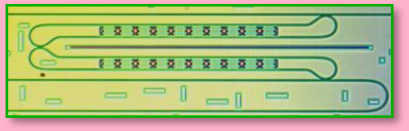


III-V Laser + CMOS Driver

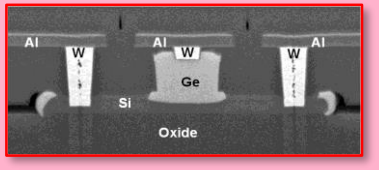
Silicon and Silicon Nitride Photonic Integration

Materials: Si, SiN_x, Al_2O_3, Ge

Waveguides and Optical Filters

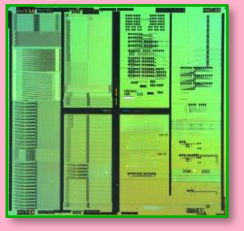


Photodiodes and Modulators



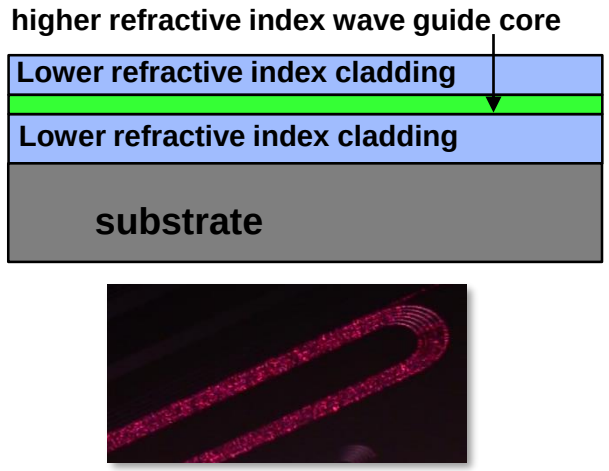
Optomechanics (MEMS + NEMS)

Multi-Project Fab Runs

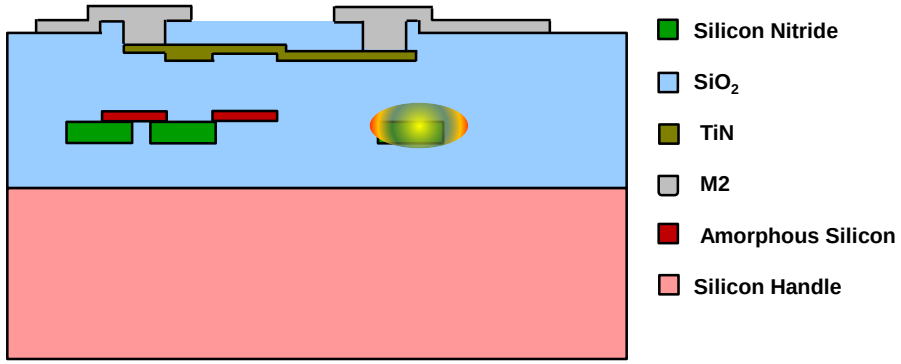


Silicon Nitride and Silicon Waveguides

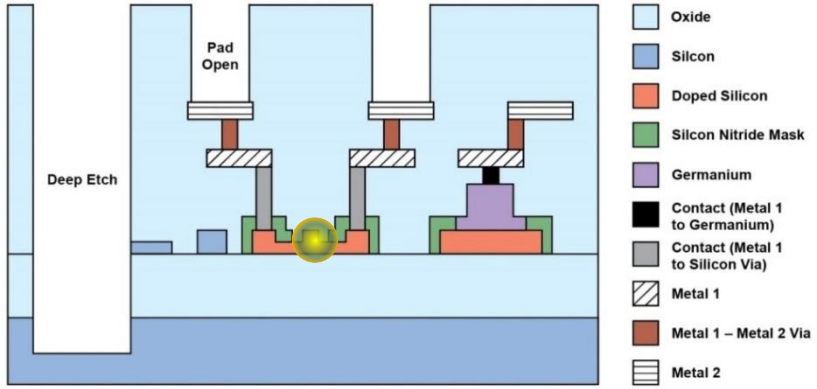
	Silicon Nitride PIC	Silicon PIC
Transparent wavelength range	~ 400 - 2000 nm+	~ 1100 - 2000 nm+
Optical power handling	> 400 mW, 10 W+	<~ 100 mW
Propagation loss	~ 0.2 dB/cm	~ 1-2 dB/cm
Mode size	Large mode 3-10 μm	Small 0.5 μm
Active components	• Thermal tuners as modulators • Slower kHz modulation • High power and thermal crosstalk	• Fast Electro-optical modulators • Germanium photodiodes



Silicon Nitride Photonics Cross-Section

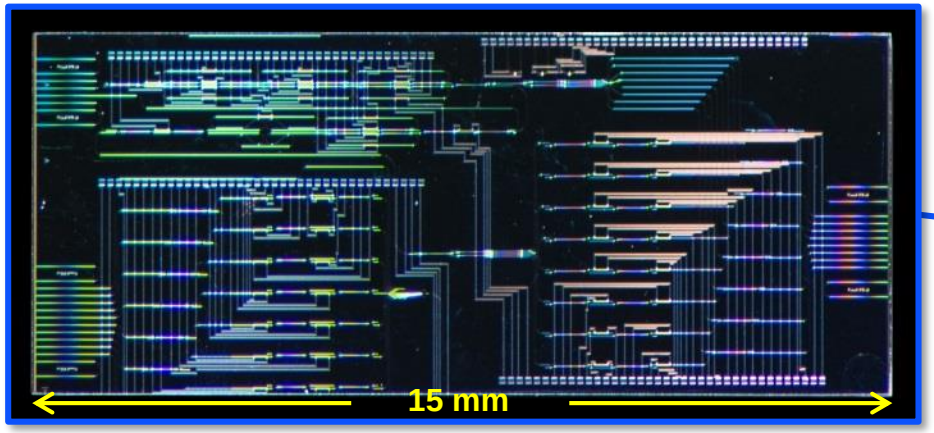


Silicon Photonics Cross-Section

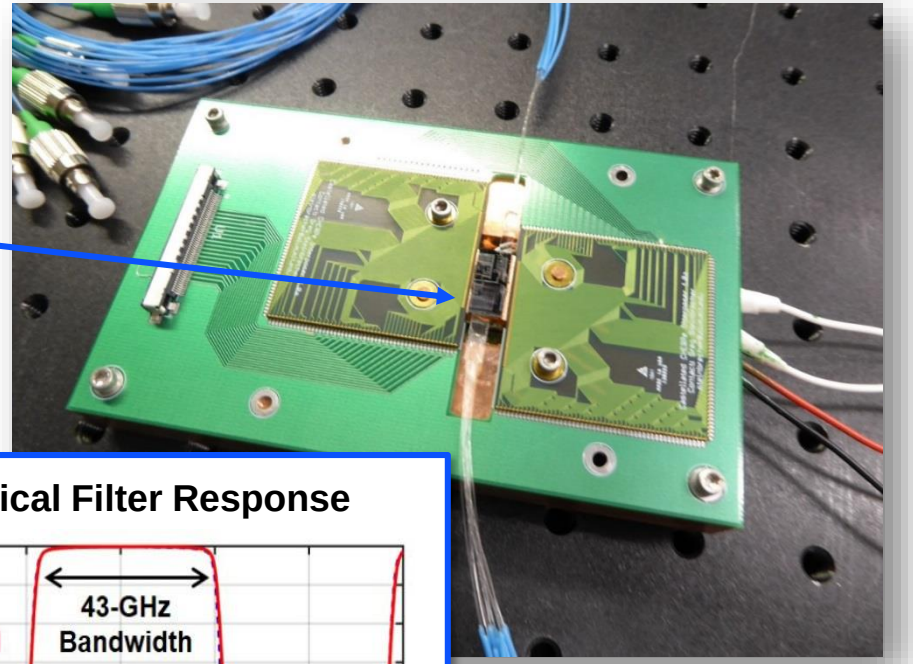


Silicon Nitride (SiN_x) Photonic Integrated Circuits (PICs)

Image of SiN_x/SiO_2-on-Silicon PIC

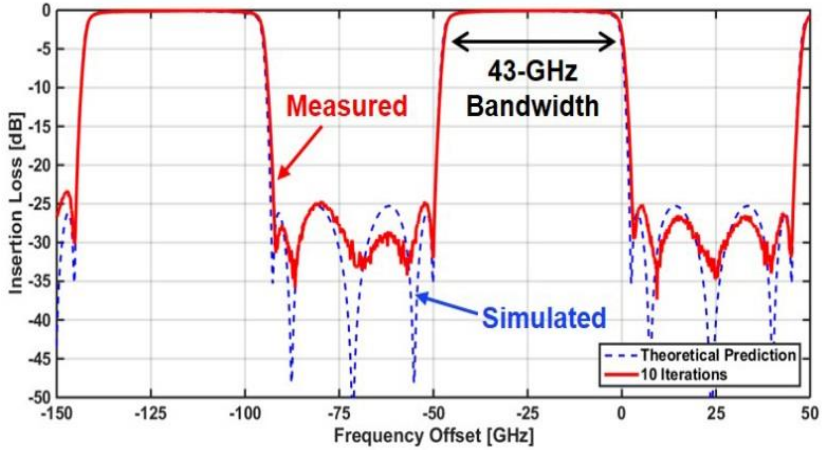


Fiber Pigtailed SiN_x PIC on Printed Circuit Interface Board



- Operating wavelength ~1550 nm
- Fabricated using MIT LL's 200 mm silicon fabrication toolset
- SiN_x PIC contains ~80 components:
  - Adiabatic 3-dB couplers
  - 1-to-N power dividers
  - Ring resonators
  - Mach-Zehnder modulators
  - Thermo-optic phase shifters

Reconfigurable Optical Filter Response



Getting The Light

- **Silicon & silicon nitride photonics are not optically active**
  - **No light sources in silicon and silicon nitride***
    - *** Though there is active research to grow III-V on silicon**
  - **Need to get light from a III-V light source**
  - **Ge photodiodes for Si photonics are available but are not as good as III-V**

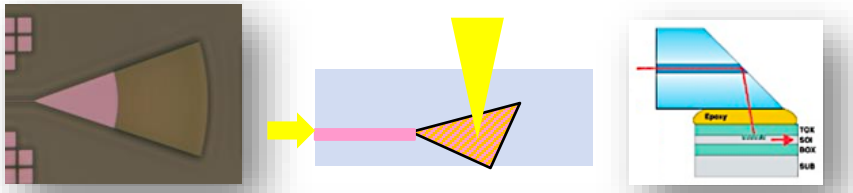
- **How do you combine III-V components with your PICs?**

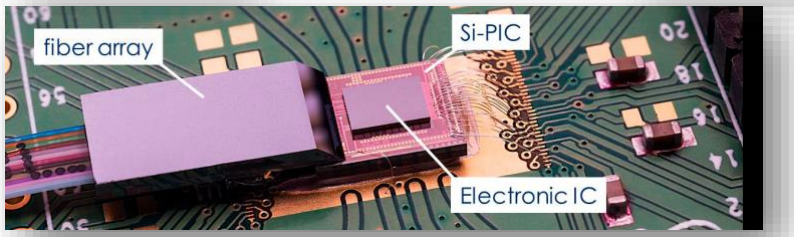
  2 options:
  - **Couple active III-V components with fiber**
  - **Hybrid Integration, couple the III-V chip to the PIC directly**

Fiber to chip coupling:

Edge fiber coupling

Vertical grating coupling

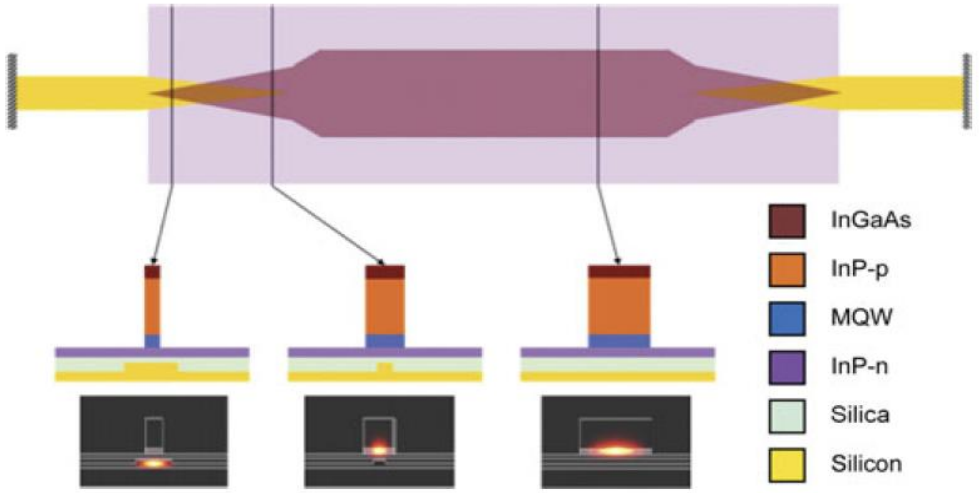




Hybrid Integration Two Approaches:

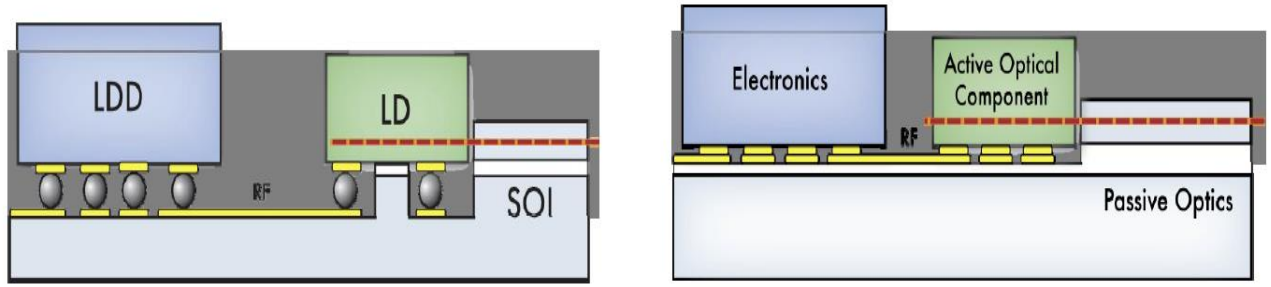
Evanescent Coupling

- III-V Epi is transferred to the surface of a PIC chip
- Device fabricated after Epi transfer
- Light optically hops from silicon waveguide up into the III-V chip



Edge Coupling

- III-V chip is flip chip bonded into PIC substrate
- Allows conventional process fabrication for both III-V and PIC
- Requires tight mechanical alignment

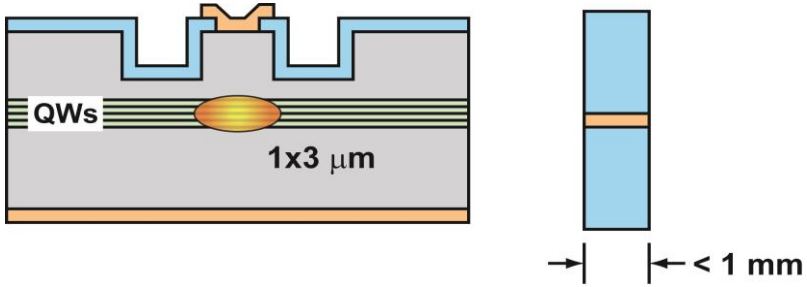


Semiconductor Waveguide Optical Gain Media

Semiconductor Optical Amplifiers (SOA) and Lasers

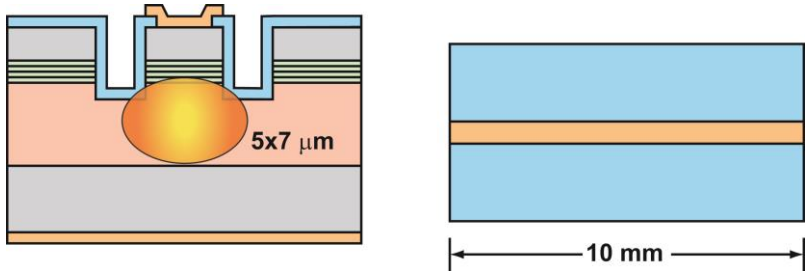
- III-V compound semiconductor p-i-n diode structures that use quantum wells (QW)
- Can act as an optical amplifier or an emitter source
- Optical mode is confined by a sandwich of lower refractive index materials

Standard Rib Waveguide



- **High gain (30 dB)**
- **Mode propagation in QW layer leads to high loss and limits power to <100 mW**
- **Small mode 1 × 3 μm size complicates optical coupling**

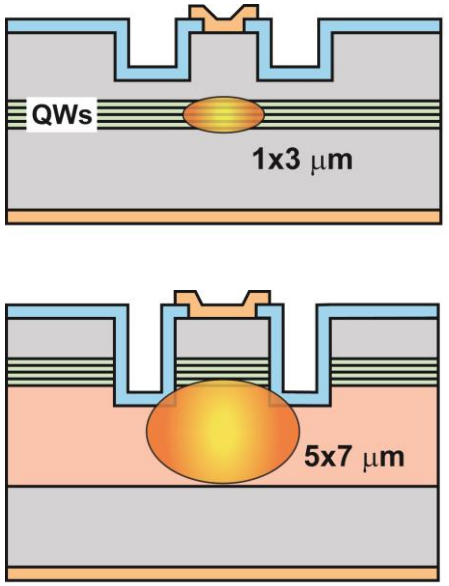
Slab-Coupled Optical Waveguide Amplifier (SCOWA)

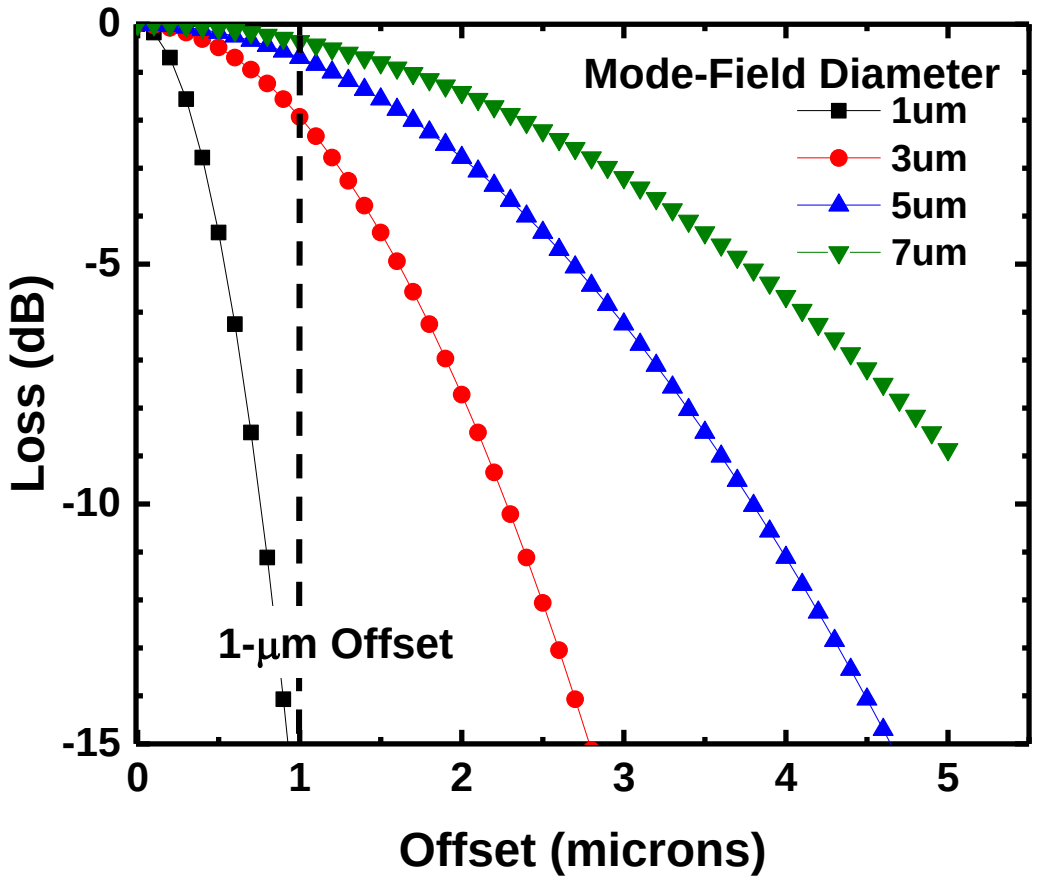


- **Moderate gain (15 dB)**
- **Propagation in low optical loss slab waveguide allows for higher optical power >1 W**
- **Large mode 5 × 7 μm improves coupling tolerance**

Waveguide Alignment Tolerance

Output Facet Cross-Section





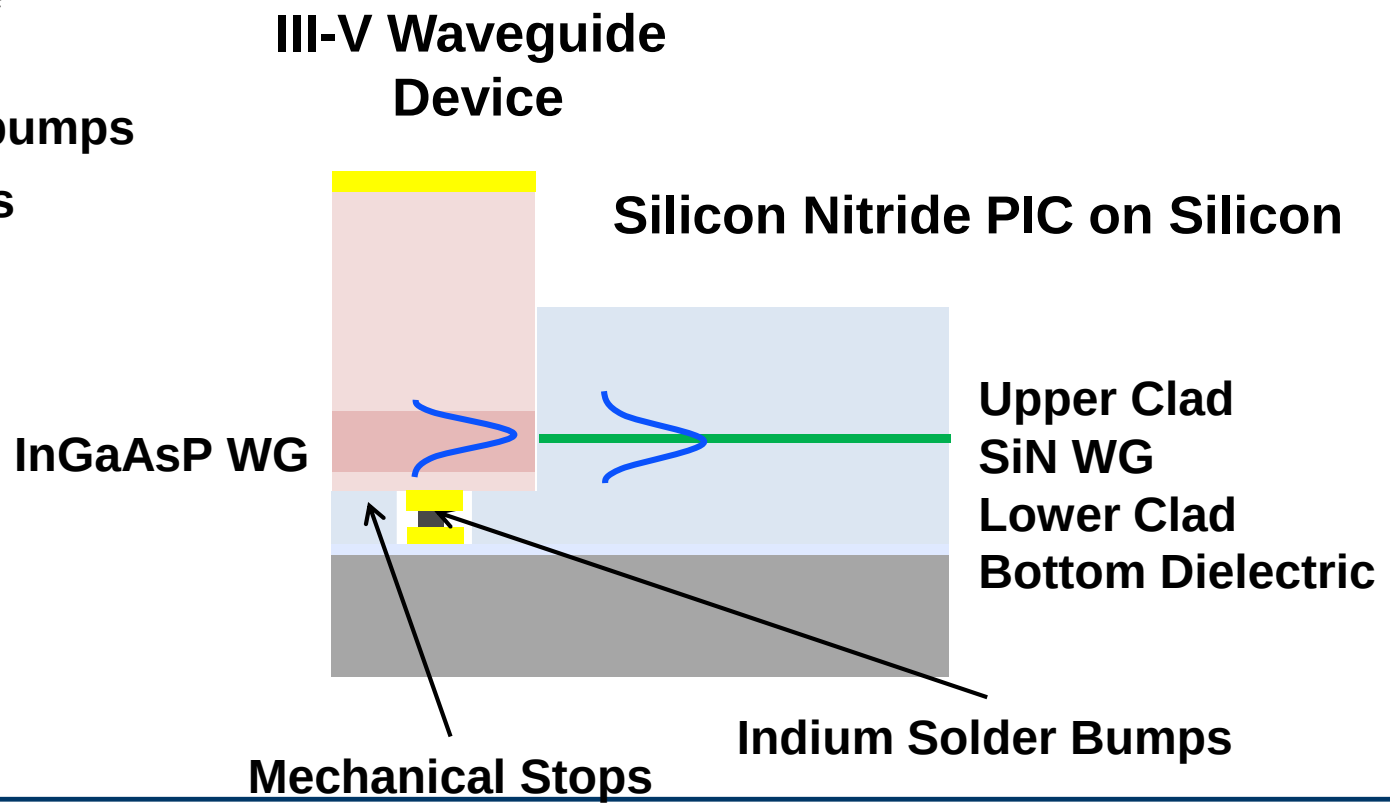
Minimal loss expected due to vertical and horizontal misalignment

Prototype Photonic Integrated Circuit (ProtoPIC)

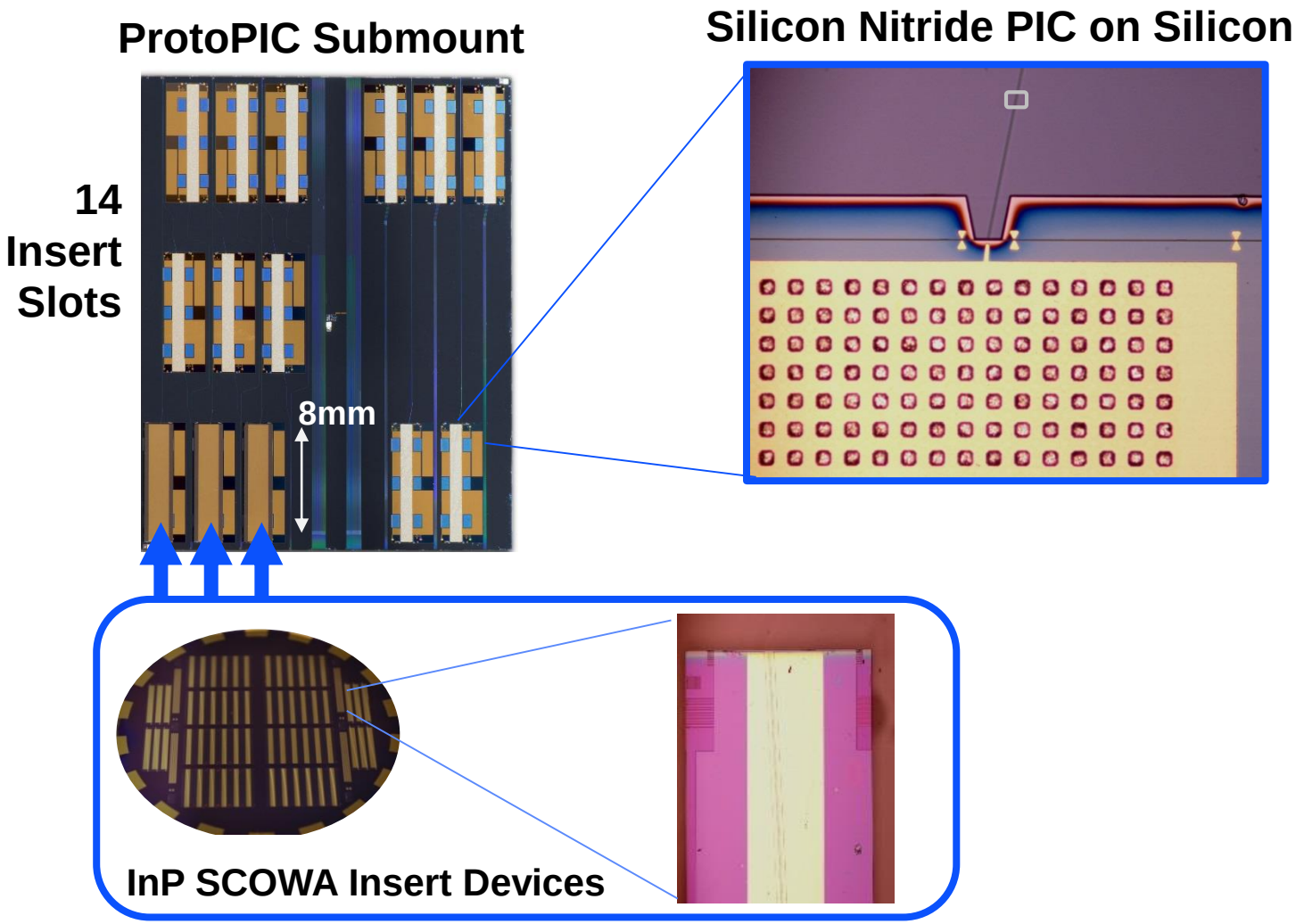
Goal: Create a platform for hybrid integration of III-V components with SiN photonics

Concept:

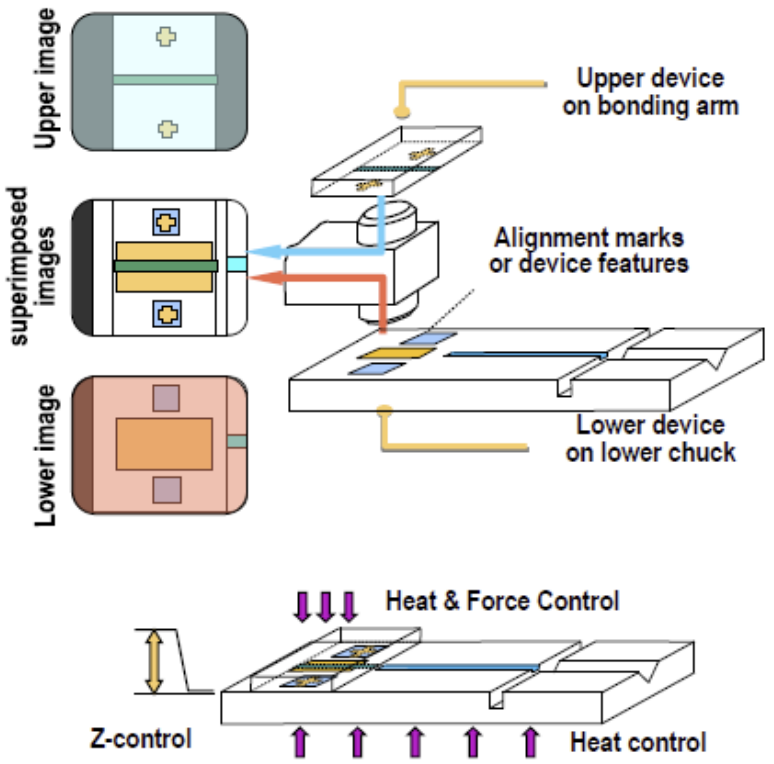
- Create a SiN PIC with a recess to receive a III-V device
- Flip chip (FC) bond III-V die with solder bumps
- Vertical alignment with mechanical stops
- Fiducials to enable sub-micron lateral alignment



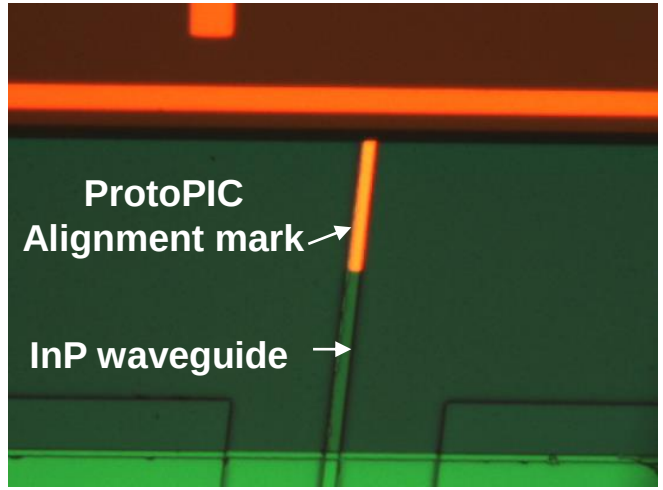
ProtoPIC Hybrid Integration Submount

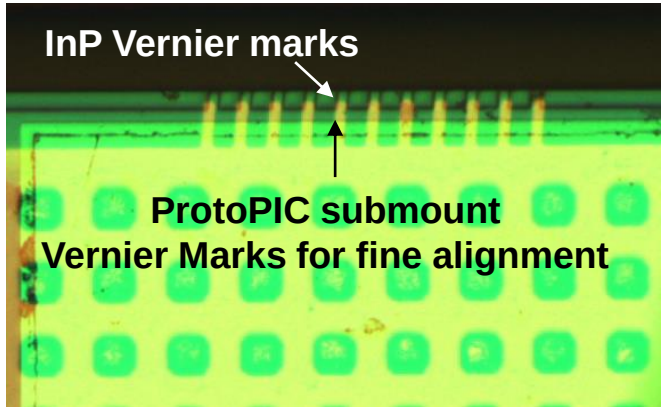


Bonding Development on FC 150



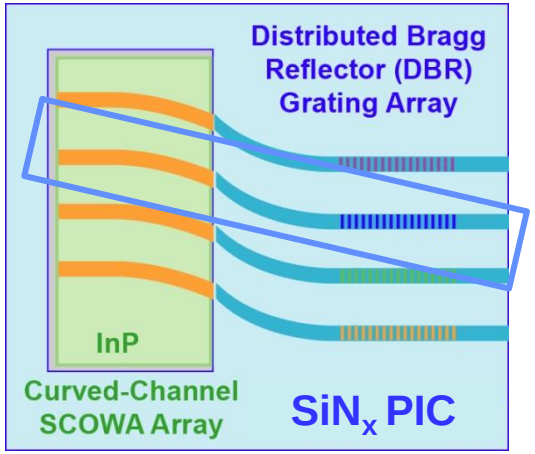
FC 150 Overlay of InP features with submount

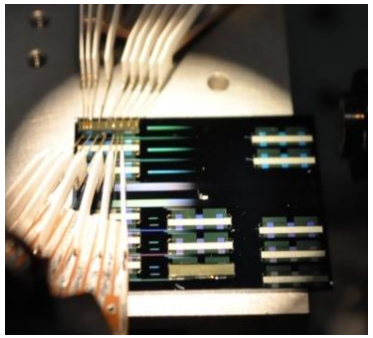


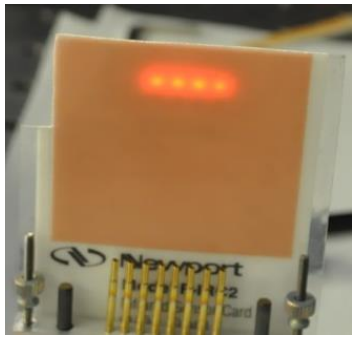


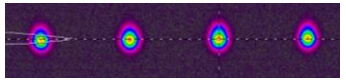
ProtoPIC Hybrid Laser with Narrow Line Width

Hybrid Laser Array (Top View)

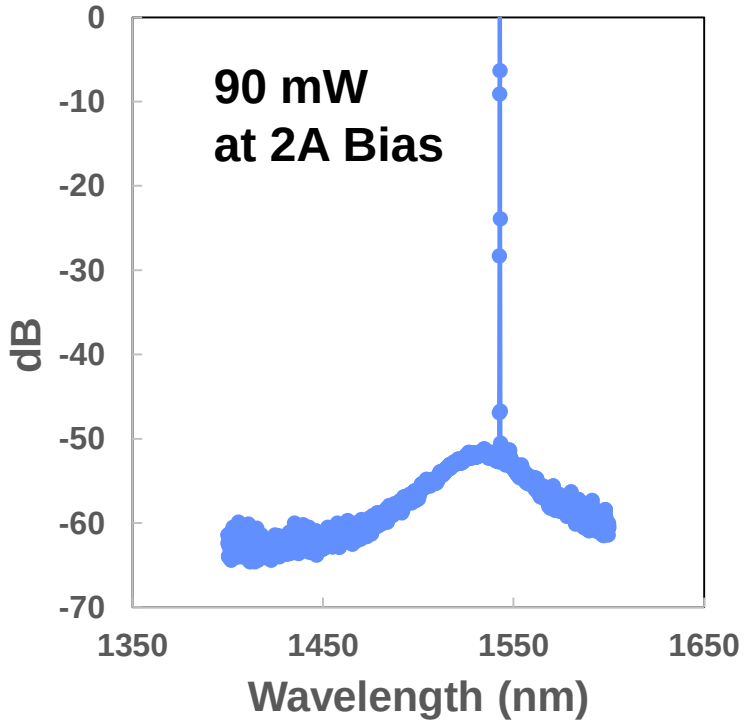




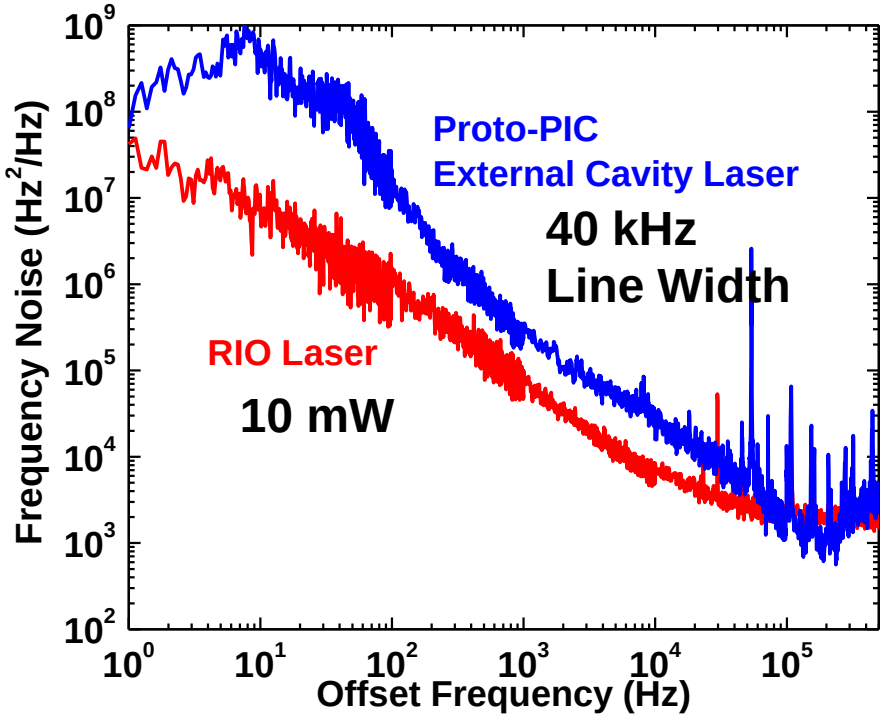




ProtoPIC Hybrid Laser Optical Spectrum



Line Width Measurement



Summary

- **MIT Lincoln Laboratory has developed a library of photonic component technologies**
  - **SiN and silicon photonics, waveguides, splitters, modulators, thermal tuners, and filter architectures**
  - **III-V SCOWA amplifiers, lasers, photodiodes, modulators**

- **Recently developed a flexible hybrid integration platform ProtoPIC that can be used to combine a variety of III-V devices with our SiN PICs**
  - **Flip chip III-V attach with ~1 µm placement capability**
  - **Initial applications of the technology have been applied to demonstrate an extended cavity hybrid laser with narrow line width 40 kHz and 90 mW optical power**

- **The technology is amenable to adoption for a wide variety of applications**

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