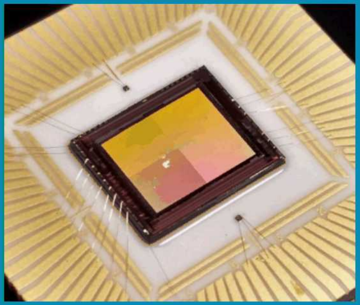
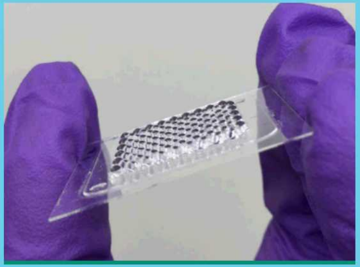
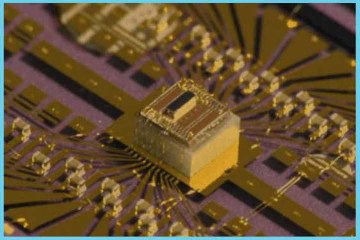
SAND2019-12475C

Heterogeneous Integration (HI) of III-V Semiconductors for Imaging and High-Speed Communication







ECS2019 10/15/2019

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Senior Member of Technical Staff

Sandia National Labs

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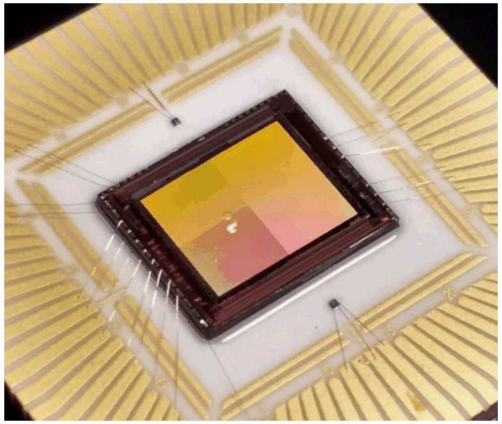
Outline

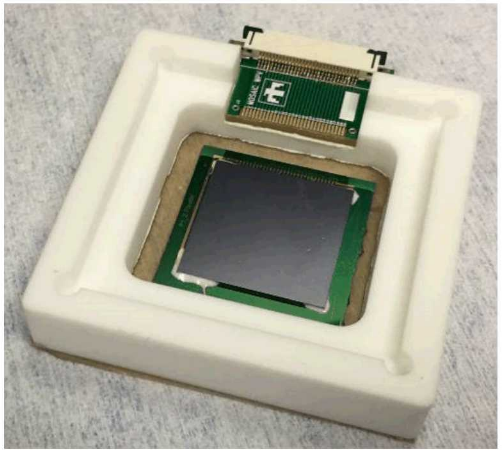
Overview of III-V HI Capabilities at Sandia

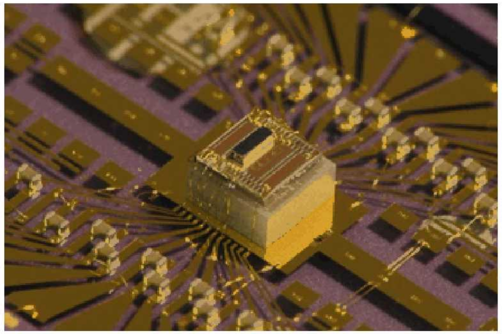
Applications of III-V HI

- Application 1: Focal Plane Arrays from IR to x-rays
- Application 2: Concentrating Solar Cells
- Application 3: High-Speed Communication

Conclusion







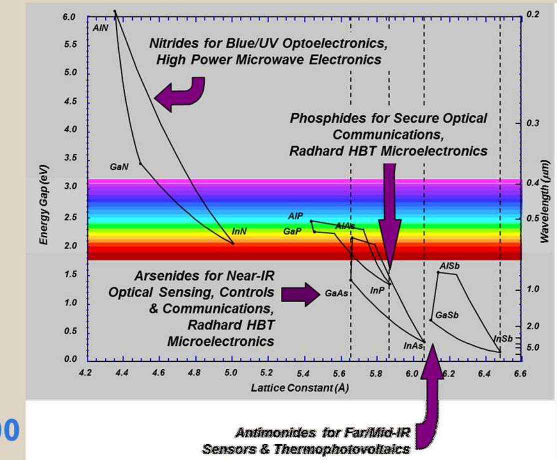
Overview of III-V HI at Sandia

Compound Semiconductors and Heterogeneous Integration

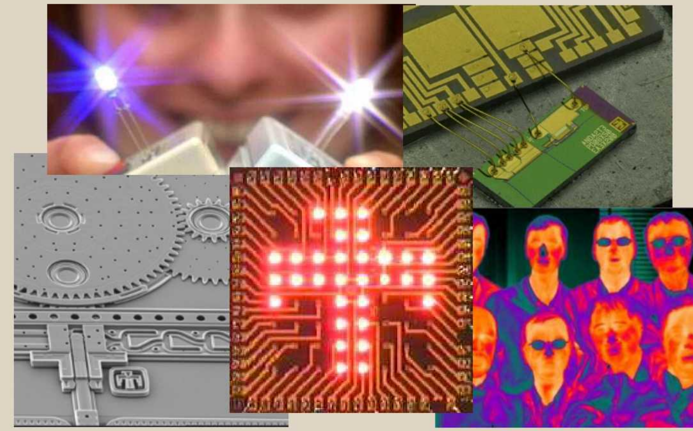
Microfabrication

MESA SiFab: 11,900 ft^2 Class 1
MESA MicroFab: 14,230 ft^2 Class 10/100
CINT NanoFab: 9,000 ft^2 Class 100

III-V semiconductor growth



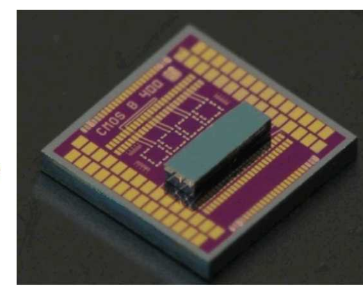
Photonics expertise



Heterogeneous integration: rationale

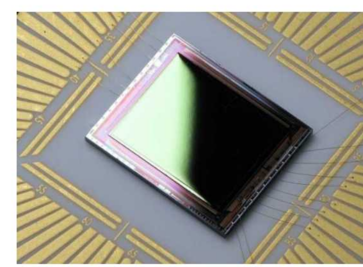
- **SWAP-C:** size, weight, and power; cost
- **performance:** combine technologies, improve interconnect
- **diverse functionality:** optical, RF, MEMS, analog, chem, bio
- **agility & turn time:** prototyping and low-volume
- **trust:** secure microsystems

} low volume, high value



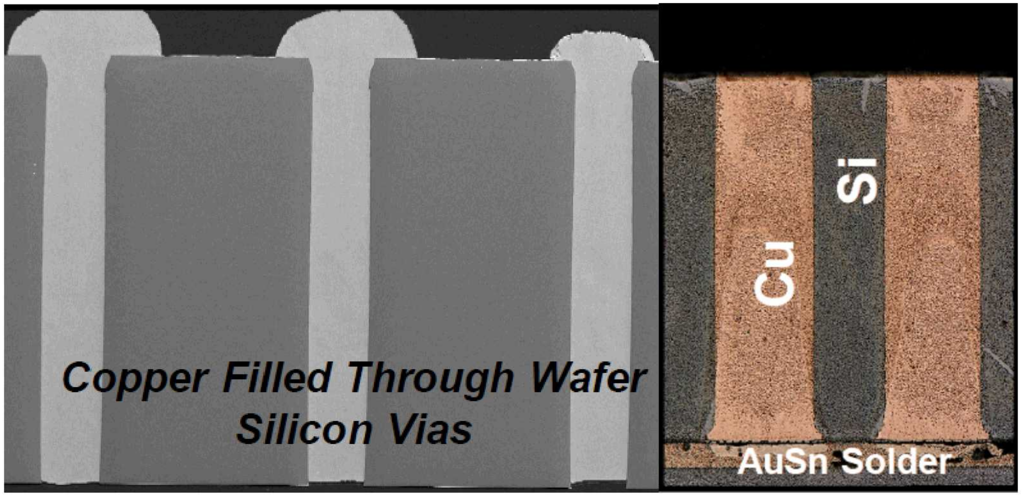
Approaches to integration

- in-package
- die-to-die: micro bump, flip-chip, micro-optics, etc. ← R&D
- wafer-level: interconnect bonding (3D DBI) ← Production
- wafer-level: epitaxy bonding (dielectric interfaces)
- monolithic integration

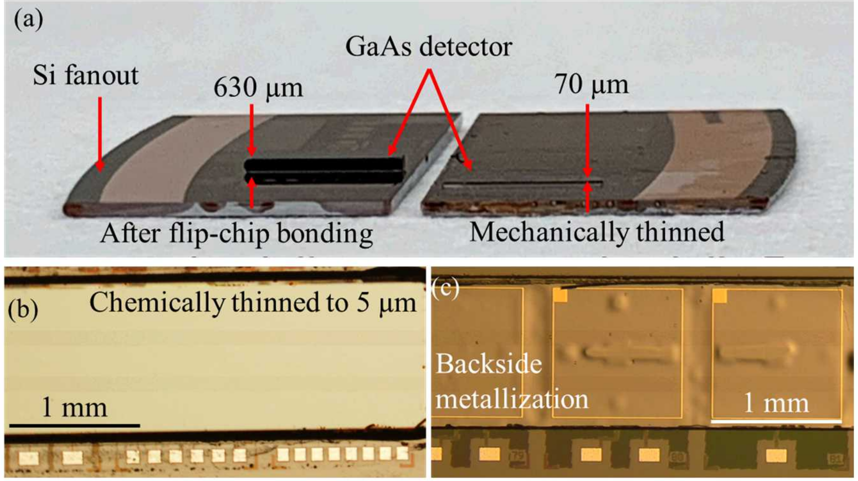


HI capabilities overview

- In-house back-end processing:
  - In bump deposition and reflow
  - Solder ball jetting
  - Metal plating
  - Through-substrate vias



- Integration capabilities:
  - Flip-chip bonding
  - Wafer bonding
  - Post-bond substrate removal
  - Automated dense wire bonding
  - 3D printed enclosures and supports



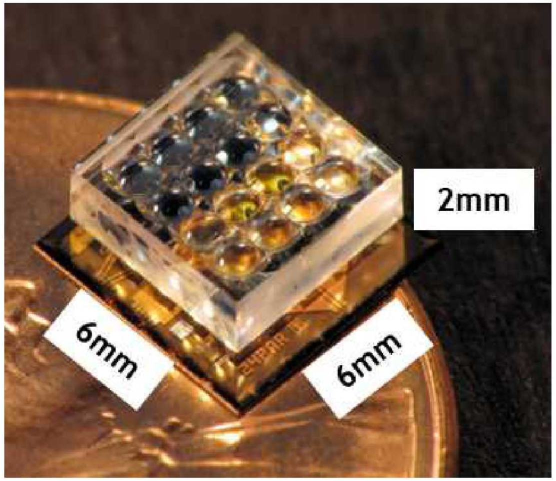
Post-bond thinning and processing

Semi-automated flip-chip bonder

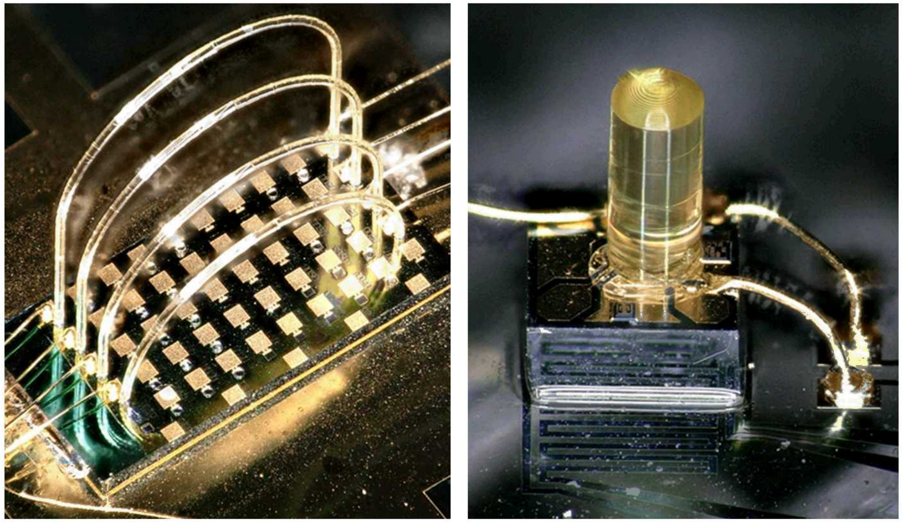
HI capabilities overview

- Optical HI:
  - Diamond turning for microlenses
  - 3D printed optics

- Device testing:
  - DC and pulsed optical and x-ray sources
  - Extreme environmental and mechanical testing



Custom microlens array on GaAs transceiver



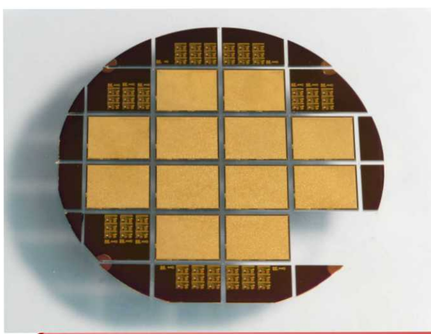
3D printed micro-optic interconnects and lenses

3D printed fiber holder and collimating lens

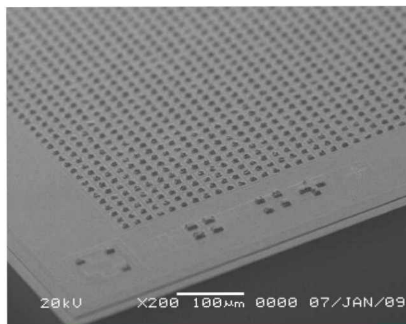
Applications of III-V HI:
1: Focal plane arrays from IR to x-rays

MWIR/LWIR focal plane imager

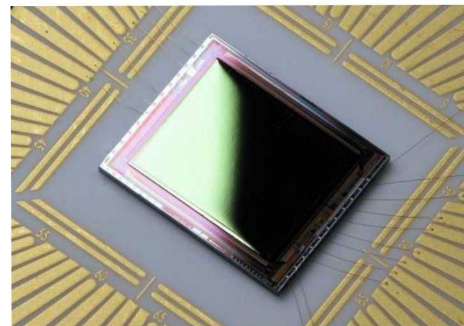
- nBn detectors for IR focal plane arrays
    - III-V detector material for IR imaging
    - Performance becoming competitive to MCT
    - Potential to scale to large arrays



GaSb detector epitaxy

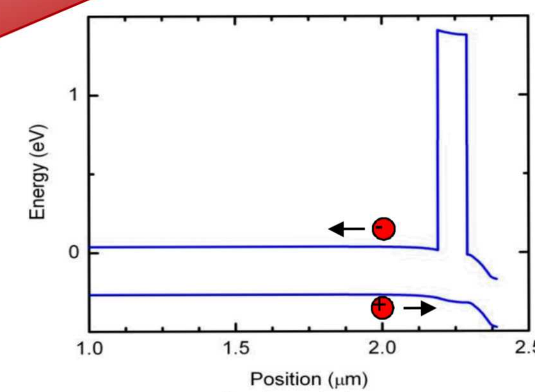


nBn array with indium bumps



hybridized nBn FPA prototype

MWIR still frame, 160K

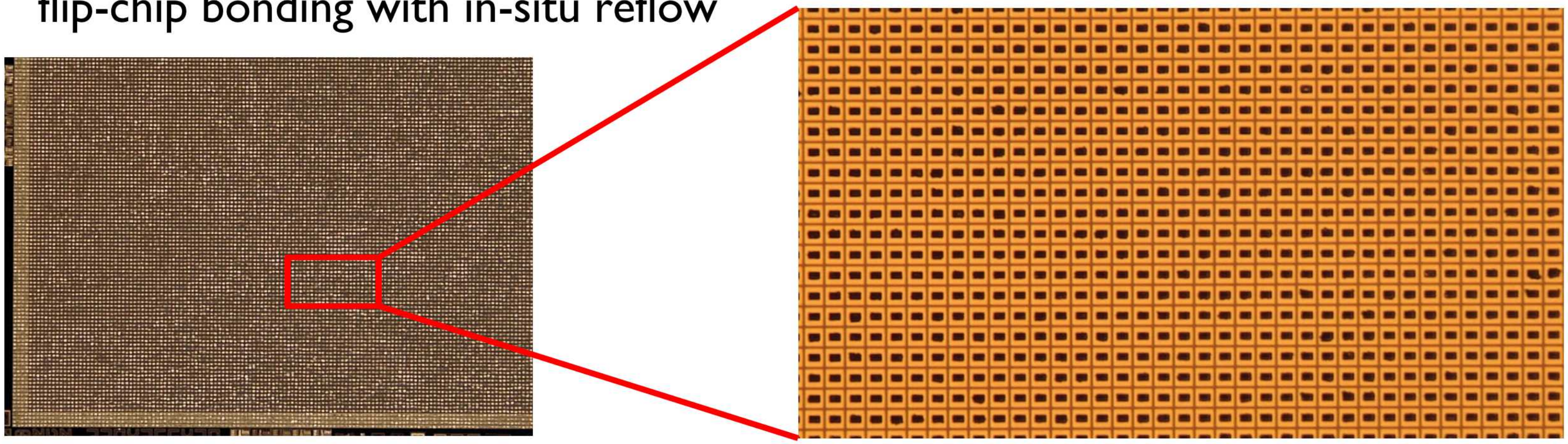


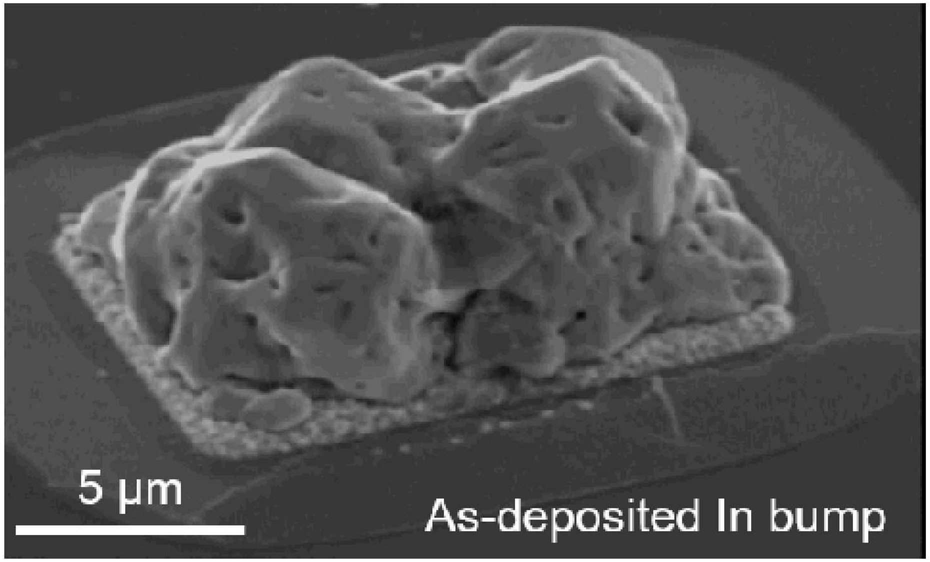
nBn band diagram

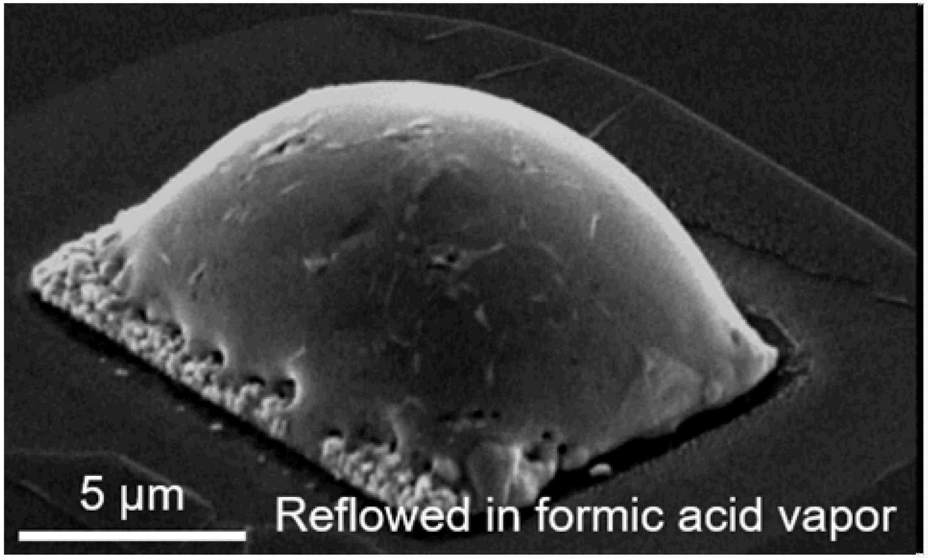
- In-house development of nBn detector technology includes growth, fabrication, integration, and device/system testing
- Requires hybridization of large (≤1MP) GaSb detectors to CMOS ROICs

Focal plane array integration

- ROIC hybridization after back-end fabrication & detector testing
    - solder dam, underbump metallization
    - indium solder bumps (electroplating or evaporation)
    - singulation
    - flip-chip bonding with in-situ reflow







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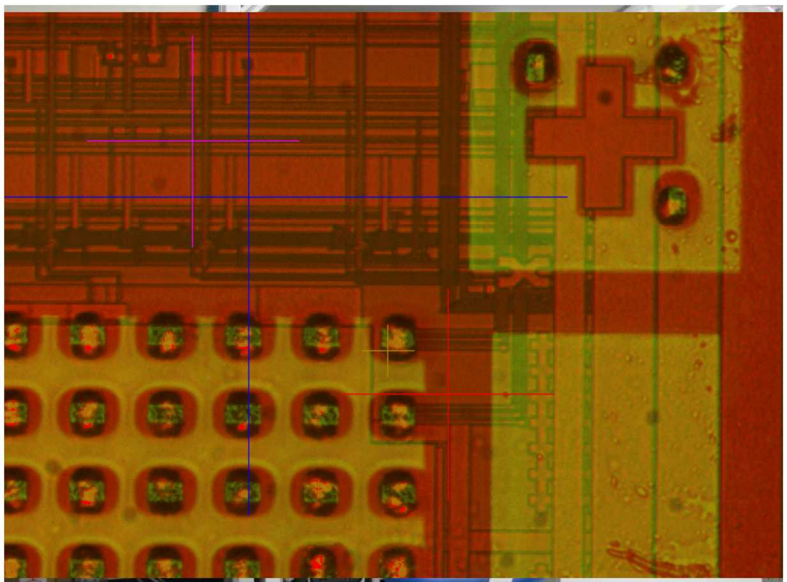
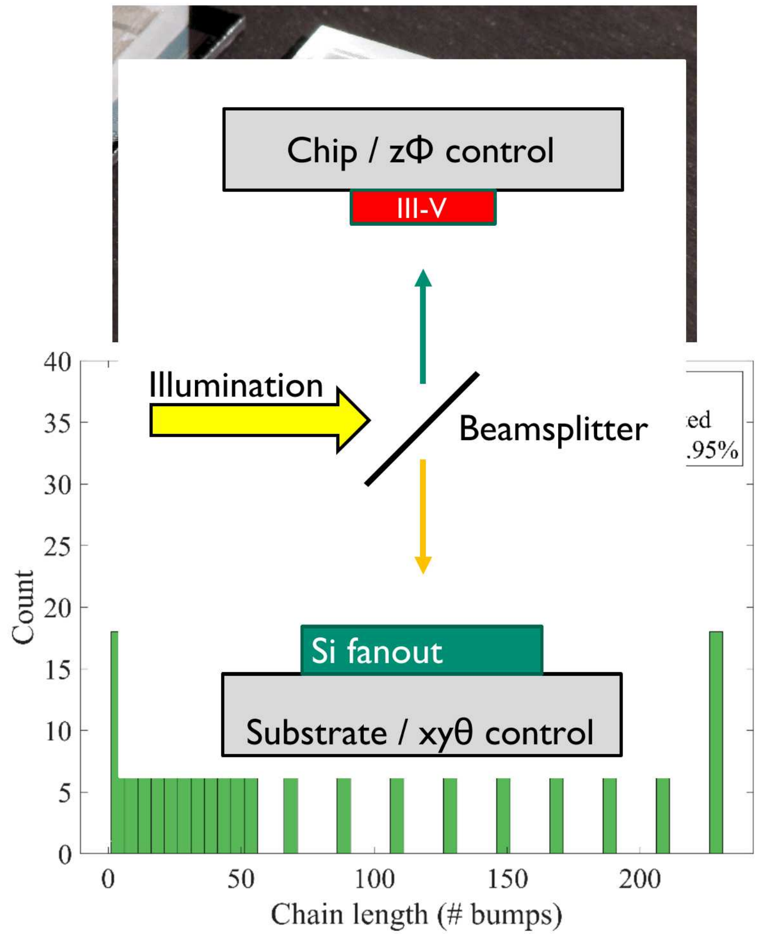


view during flip-chip bonding
semi-automated flip-chip bonder



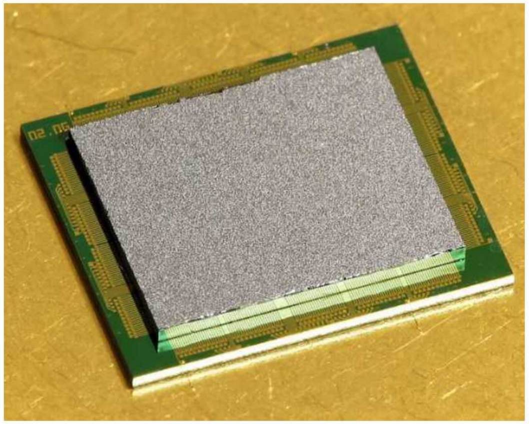
Capabilities:

- +/- 1 micron xyz accuracy, excellent planarity
- 400x imaging, alignments at >450C
- thermocompression bonding up to 100 kg
- flip-chip, die attach, UV-curing, fiber alignment, replication
- "dry flux" vapor removes oxides to improve bonds

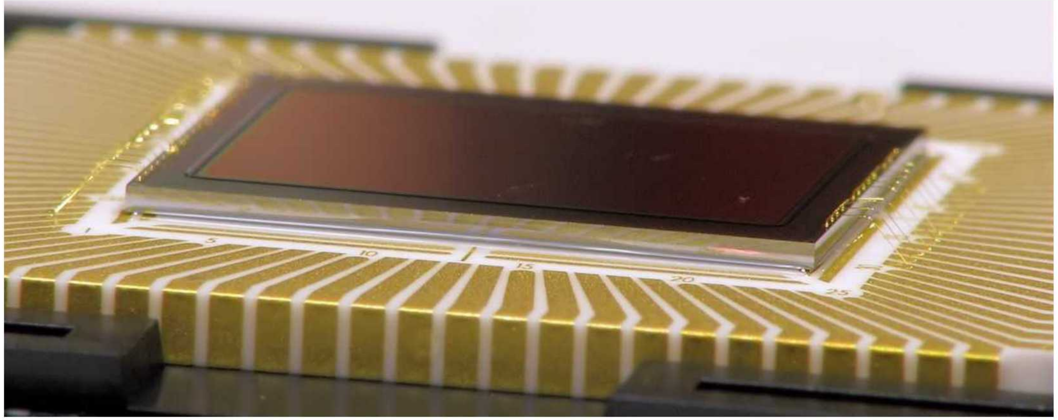
Daisy chain test vehicle showing yield >99%
Average bump-to-bump resistance: 3.35 Ω

Focal plane array integration

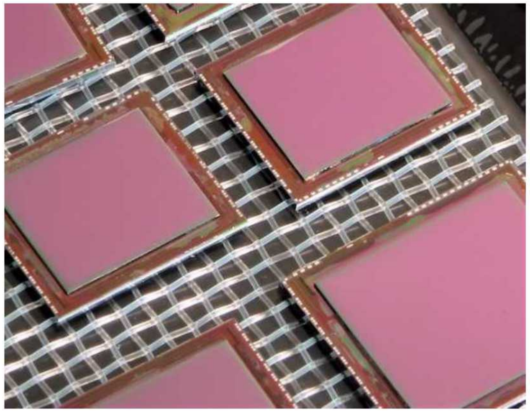
- Post flip-chip processes
  - epoxy underfill
  - backside grinding & polishing
  - precision optical coatings
  - packaging and testing



Full thickness hybridized chips



FPA packaged for cryogenic testing

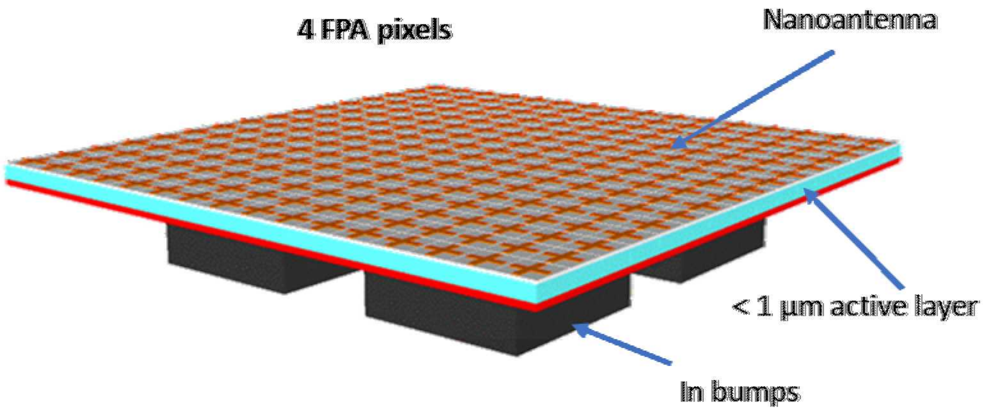


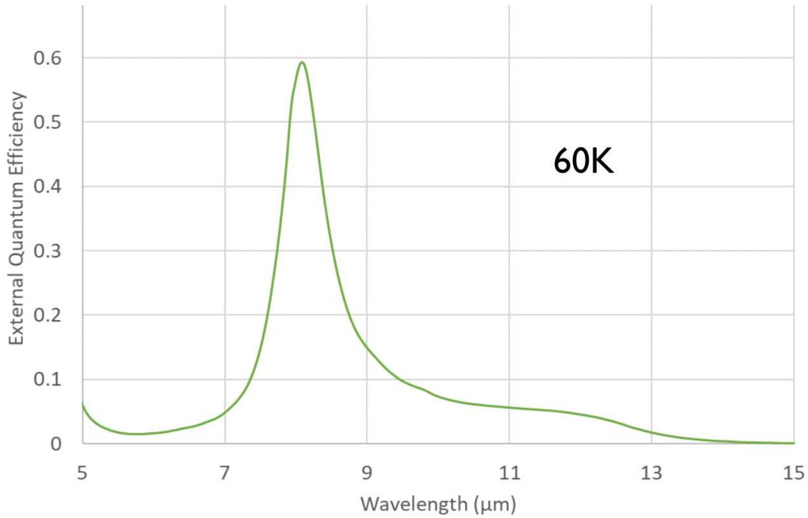
FPAs after thinning and AR coat

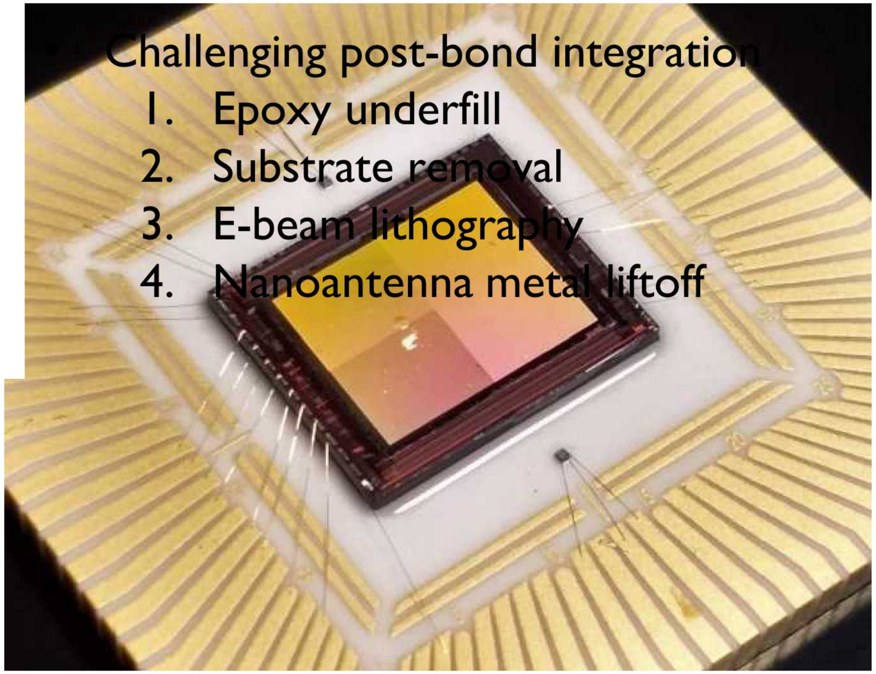
MWIR imaging with nBn sensor

Longwave IR FPA with nanoantennas

- Resonant nanoantennas to boost quantum efficiency
  - Sub-wavelength metal antennas patterned on illumination-side after bonding and thinning
  - Resonant design allow reduced detector thickness for lower dark current while maintaining QE>50%



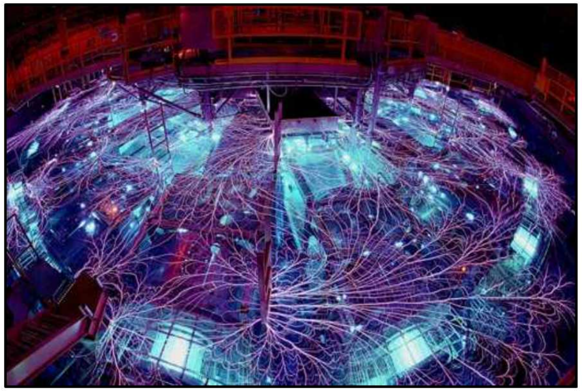




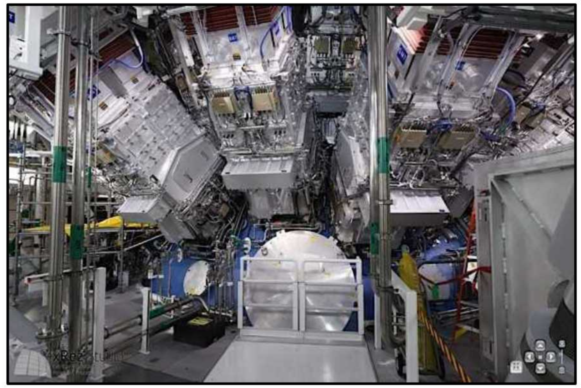
Packaged nanoantenna enabled FPA
Each quadrant has a different nanoantenna design for peak performance at different wavelengths

D. Peters, et al. IEEE RAPID (2018).

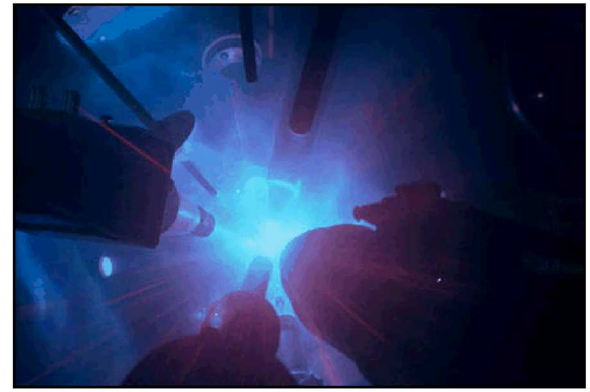
Ultrafast x-ray imager (UXI) program



Z-Machine

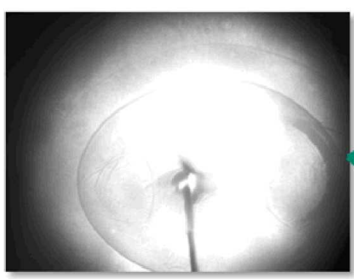


National Ignition Facility

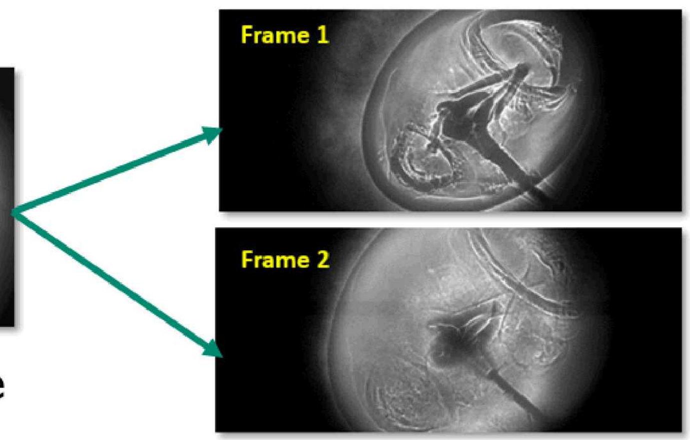


Omega

- 2D, nanosecond gated imaging diagnostic for inertial confinement fusion research
  - Fast frame-rate reduces motion blur and provide temporal information
  - Cameras fielded in fusion facilities around the US
  - Current cameras use Si detectors; improved sensitivity possible with III-V detectors



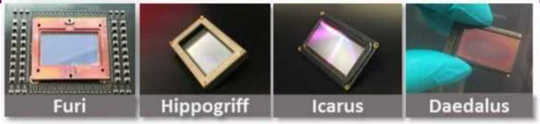
Integrated image



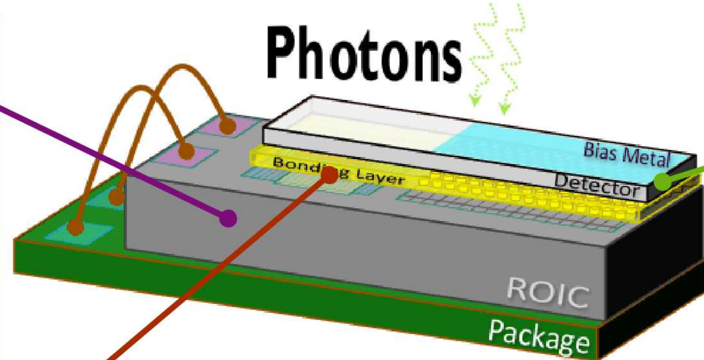
Gated image show nanosecond evolution of ICF physics

Ultrafast x-ray imager (UXI) program

Readout Integrated Circuit (ROIC)

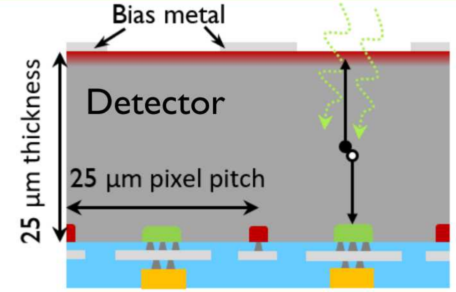


- Fabricated in SNL's 6" 350nm CMOS
- 1-2ns min shutter, 2-8 frames
- 1024x512 array of 25μm x 25μm pixels
- Adjustable shutter timing



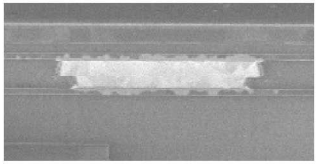
Hybrid CMOS Sensor

Detector Array



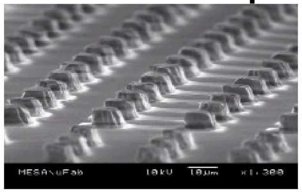
Integration

Direct Bond Interconnect (DBI)

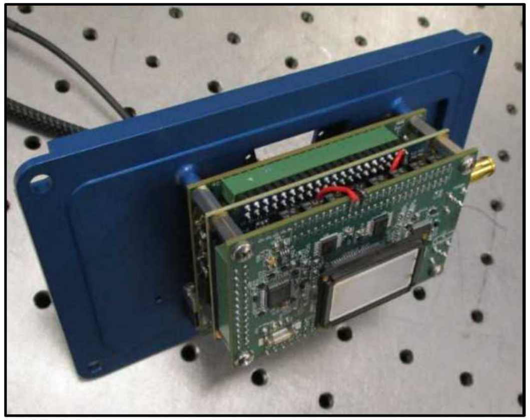


- Wafer-to-wafer bond

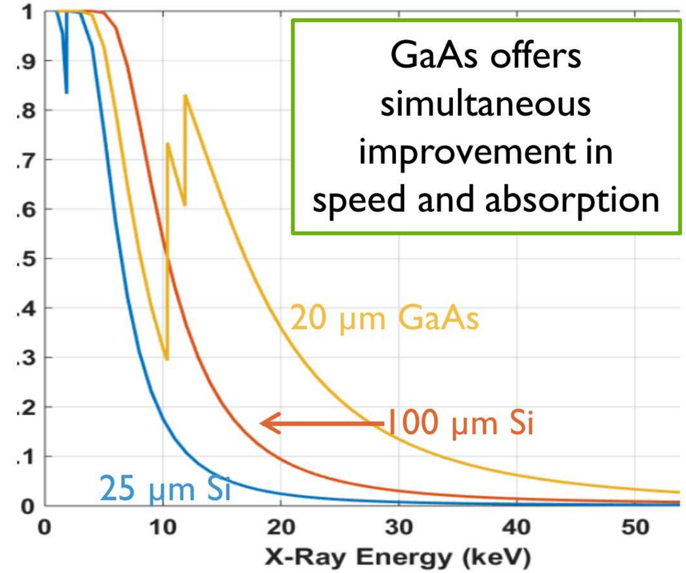
Indium bump



- Die level processing



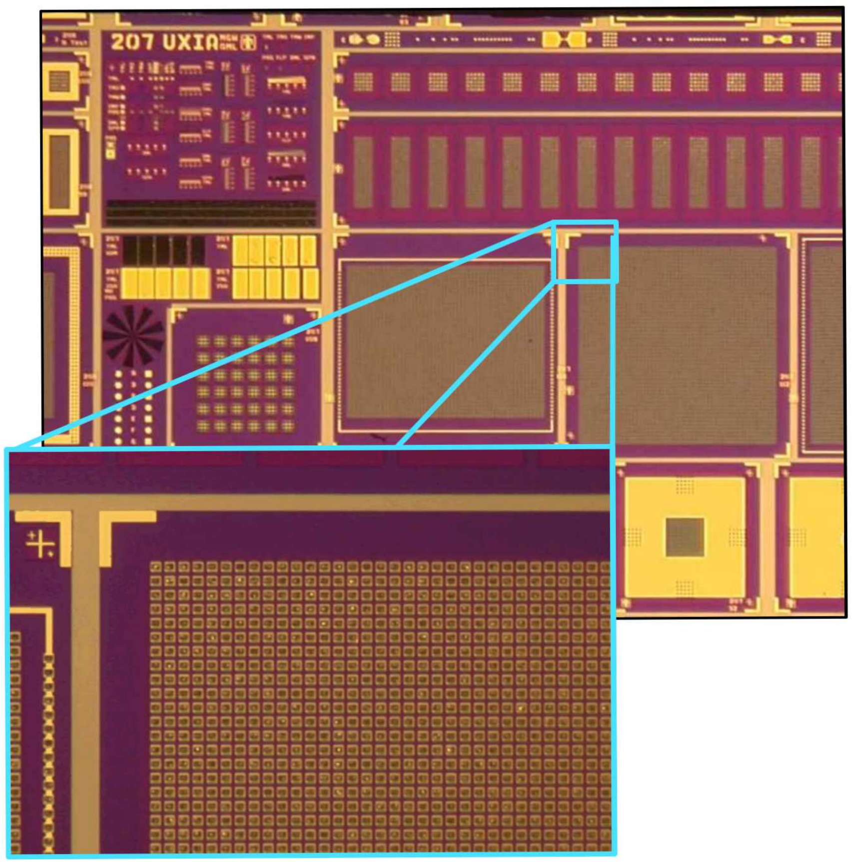
UXI Camera System Development for Application-Specific Needs



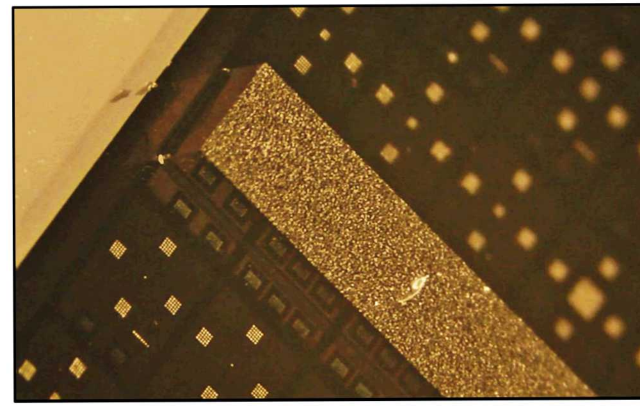
GaAs offers simultaneous improvement in speed and absorption

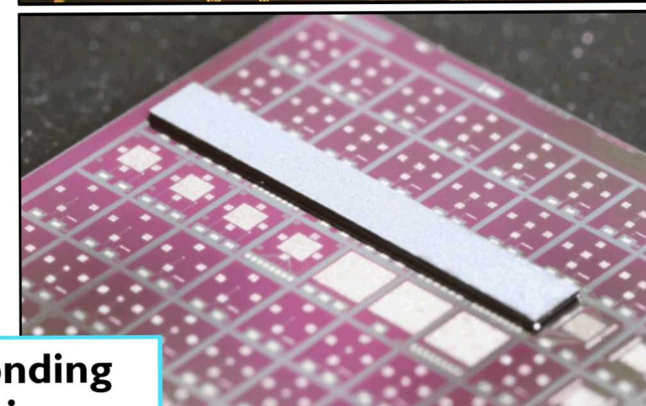
Ultrafast x-ray imager (UXI) program

- Recent work on HI of pixelated GaAs arrays for UXI
  - Adopt techniques from IR FPAs to a new application
  - First bonded test arrays complete
  - 0.5 Mpix Icarus/Daedalus arrays available next year

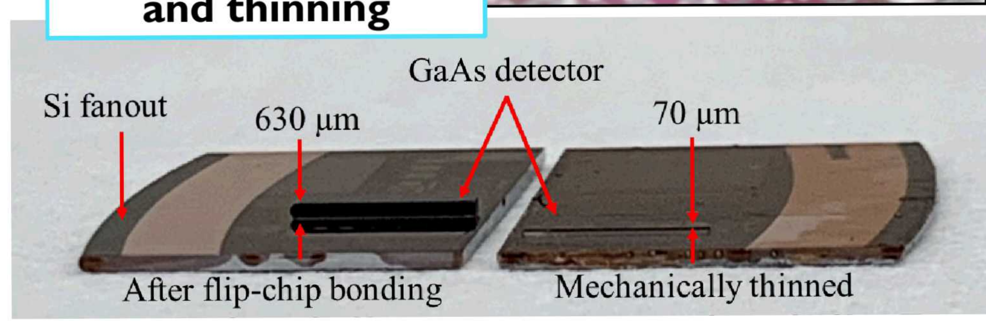


GaAs test arrays with 25 µm pixel pitch





Flip-chip bonding and thinning

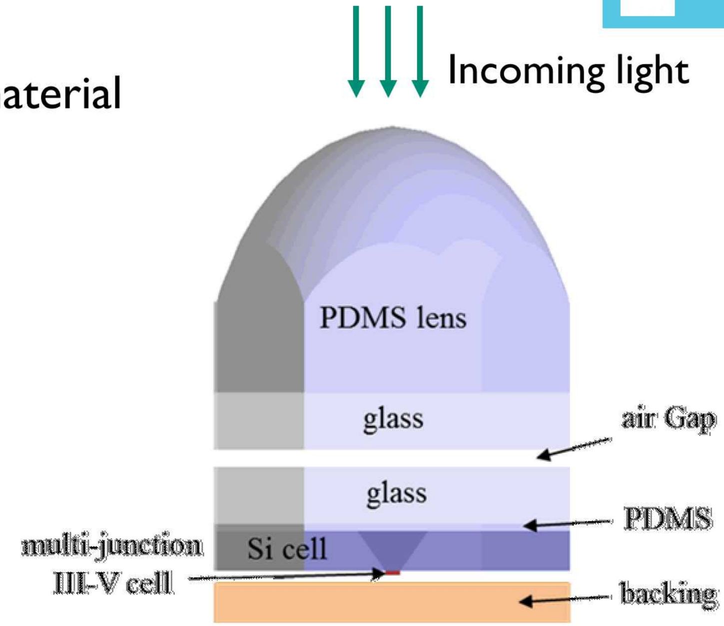


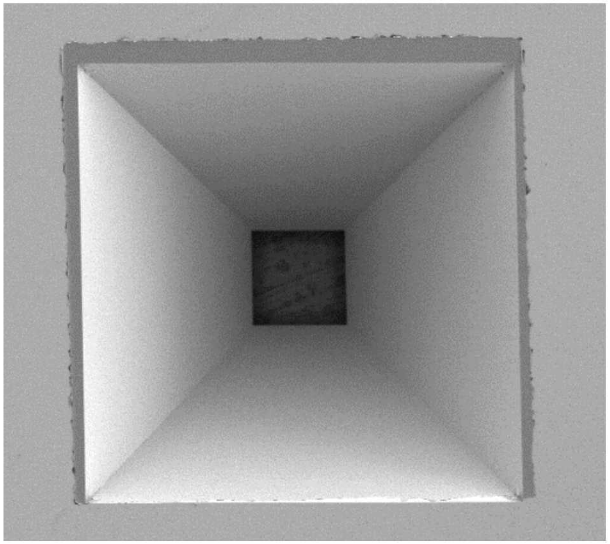
Q. Looker, et al. IFSA (2019).

Applications of III-V HI:
2: Concentrating solar cells

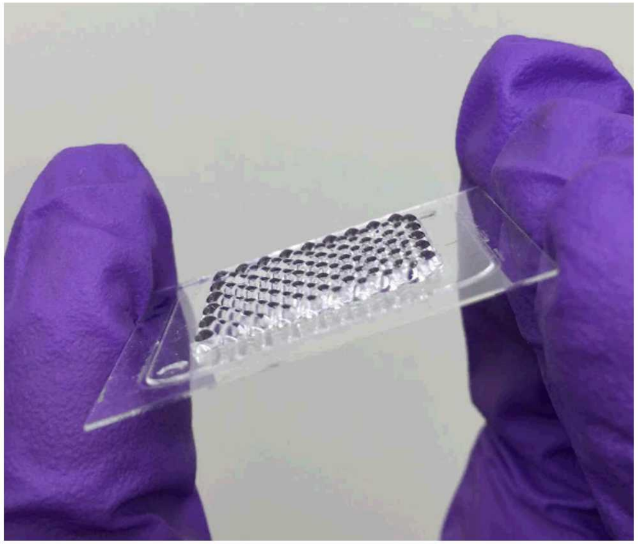
Concentrating microphotovoltaics for reduced cost solar

- HI used to maximize usage of high-cost III-V epitaxial material
  - Molded lenses and microfabricated reflector focus incoming light onto high efficiency III-V solar cell
    - III-V active area 100x smaller than cell area
  - Diffuse light absorbed in Si substrate for improved capture efficiency
  - Collaborative effort between MIT and Sandia

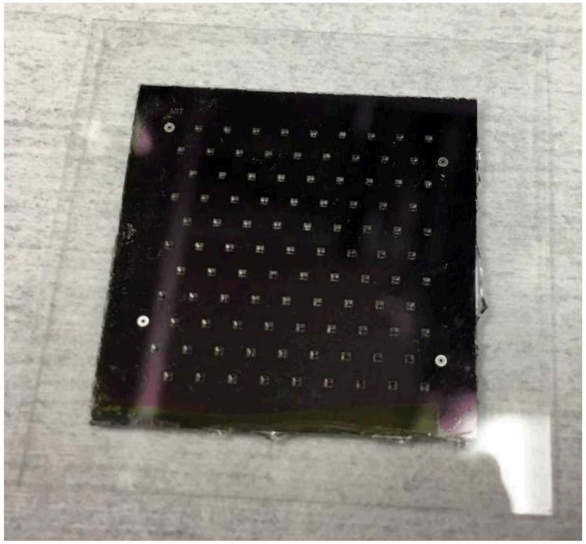




KOH-etched Si reflector groove



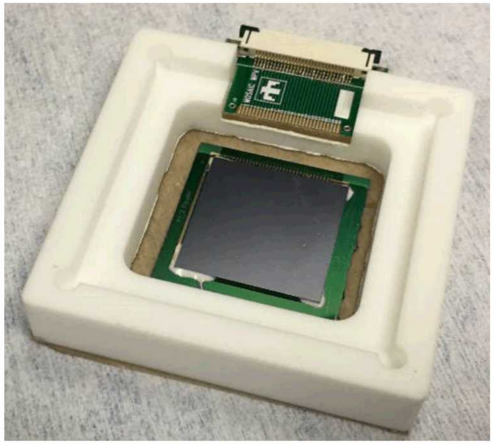
Molded PDMS lens array

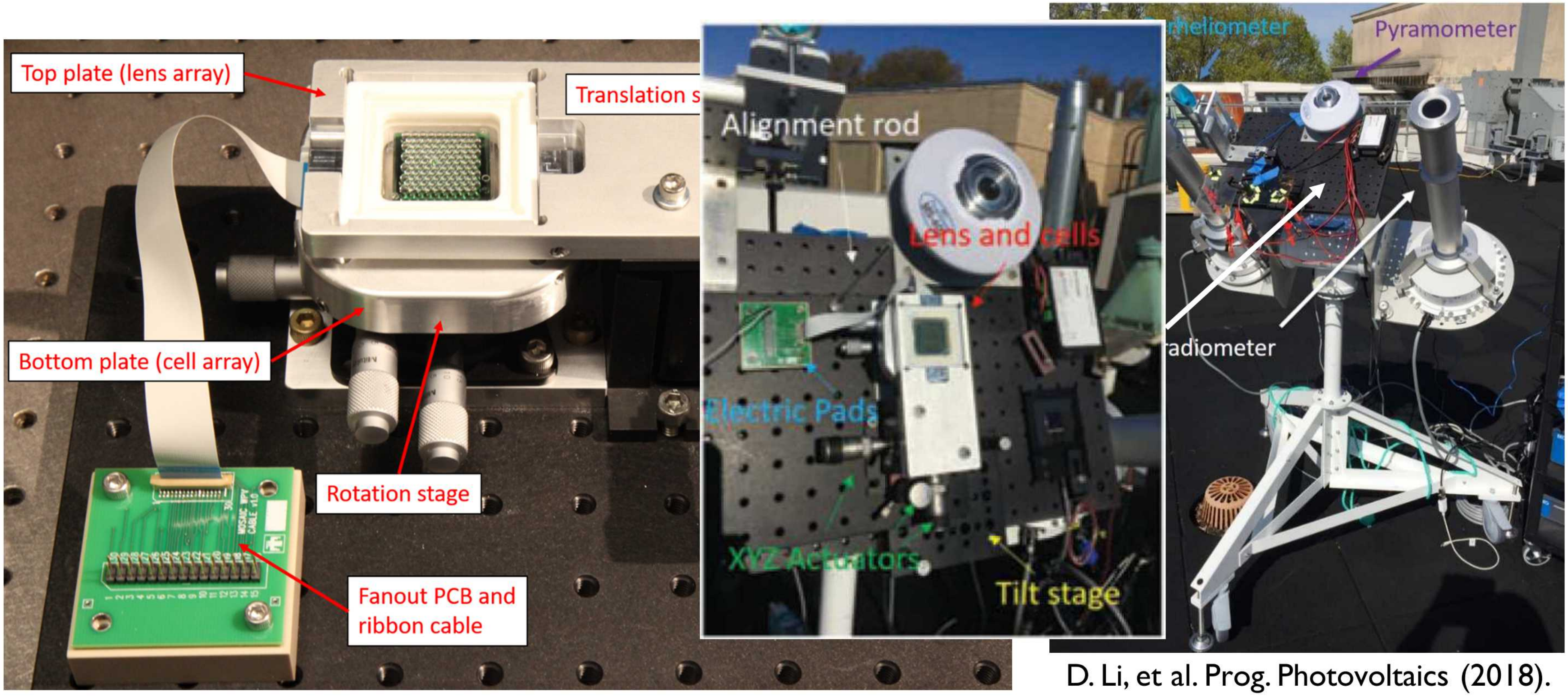


III-V cell array flip-chip bonded to Si fanout and coverglass

Concentrating microphotovoltaics for reduced cost solar

- Packaging and testing
    - Custom Macor frames machined to hold III-V/Si cell assembly and lens arrays
    - As proof-of-concept, manual alignment of lens array used to demonstrate concentration of incident light (~30x)
    - Assembly tested on calibrated solar measurement system at MIT



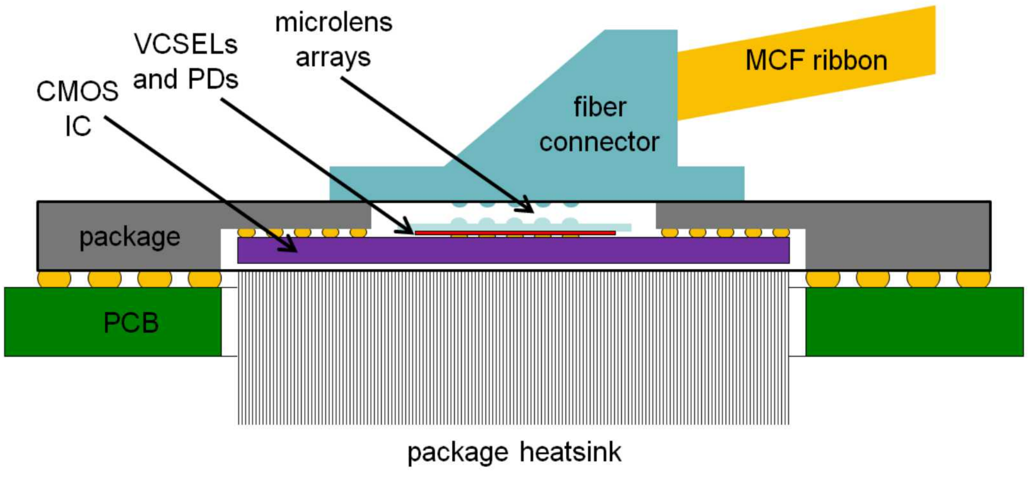


D. Li, et al. Prog. Photovoltaics (2018).

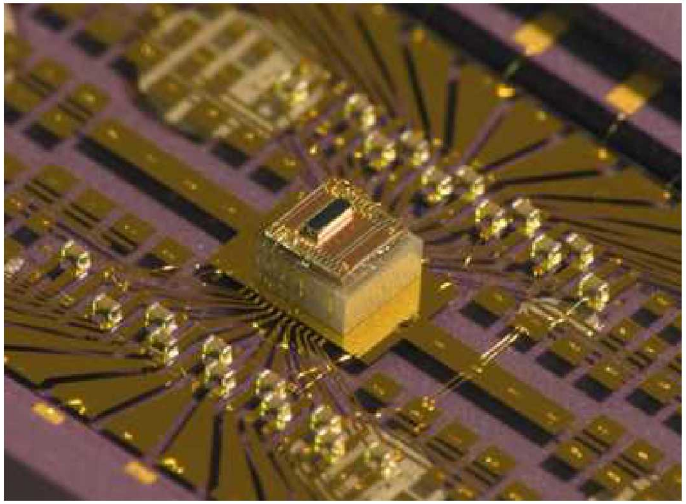
Applications of III-V HI:
3: High-speed communication

High-density photonic interconnects: overview

- Dense integration of photonics and CMOS for advanced interconnect technologies
    - III-V vertical-cavity surface-emitting lasers (VCSEL) and photodiodes (PDs) for high-speed optics and Si CMOS for low-power computing
    - Hybrid integration for very high density and low electrical parasitics
    - Targets low energy (pJ/bit) and high density (Tbps/mm^2) into a multi-core fiber (MCF)
- Development of circuits, photonics, optics and integration techniques
    - Transmit/receive circuits in 32-nm and 45-nm CMOS
    - Combines VCSEL and photodiode arrays, micro-optics, custom fiber



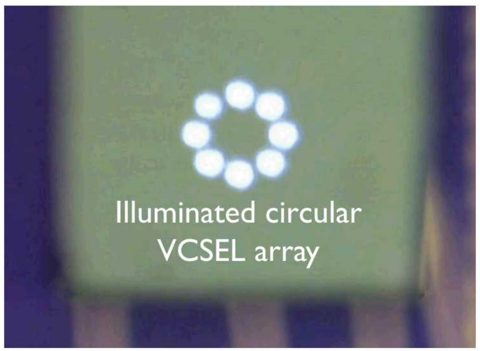
Multichannel interconnect concept

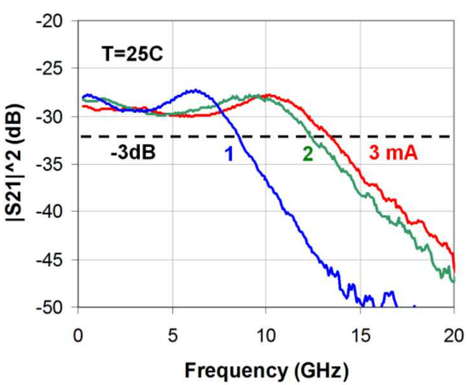


Packaged CMOS/VCSEL assembly

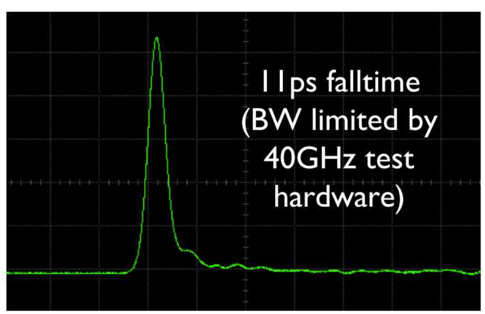
High-density photonic interconnects: components and HI

- Development of high-density optoelectronics arrays
  - Low-power VCSELs designed for high BW at low drive current
  - Photodiodes >40Gb/s with very low capacitance through flip-chip integration
- Micro-optics designed for coupling to multicore fibers

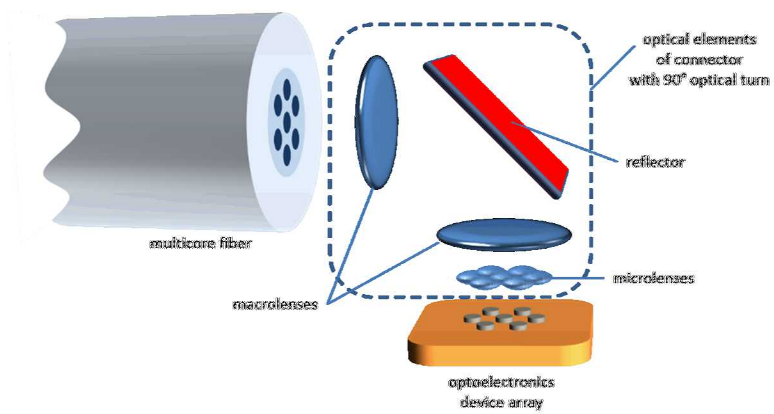


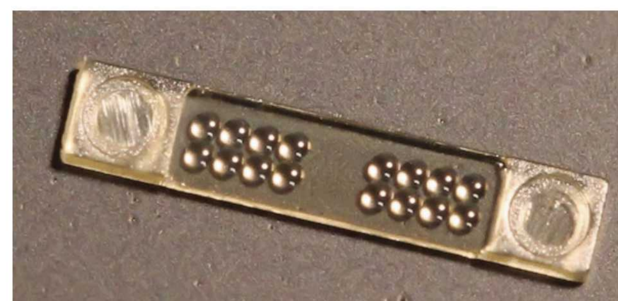


VCSEL performance



Photodiode performance

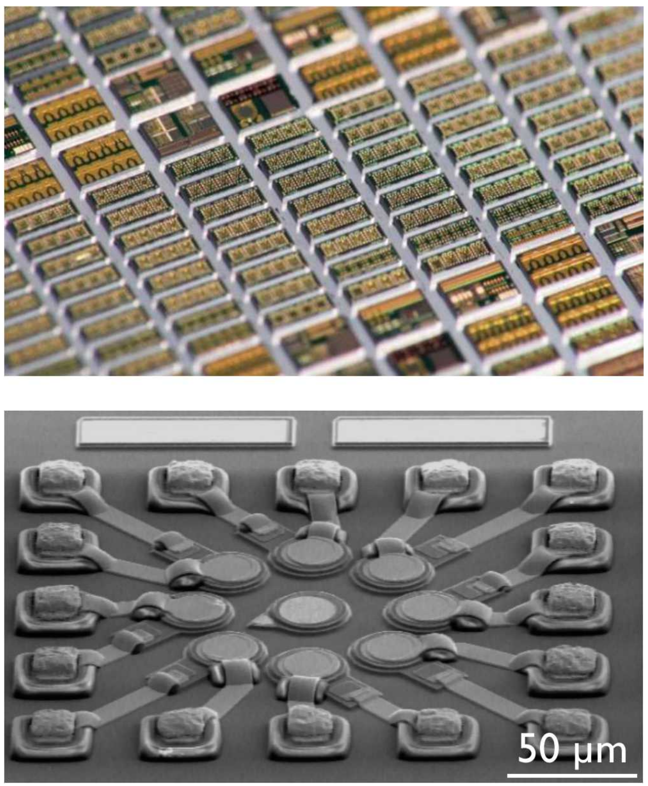




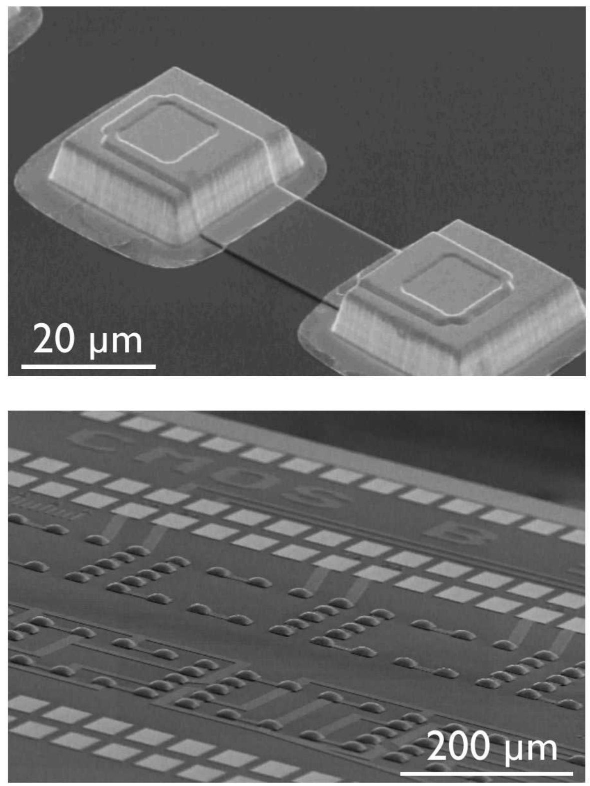
Micro-optics and multicore fibers

High-density photonic interconnects: components and HI

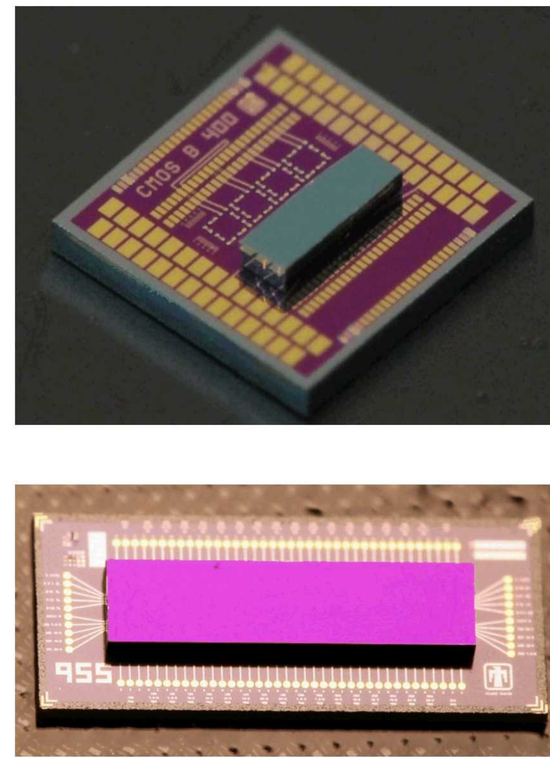
- III-V processes combined into photonics fabrication
  - AuSn bumps, 100µm substrate thinning, AR coating, scribe and break
- CMOS processed at die level: plated under-bump metal and bumps
- Flip-chip integration



VCSEL and PD arrays on GaAs and InP



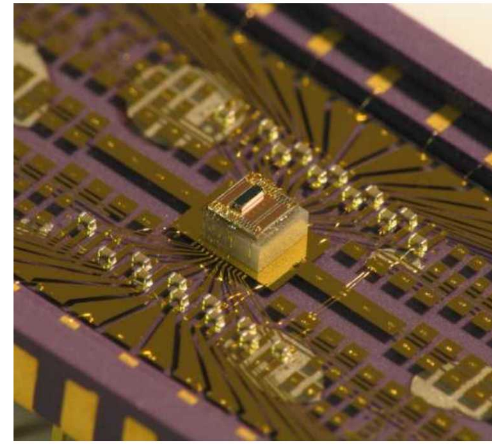
CMOS IC prior to flip-chip 50µm bump pitch



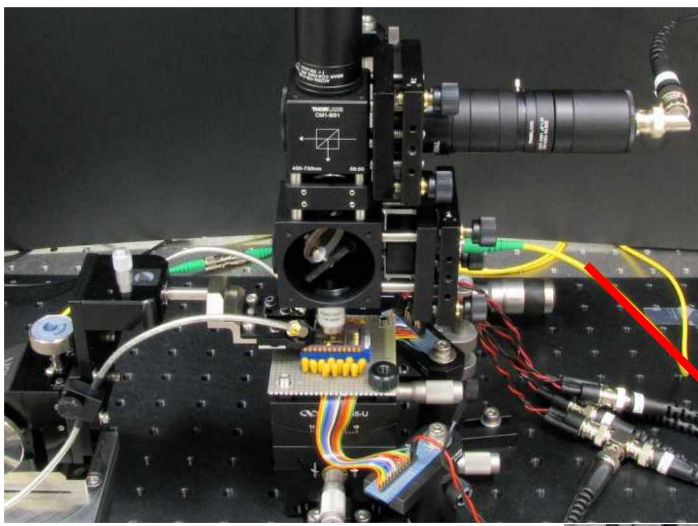
CMOS IC with III-V optoelectronics

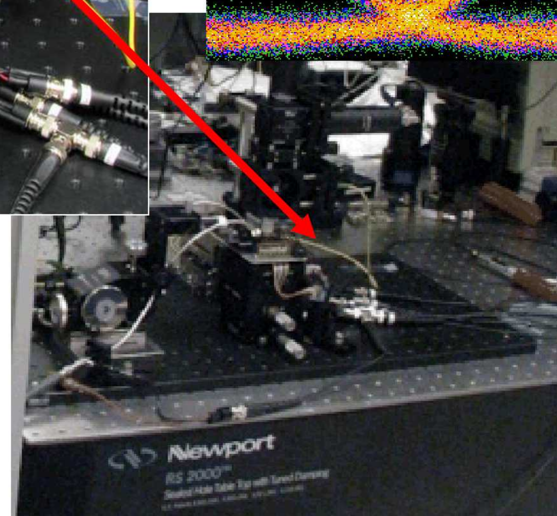
High-density photonic interconnects: testing

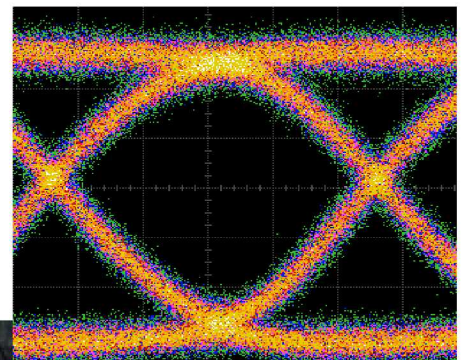
- Hybridized parts packaged for high-speed opto-electronic testing
  - DC wirebonding, RF probing
  - Active fiber alignment
- Single channel links demonstrated using 45-nm CMOS: 10+ Gbps at 1.7 pJ/bit



Packaged CMOS/III-V photonics

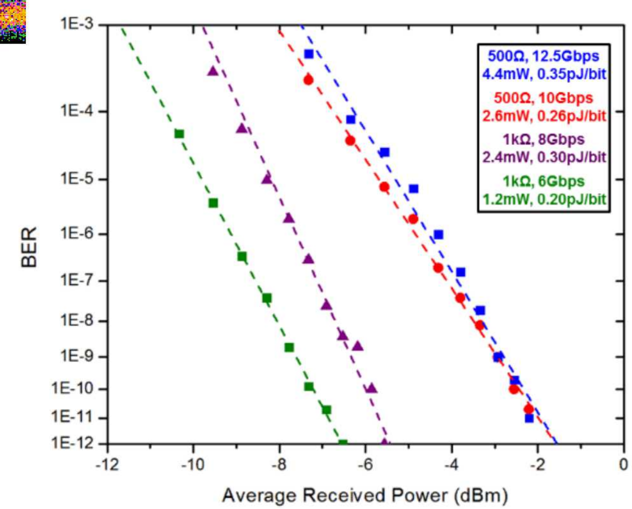






Lab-to-lab link demonstration

System link testing



Conclusion

Conclusion

- Heterogeneous integration of compound semiconductors with silicon electronics enables new devices, improved performance, and compact form factors

Heterogeneous integration: rationale

- **SWAP-C:** **size, weight, and power; cost**
- **performance:** **combine technologies, improve interconnect**
- **diverse functionality:** **optical, RF, MEMS, analog, chem, bio**
- **agility & turn time:** **prototyping and low-volume**
- **trust:** **secure microsystems**

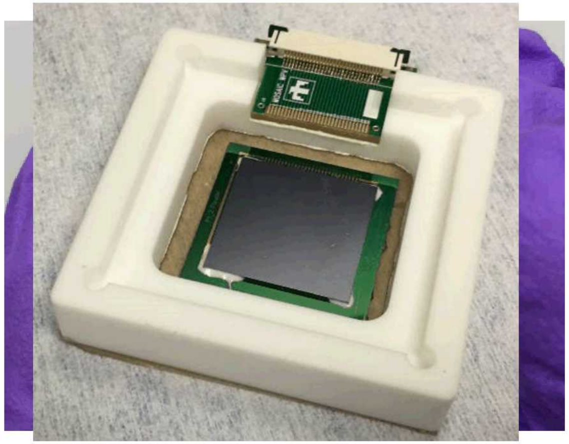
} **low volume, high value**

Approaches to integration

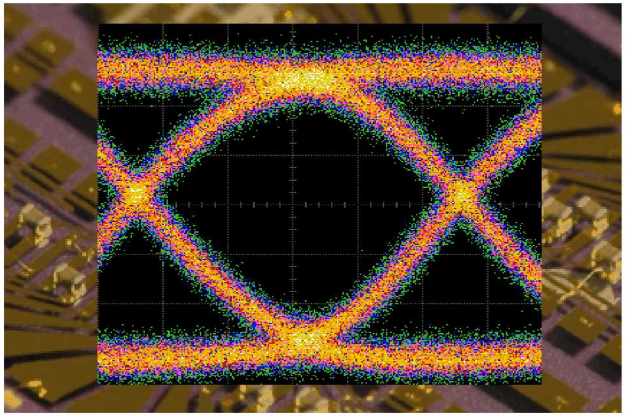
R&D → – **die-to-die:** **micro bump, flip-chip, micro-optics, etc.**

Production → – **wafer-level:** **interconnect bonding (3D DBI)**

Focal Plane Arrays from IR to x-rays



Concentrating Solar Cells



High-Speed Communication

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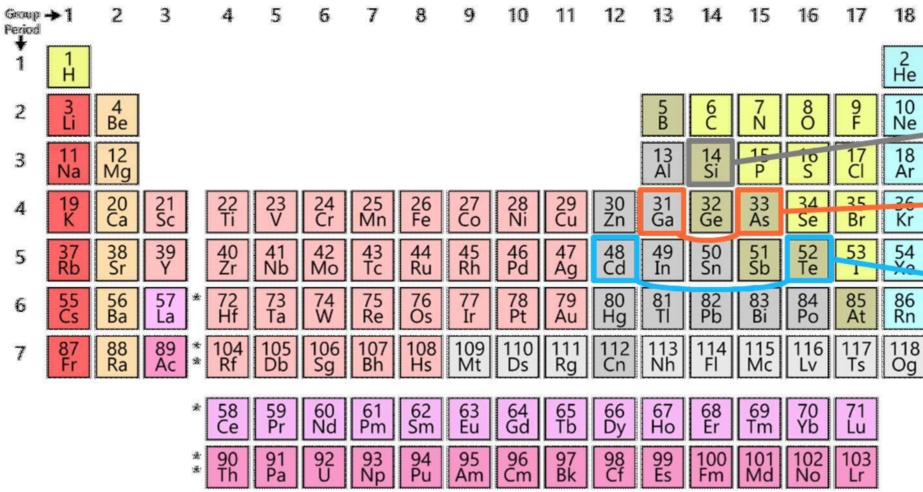
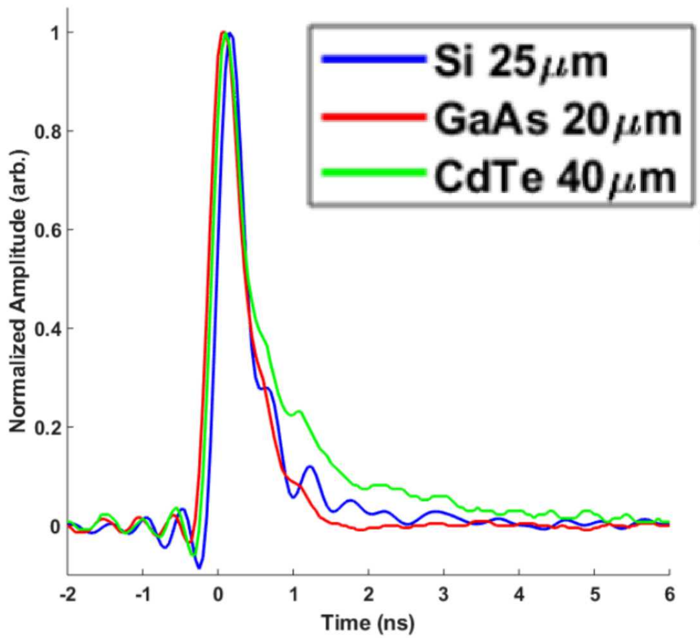
Sandia National Laboratories

Backup slides

Other x-ray detector materials



Material Investigated	Notes
Si	Mature fabrication, low Z
GaAs	Demonstrated fast detectors
CdTe	Demonstrated fast detectors
CZT	Cannot obtain small detectors
GaN	Background doping too high
AlSb	Leakage current too high



Detector pulse shapes obtained with Advanced Photon Source white beam

Diamond turning and lens molding

- PDMS optics
  - eighth order aspheric curves
    - targeting >90% optical efficiency at III-V
  - cast onto 300μm thick Schott AF32 glass
- Aluminum mold fabrication
  - optical surfaces micro-machined & diamond milled
  - lenses & glass edges aligned mechanically
  - trapping bubbles challenges mold filling
- Assembled into machined Macor frame
  - bottom: optic array, facing inward
  - top: 3mm thick Schott BK-7 cover glass, provides protection