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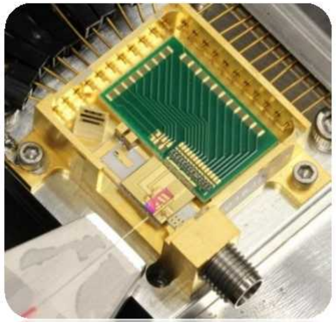

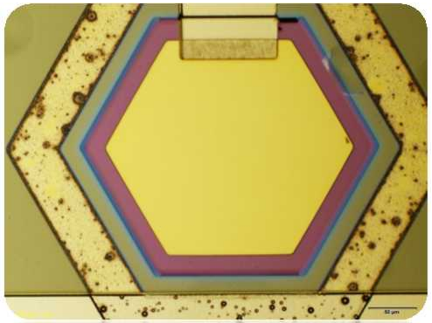

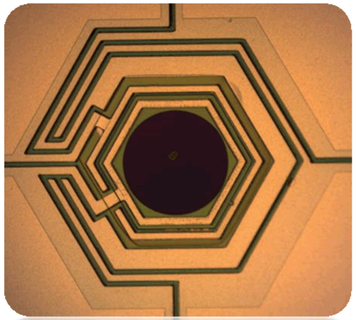

Compound Semiconductor Integrated Photonics for Avionics

A Tauke-Pedretti, A. Vawter, E. Skogen, C. Alford, F. Cajas, M. Overberg, G. Peake, J. Wendt,
W. Chow, G. Nielson, JL Cruz-Campa, M. Okandan, A. Lentine, J. Nelson, W. Sweatt,
J. Cederberg, B. Jared, P. Resnick, C. Sanchez, J. Barrios, C. Alford, I. Luna, G. Girard
Sandia National Laboratories

AVFOP, Long Beach CA
November 1, 2016

U.S. DEPARTMENT OF ENERGY · NNSA National Nuclear Security Administration

Part of this work was supported by the U.S. Department of Energy's Laboratory Directed Research and Development (LDRD) program at Sandia National Laboratories.
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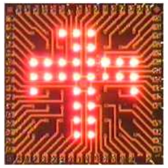
Outline

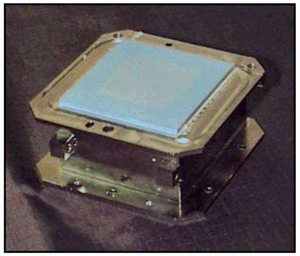
- Overview of Sandia National Laboratories
- InP-based Photonic Integrated Circuits
- Microsystems Enabled Photovoltaics
- Conclusions

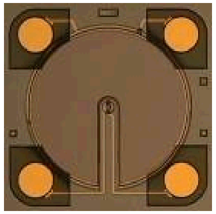
Sandia National Labs MESA Complex

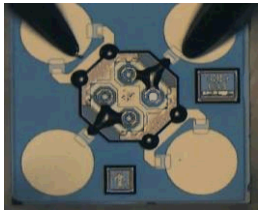
Sandia National Laboratories

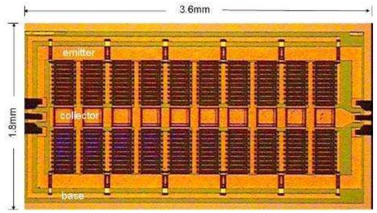
- Co-located SiFab and MicroFab
- Responsible for:
  - Advanced microsystem R&D
  - Rad Hard Microelectronics
  - Trusted microsystem design, fabrication, packaging and testing
- Foundational Capabilities
  - III-V compound semiconductor epitaxy
  - Microfabrication
  - Integration
  - Device physics, modeling, simulation

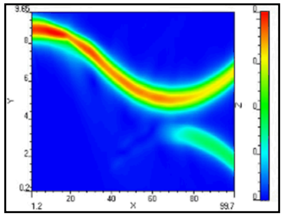


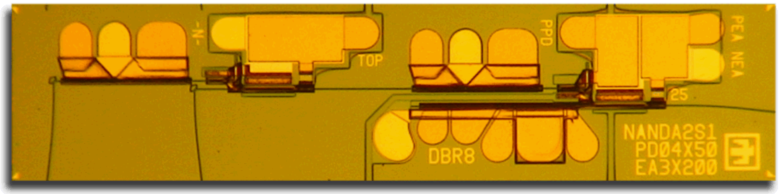


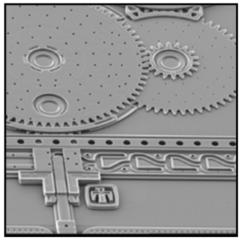


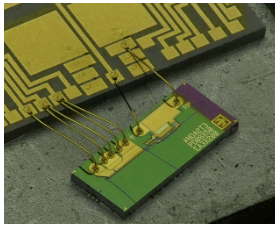










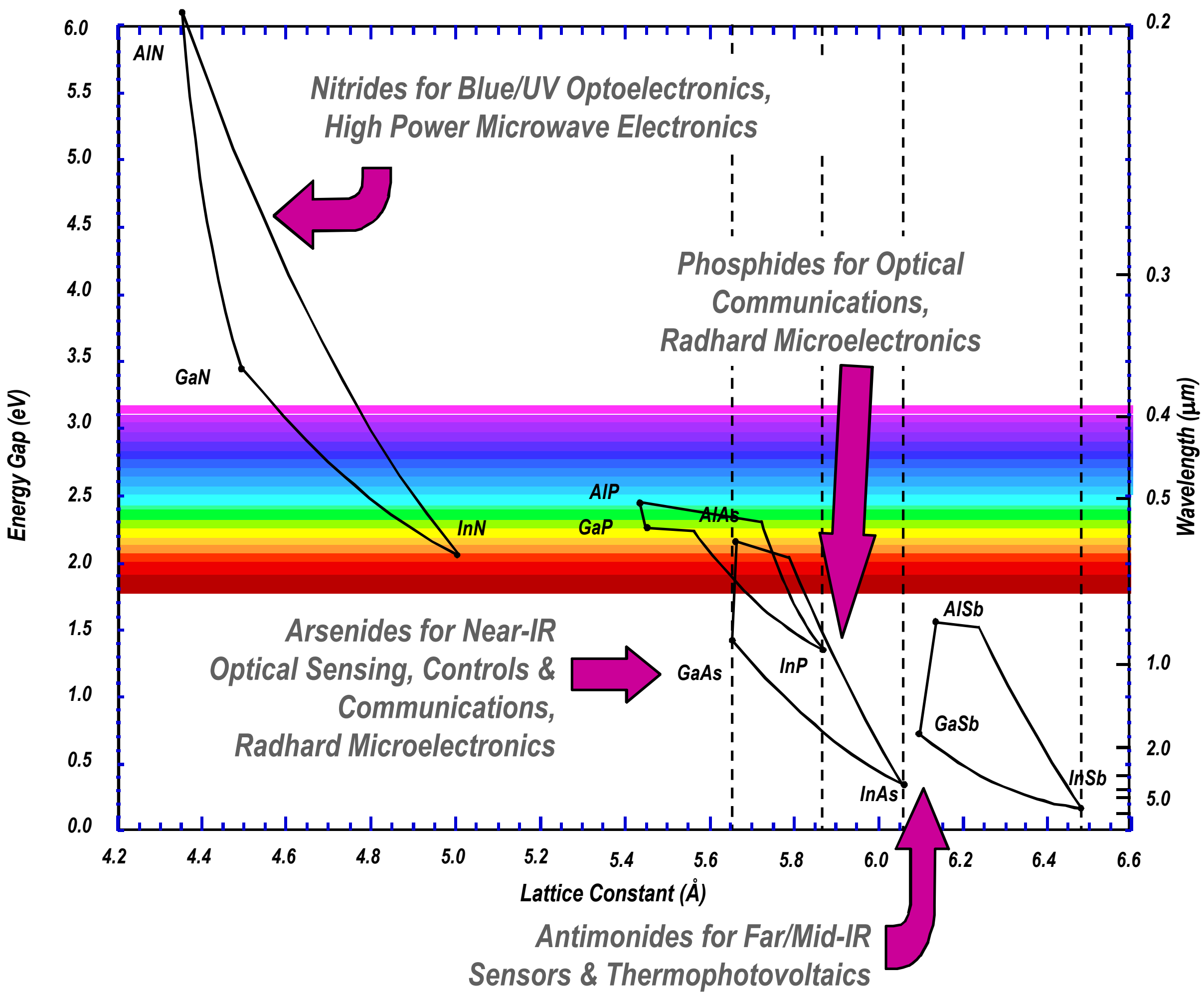


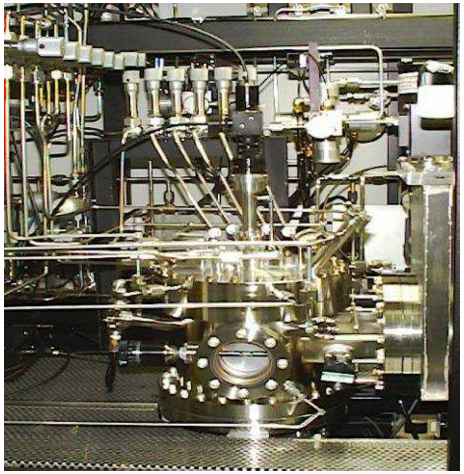
http://www.sandia.gov/mstc/

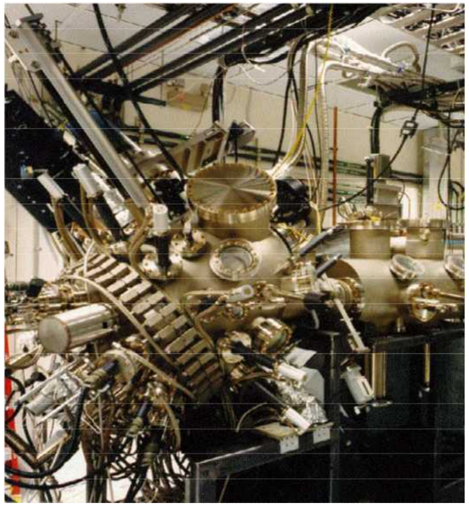
Group III-V Semiconductor Photonics at Sandia

Sandia Grows the Full Spectrum of III-V Materials

6 – MOCVD: As, P, Sb, N
4 – MBE: As, P, Sb

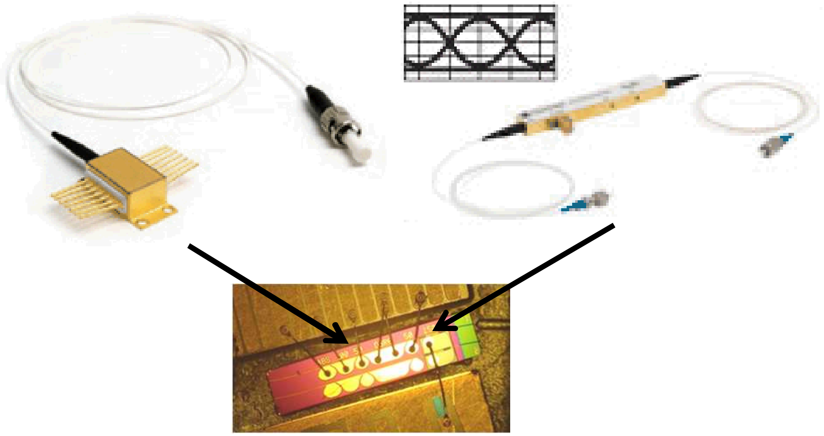






Photonic Integration

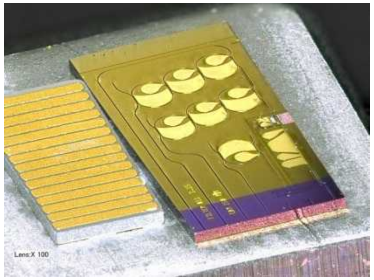
- Integration has been driven by the benefits of:
  - Smaller size
  - Lower power
  - Mechanical robustness
  - Simplified packaging
  - Lower costs
  - Optical interface coupling loss reduction
  - *More complex optical functions*

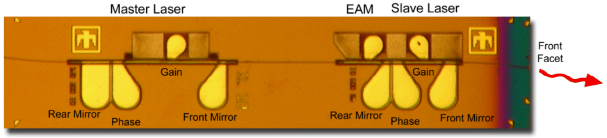


- Offers opportunities to make impacts in applications beyond telecommunications including:
  - Optical signal processing
  - Sensors
  - Applications where SWaP is important
  - Scientific research: lab on chip
  - *Significant innovation is possible on the circuit level*

InP-based Photonic Integrated Circuits

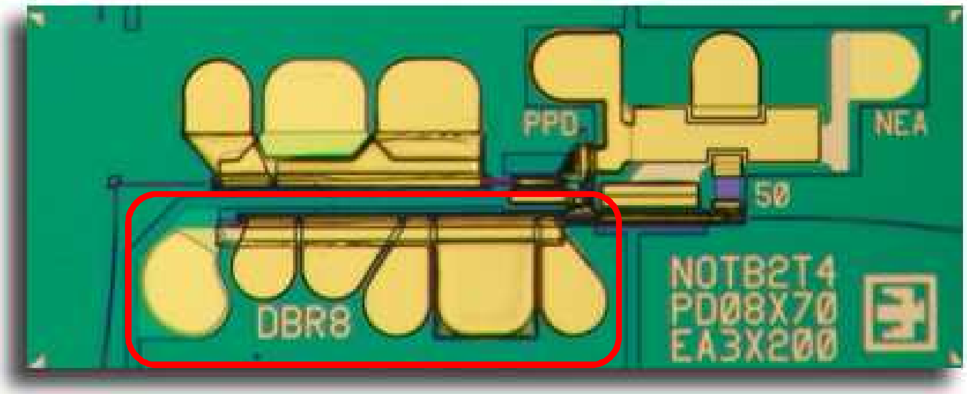
- Efficient light generation, modulation and detection
  - Direct bandgap
  - Operation in the low fiber loss band around 1550 nm
- Well-suited for high performance needs
  - High-speed, high-extinction modulators
  - Narrow-linewidth, low-noise lasers
  - High-speed, high-efficiency detectors
- Highly customizable platform allows device integration without compromising performance
- Utilized in commercial telecommunication systems
  - Devices continue to improve as they address needs for higher data rates and new modulation formats

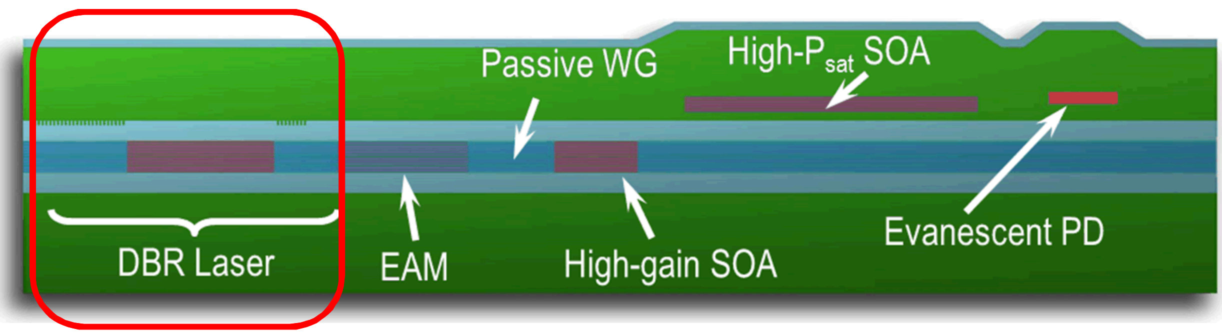




Sandia's PIC toolkit

- Sandia developed toolkit incorporating many components allows for new PICs with reduced overhead
  - Components:
    - **Lasers**
    - Electroabsorption modulators
    - Passive waveguides
    - High-gain SOAs
    - High-saturation power SOAs
    - Evanescently-coupled photodetectors
    - Quantum well photodetectors
    - Resistors
    - Capacitors





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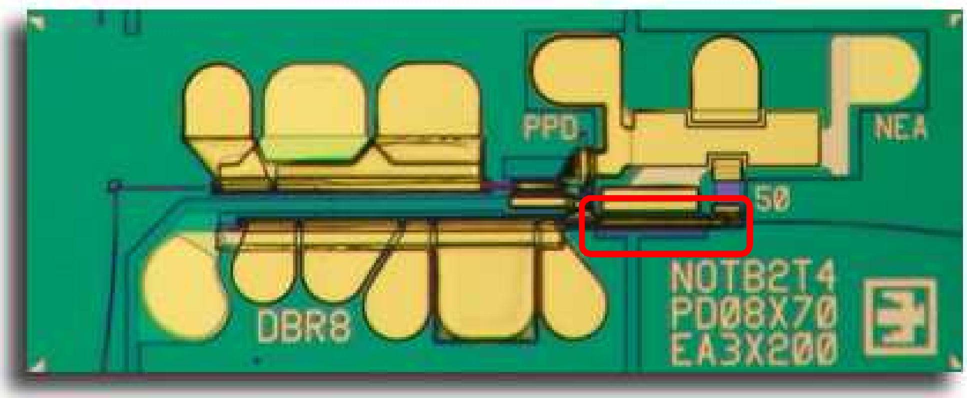

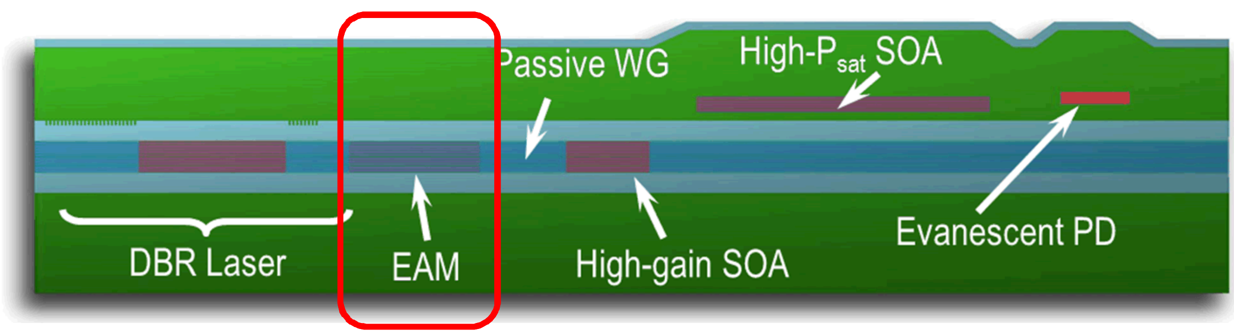

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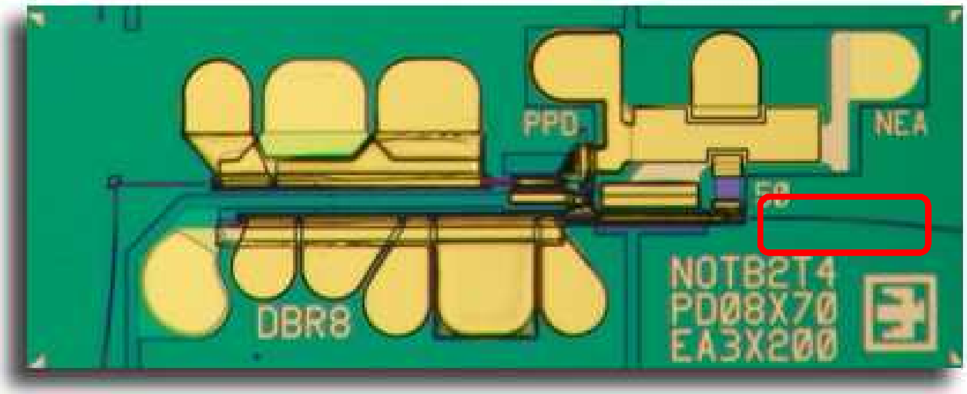

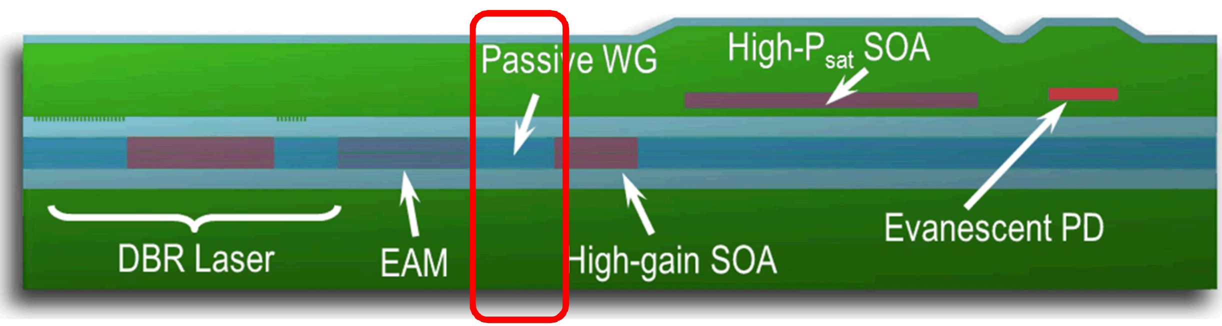

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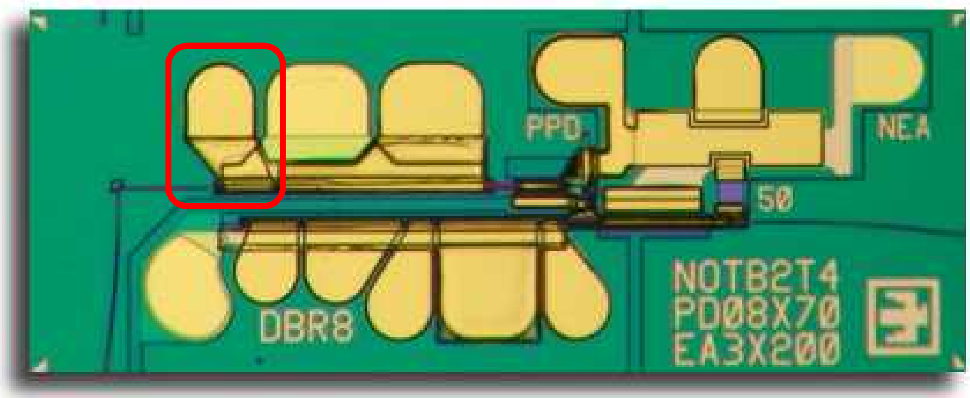

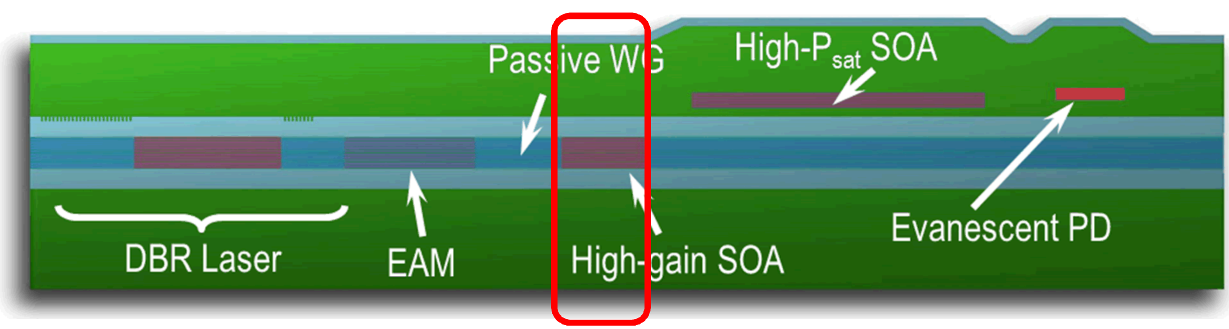

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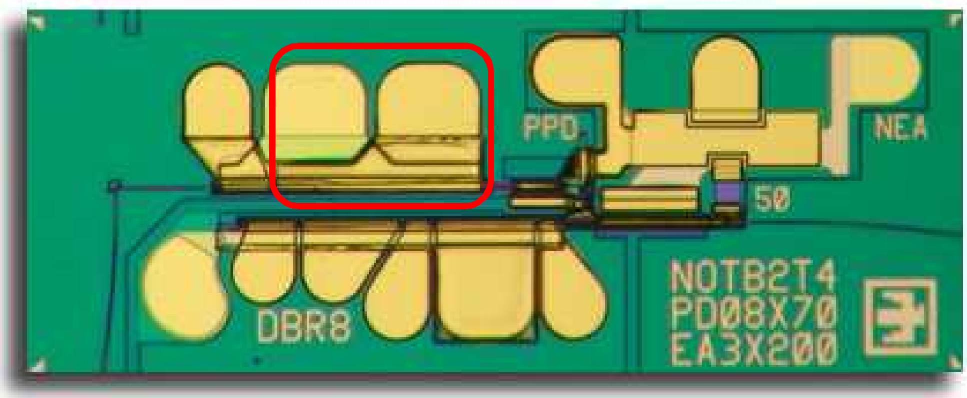

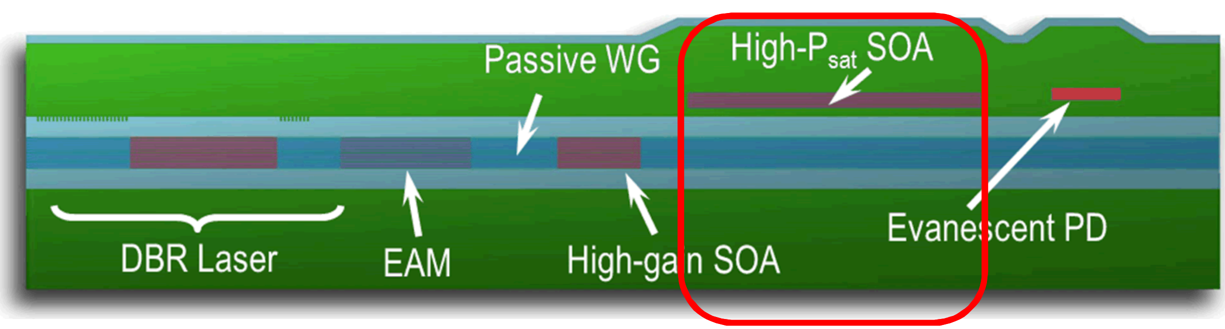

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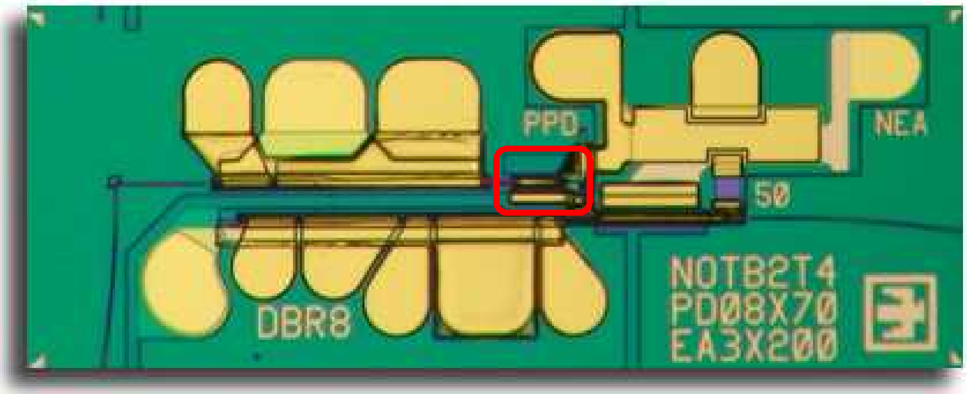

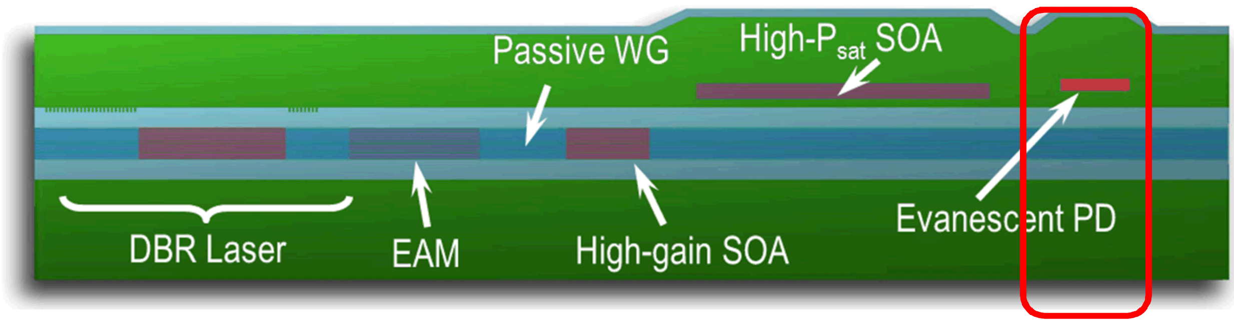

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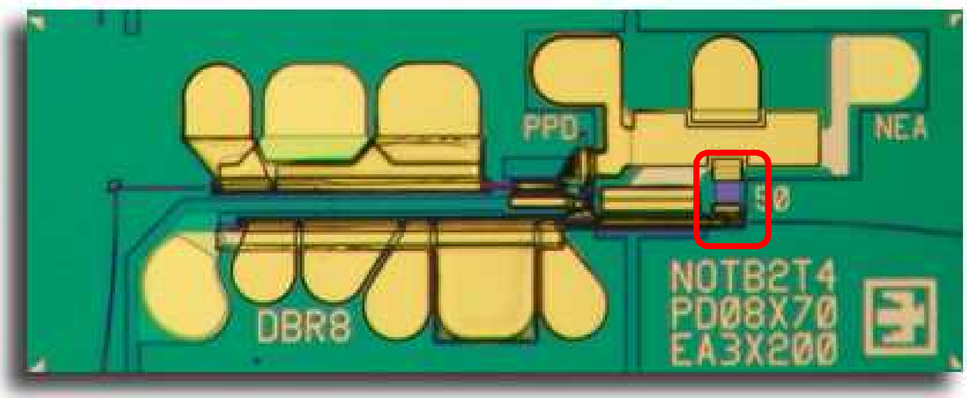

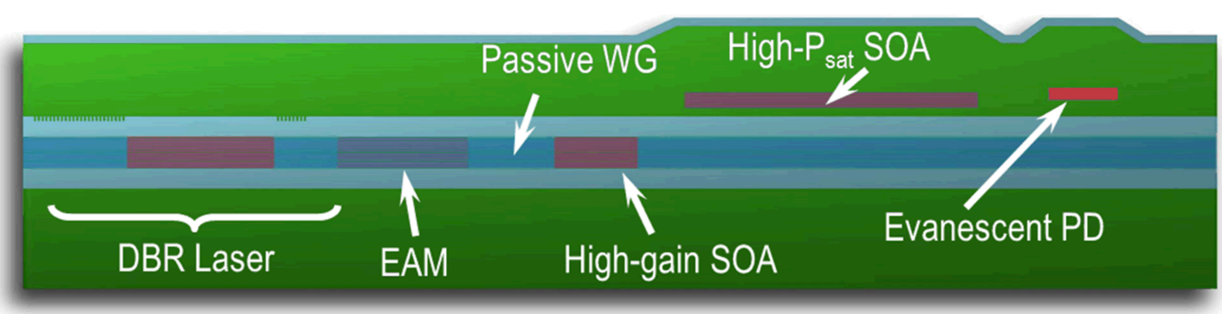

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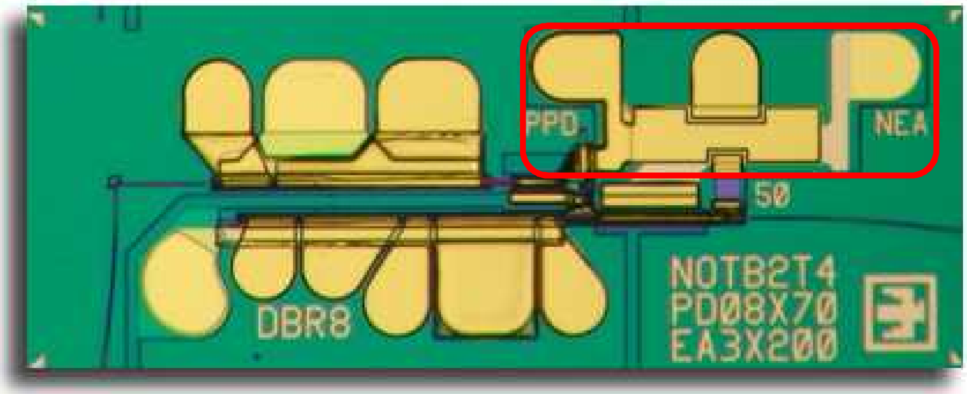

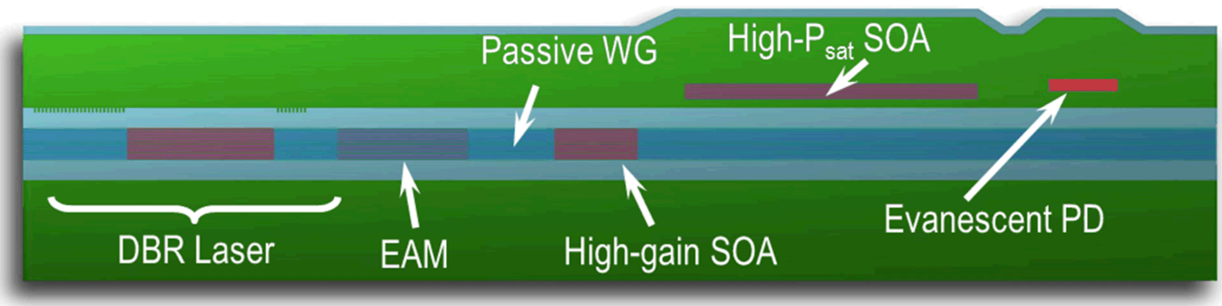

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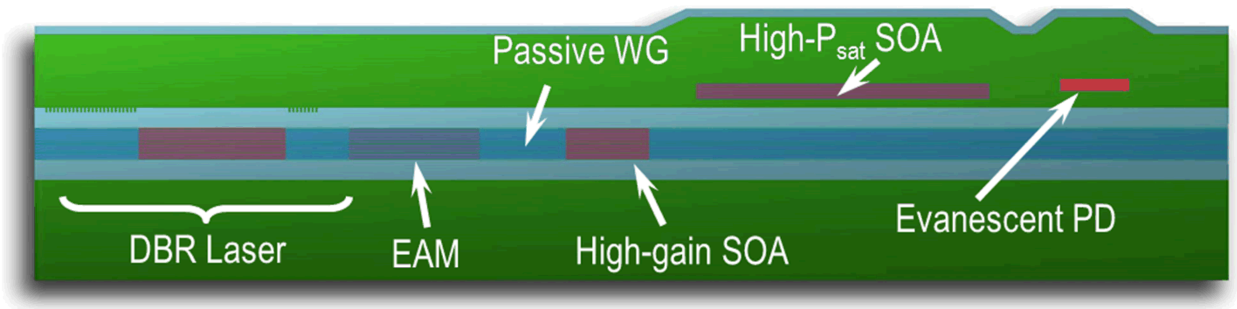
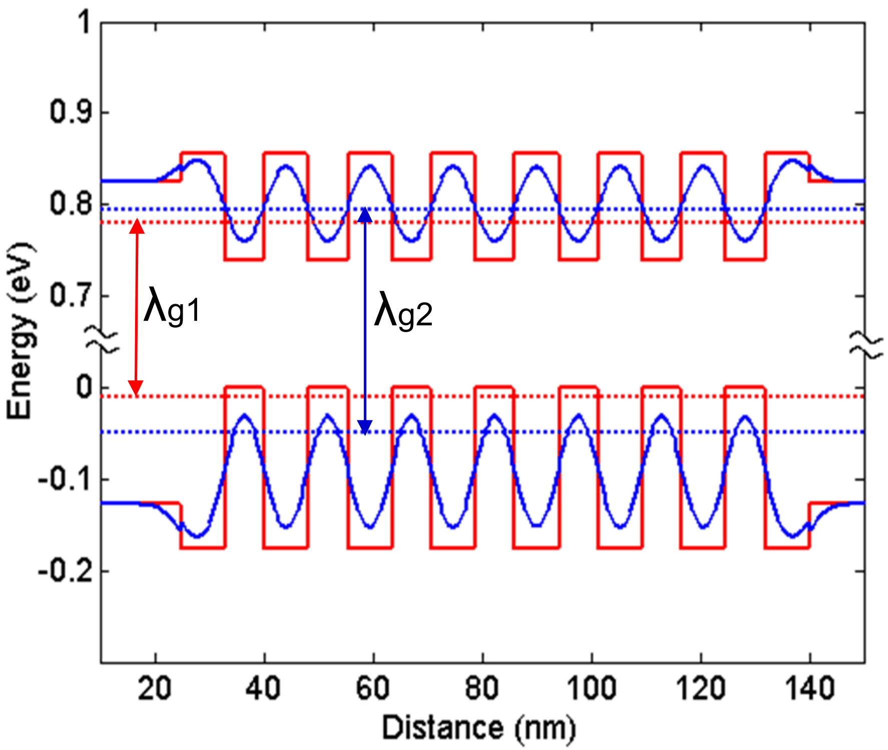
    - Resistors
    - Capacitors
  - Partner with customers to create custom circuits such as:
    - Transmitters
    - Receivers
    - Optical logic gates
    - Optical RF channelizers
    - Coupled-cavity lasers

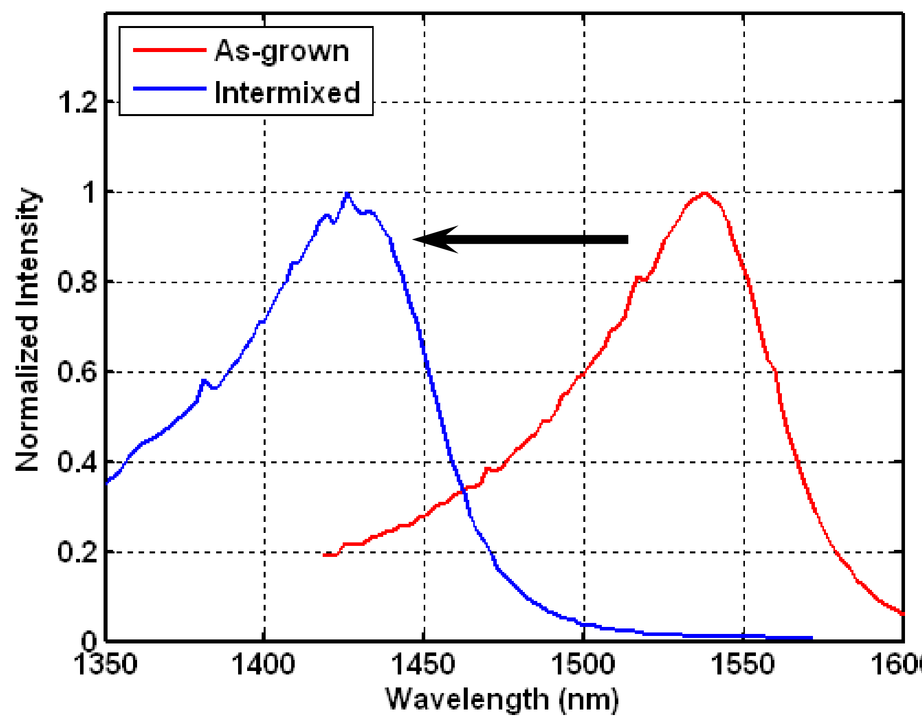


Monolithic Integration Platform

- Quantum well intermixing
  - Metastable interface between well/barrier
  - Add catalyst to enhance interdiffusion
  - Reshaping increases the energy level
    - Reduces the bandgap wavelength

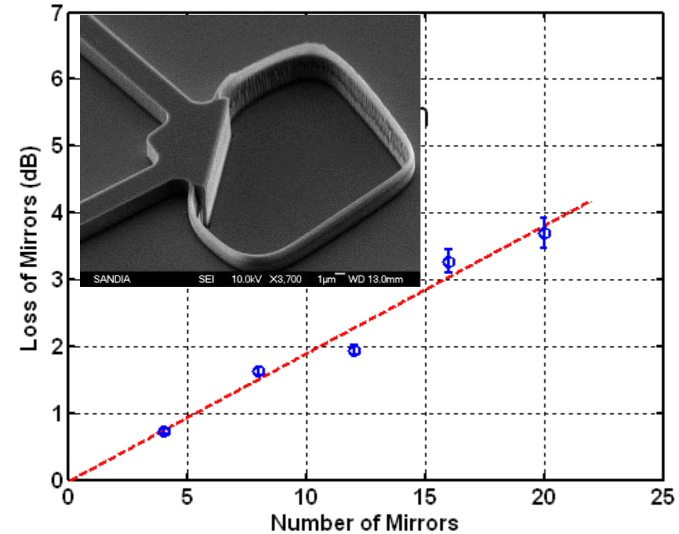


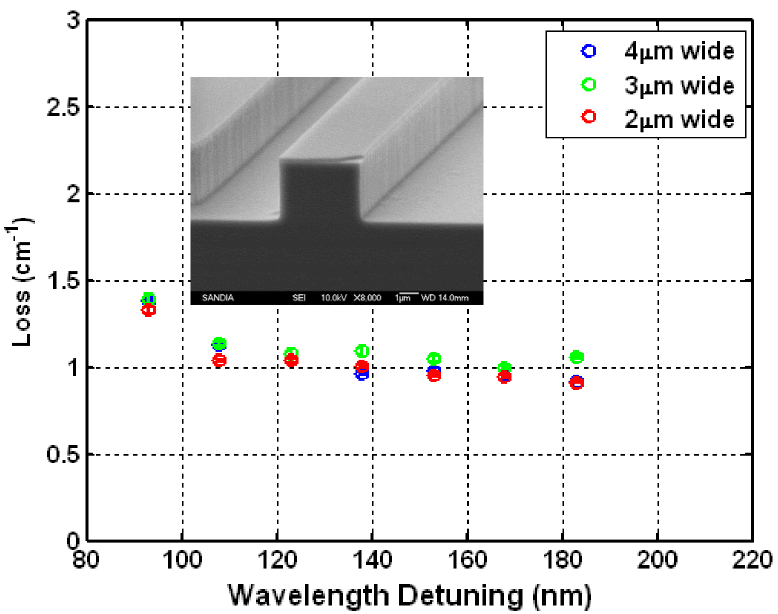
- Photoluminescence
  - Active =1540nm, Passive = 1425nm

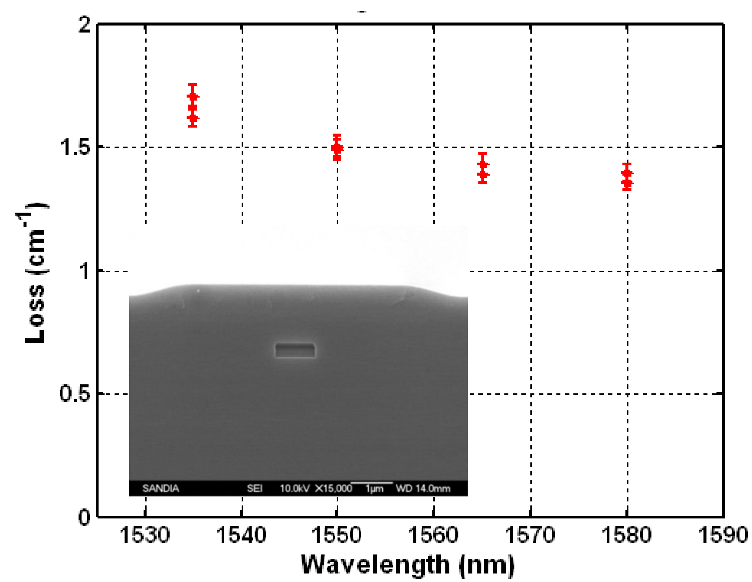


Waveguides and Mirrors

- Ridge waveguide formed by dry etch
  - 1 cm^{-1} loss in doped waveguide
- Buried heterostructure waveguides
  - 1.5 cm^{-1} loss at 1550 nm in doped waveguides
- Total internal reflecting mirror
  - Deep etched mirror face
  - Low loss: 0.19 dB/turn (96% transmission)

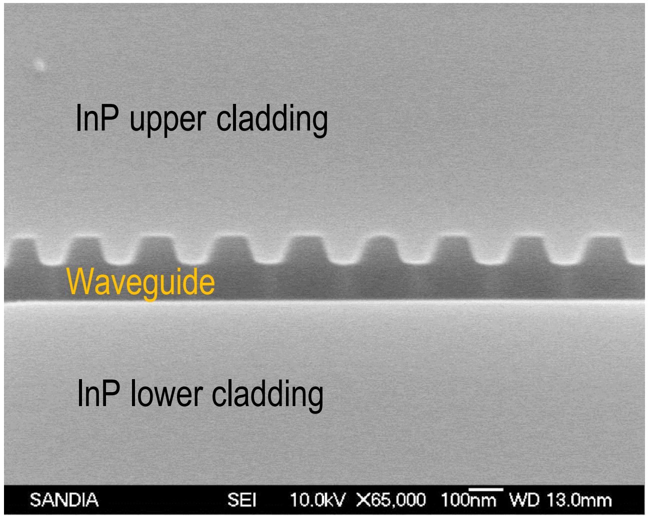


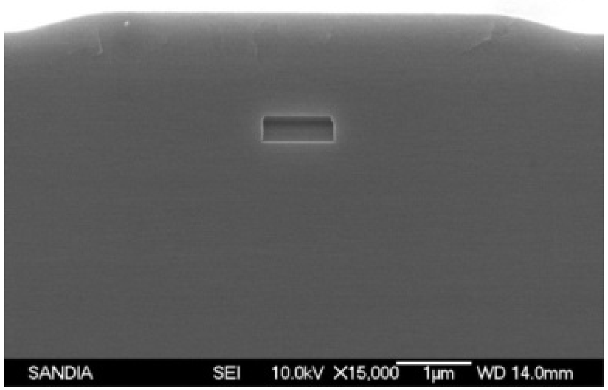


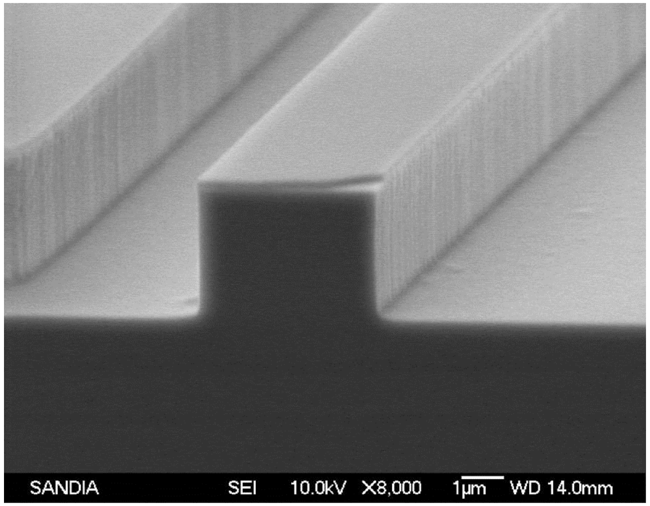


DBR Gratings and Regrowth

- Gratings
  - Used for laser mirrors
  - Defined with ebeam lithography
  - Etched into waveguide
- Single blanket regrowth
  - Fill in the gratings
  - Provide the upper p-contact
  - Form the upper cladding of waveguide

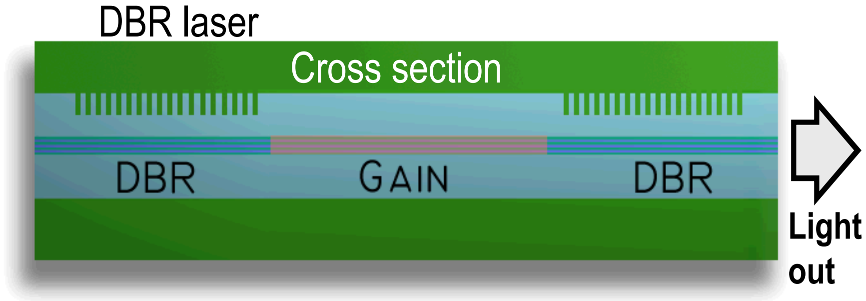


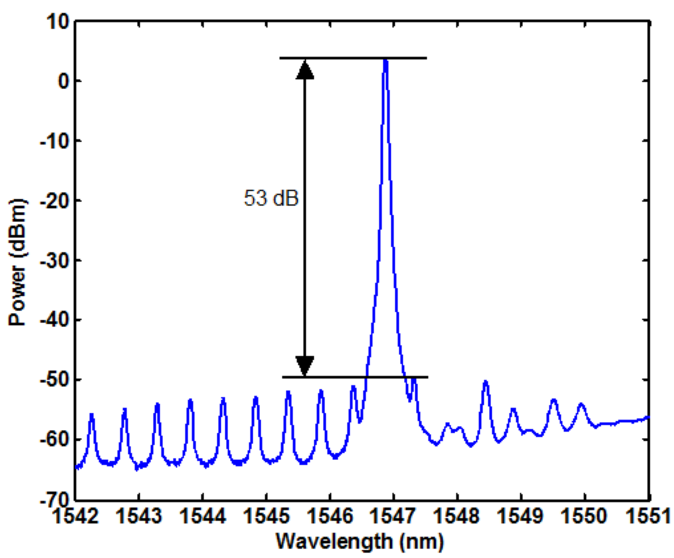


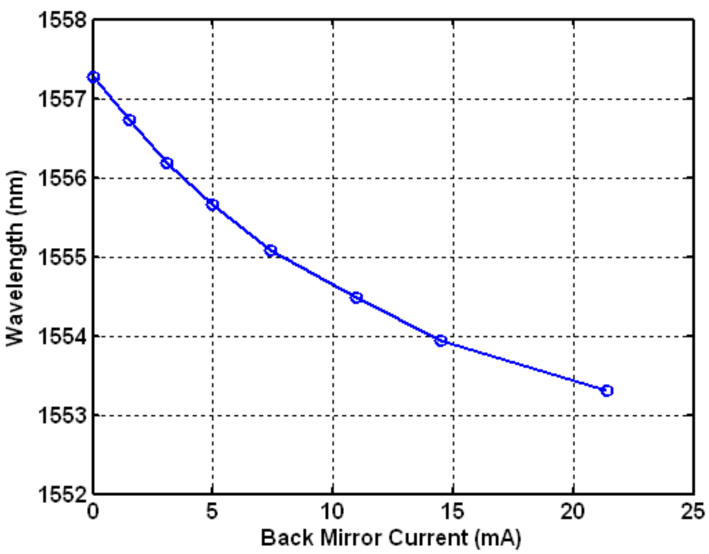


DBR Laser Technology

- DBR Laser Characteristics
  - Threshold: 10 mA
  - Output power: 20 mW
  - Side-mode suppression: >50 dB
  - Tuning: ~4 nm

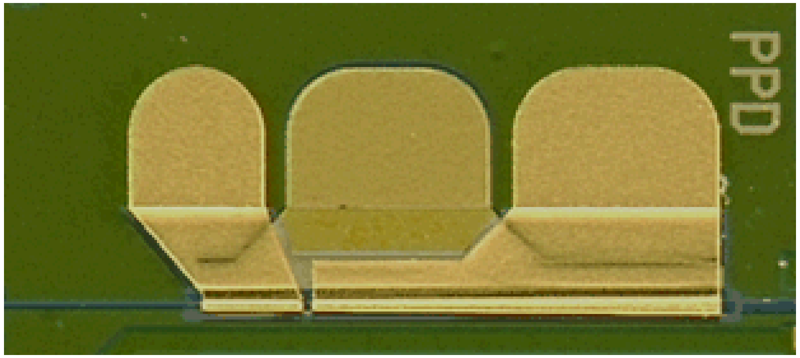


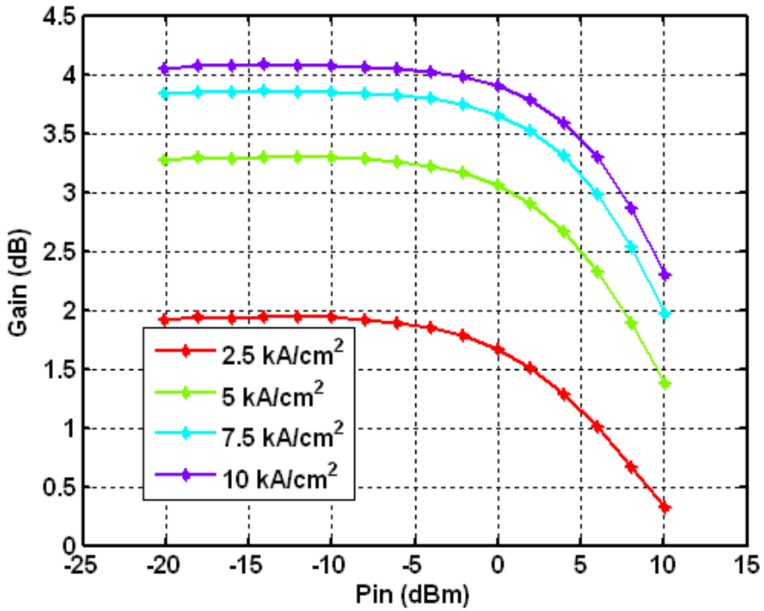




Semiconductor Optical Amplifiers

- Optimize for application
- High confinement factor
  - High gain
    - 435 dB/cm gain
- High saturation power
  - High confinement QWs
    - 10 dBm 1-dB saturation
  - Flaring to reduce power density
    - 13.2 dBm 1-dB saturation
  - Reduced optical confinement factor with offset wells
    - 16 dBm 1-dB saturation



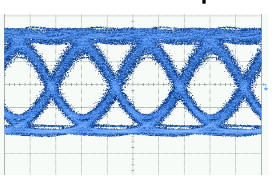


Modulators

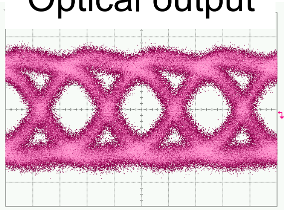
- Electro-absorption modulator
  - Utilize Stark shift in QWs
  - Compact footprint
    - 50-300 um long
  - High extinction efficiency
    - 19dB/V DC
  - High Speed
    - 40 GHz bandwidth
    - Integrated load resistor
- Mach-Zehnder modulators
  - Traveling wave designs
  - High Speed
    - >50 GHz bandwidth
    - Integrated load resistor

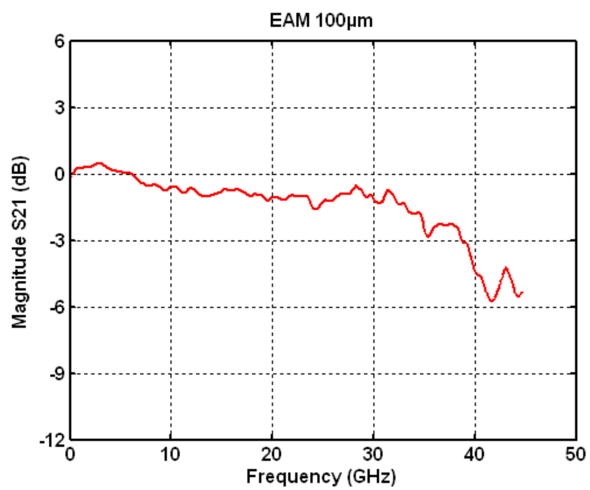
40 Gb/s eye patterns

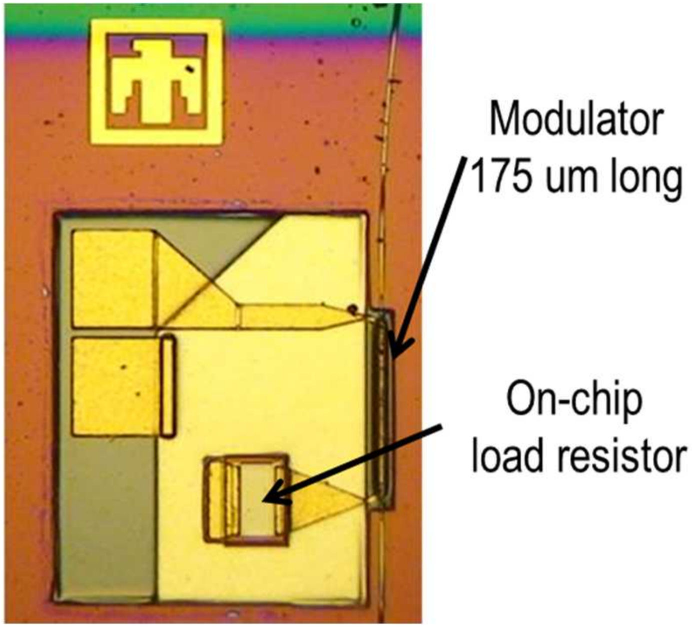
Electrical input



Optical output



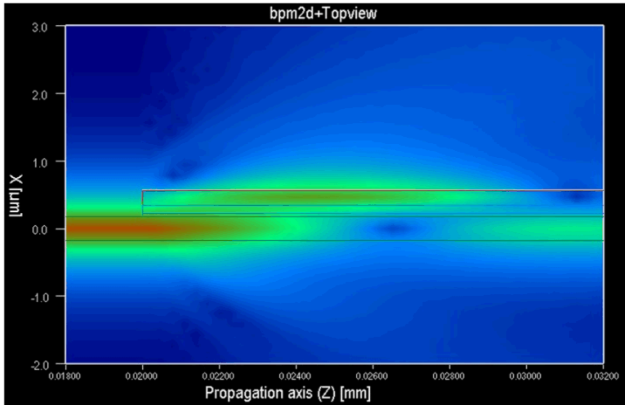


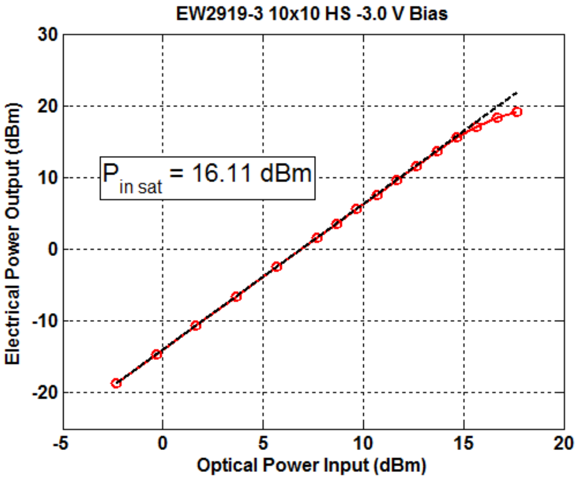


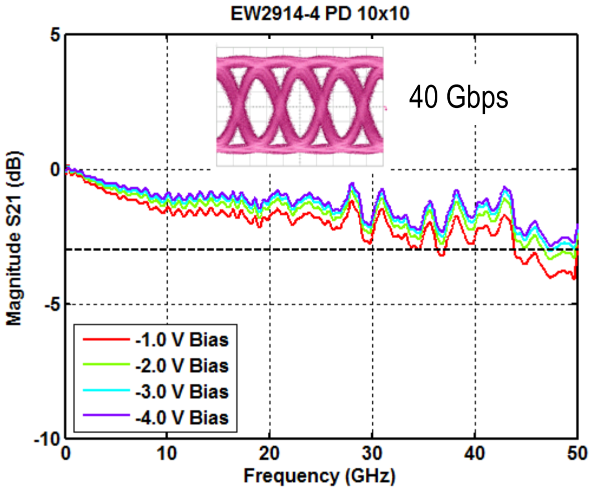
High-speed, High-power Photodetectors

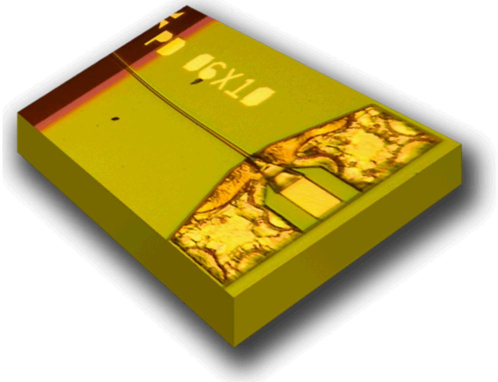
Sandia National Laboratories

- Bulk, evanescently coupled photodiode
- > 40 GHz bandwidth
- 90% quantum efficiency
- 1.12 A/W responsivity at 1550 nm
- 16.11 dBm (>40 mW) input saturation power



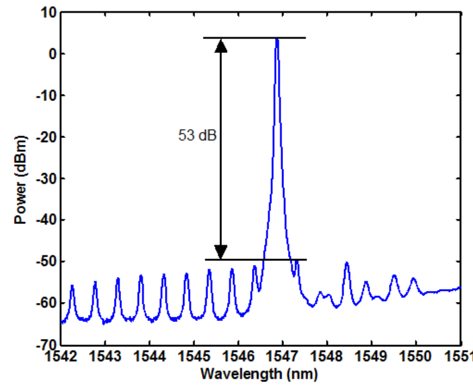


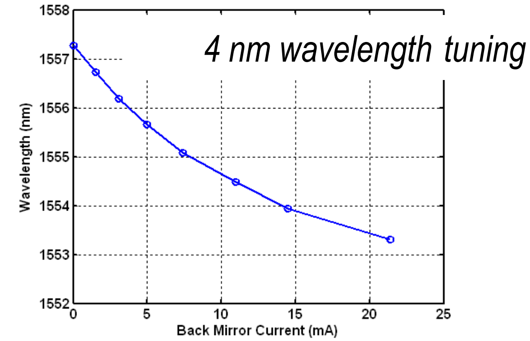




E. Skogen, *et al.*, Photonics Technology Letters. (2013).

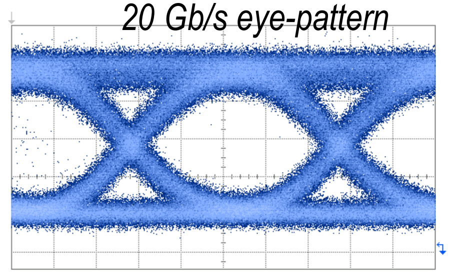
High-Speed Transmitter

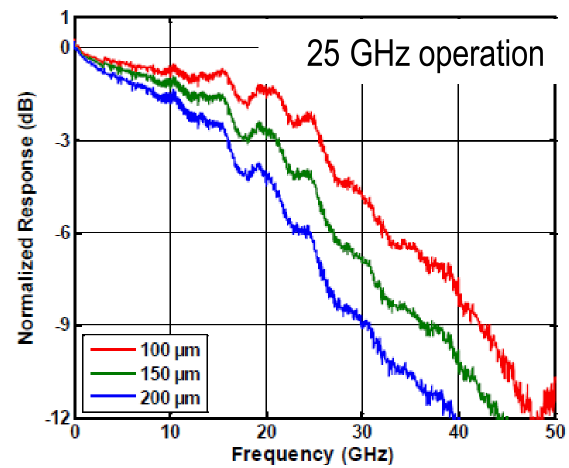




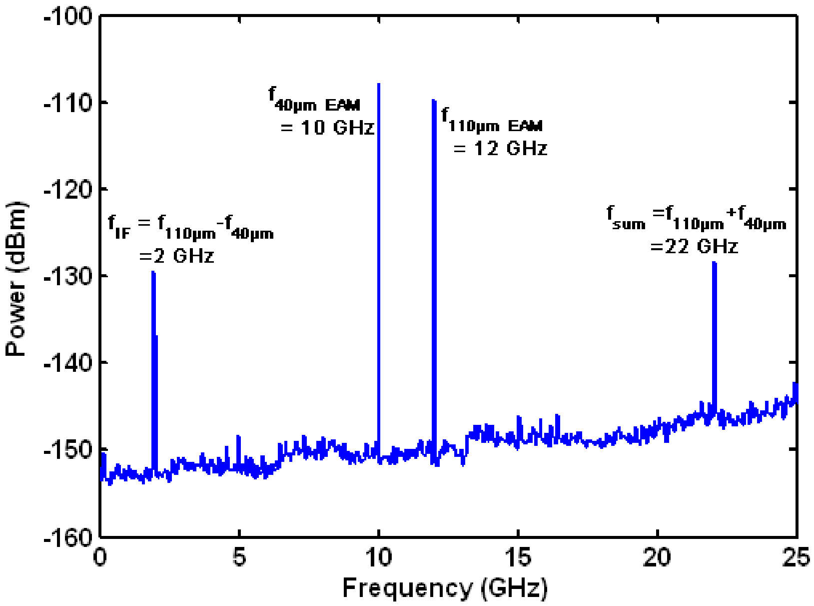
- InGaAsP Diode laser and modulator chip
  - DBR lasers
    - 6 mW fiber-coupled power
      - ~20 mW out from chip
    - 4 nm wavelength tuning
  - EAMs
    - Efficiency ~19dB/V DC
    - Bandwidth 20GHz
- Wavelength tuning
  - Track filter frequencies
  - Tune to WDM channels

20 Gb/s eye-pattern

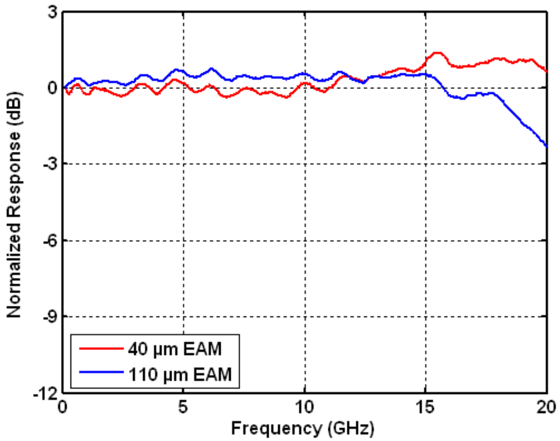




Ultra Compact Optical Heterodyne

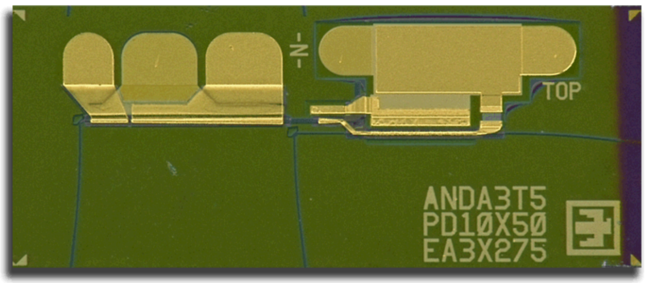


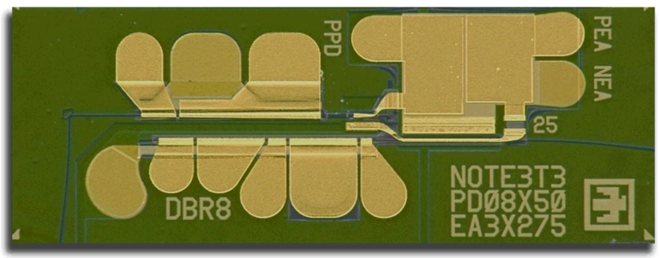
- DBR laser integrated with two EAMs
- Optical downconversion for RF signals
- f_{Mod1} = 10 GHz; f_{Mod2} = 12 GHz
  - $P_{electrical\ input}$ = 5 dBm for both EAMs
- 2 GHz IF signal

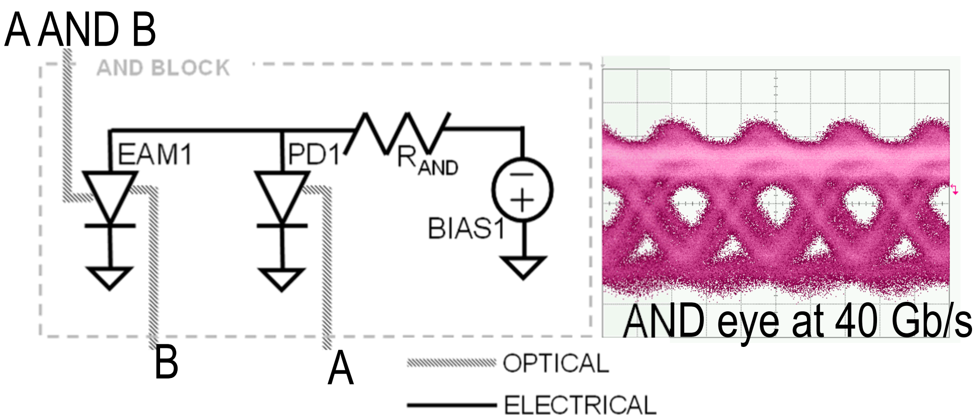


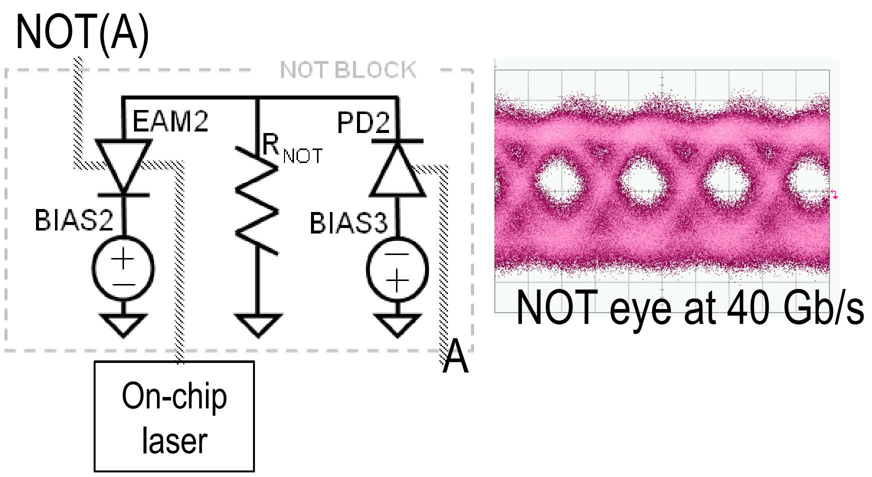
All-Optical Logic Chips

- EAMs, PDs, DFB lasers, etc. integrated to form all-optical logic gates
  - AND, NOT gates operating at 40 Gb/s
  - PDs detect input light and drive EAMs to modulate output

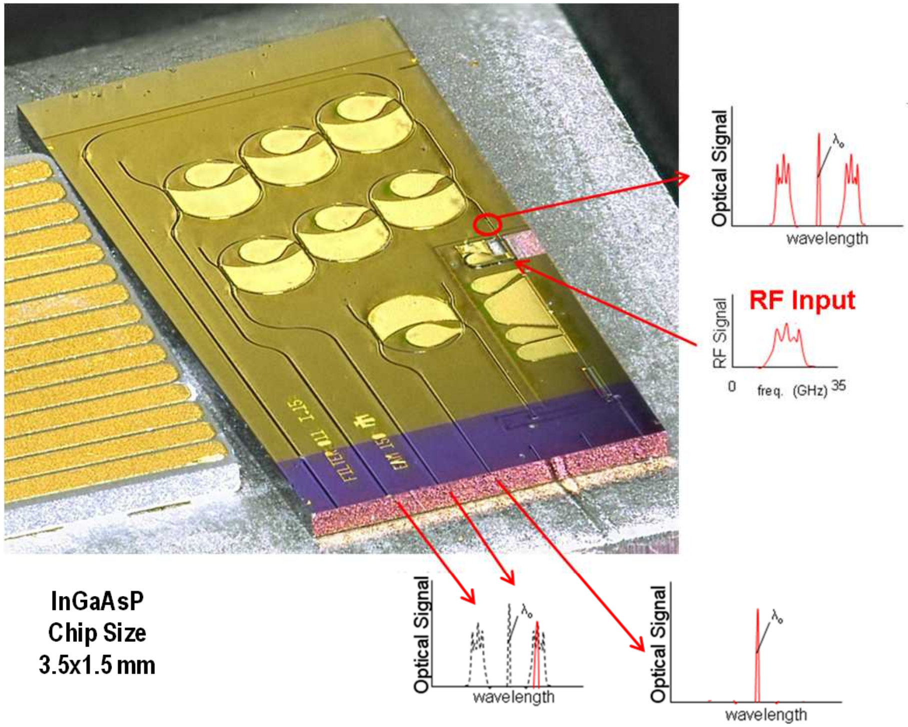


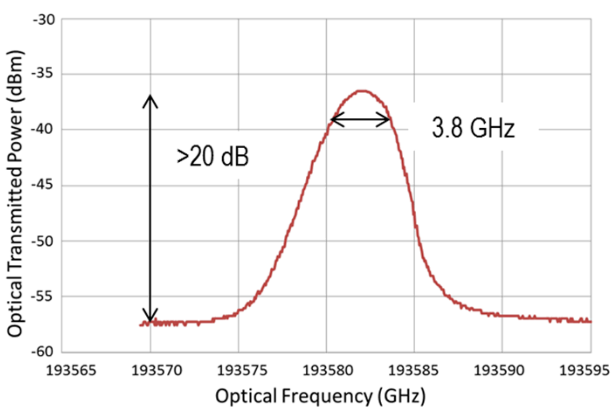


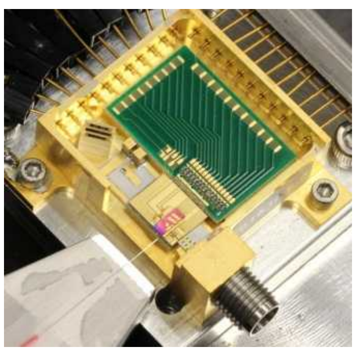




Optical RF Channelized Receiver







- Analyze an RF signal for frequency content
  - Filter outputs are spectral power density integrated over the filter bandwidth
- Compact, highly functional photonic integrated circuits (PICs) features:
  - 3-pole ring resonator filters
    - Tunable over 10's GHz
    - GHz-class pass bands
    - 65 GHz free spectral range
  - Integrated laser-modulator
    - RF input provides signal to EAM
  - Integrated extra filter for wavelength monitoring

Summary

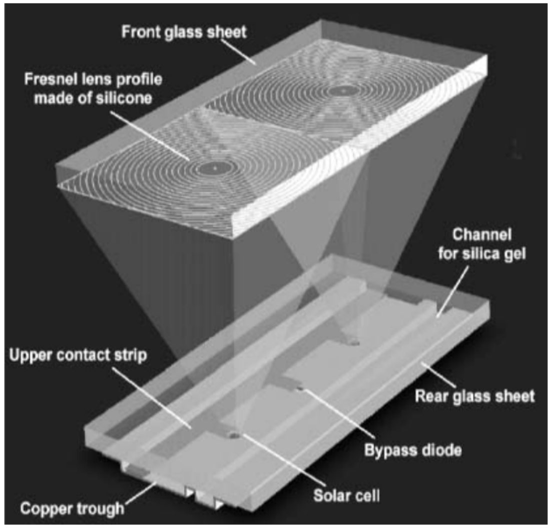
- Sandia has created a wide array of PICs using a common toolkit
- PICs continue to evolve and impact applications outside of telecommunications and datacom including:
  - optical signal processing, sensors, fundamental device research, RF photonics
- InP PICs offer unique capabilities as standalone circuits and can be complementary to other platforms
- Performance of individual components rival discrete counterparts

Outline

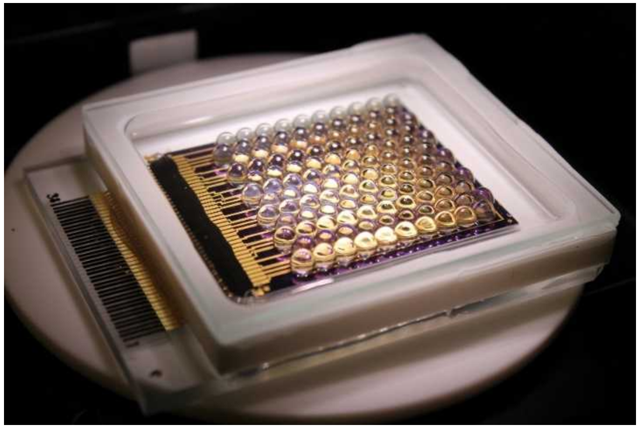
- Overview of Sandia National Laboratories
- InP-based Photonic Integrated Circuits
- Microsystems Enabled Photovoltaics
- Conclusions

Microsystems Enabled Photovoltaics

- Utilizing small cells can enable many benefits:
  - Thinner modules
  - Increased tolerance to shading and cell failures
  - Refractive optics with larger acceptance angles and lower loss
    - Reduce balance of system costs
  - Concentrated systems with flat plat form factors
    - 2 cm instead of >20 cm
  - High efficiency flexible cells



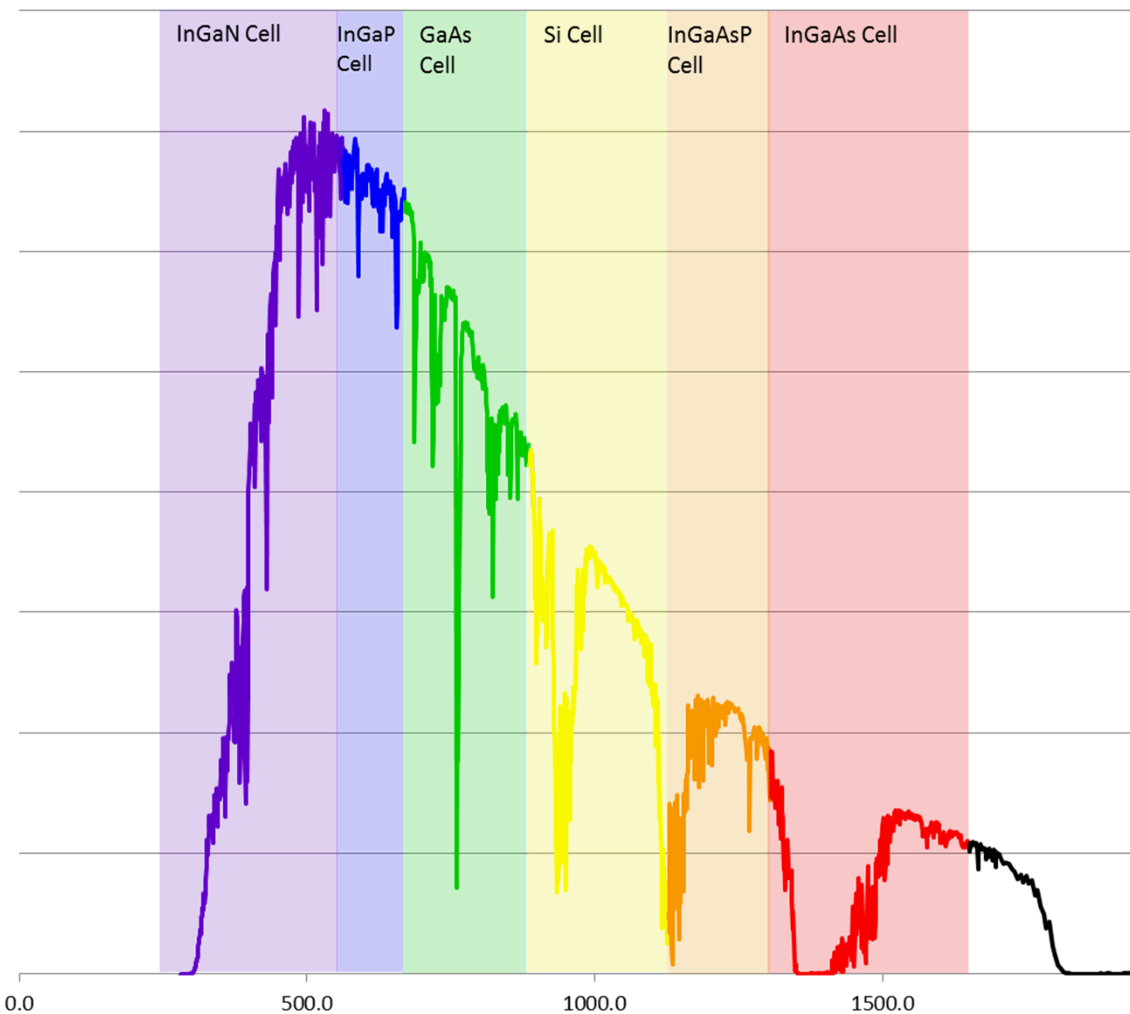
Typical structure of a CPV module



MEPV concentrated PV module

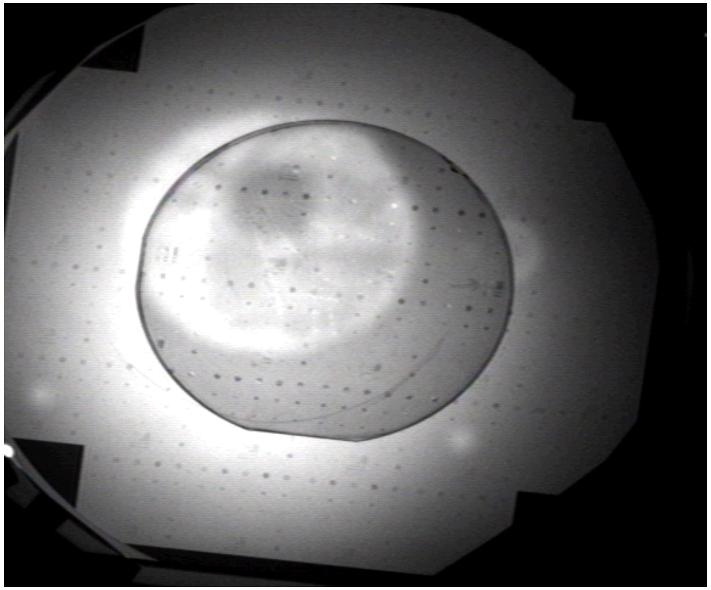
MEPV Multi-junction Solar Cells

- Multi-junction cell design for increased efficiency by collecting photons at a bandgap close to their energy level
- Independent connections for all cell contacts allow for greater versatility
- Utilizing wafer bonding for integration of lattice mismatched designs



III-V Cells to Si Integration

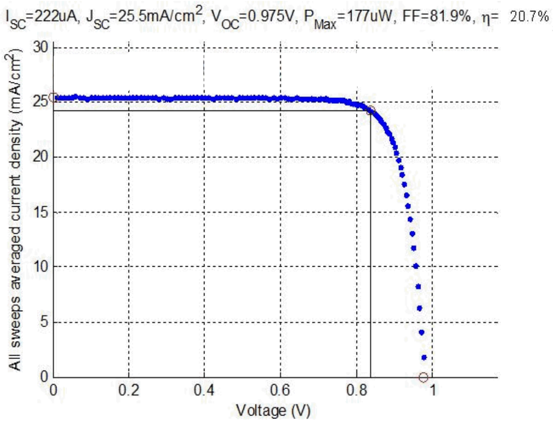
- Integration method
  - Optically transparent
  - Electrically isolating
  - Wafer scale
  - Compatible with epitaxial liftoff
- Approach: Wafer bonding
  - Dielectric bond interface
    - Designed to be 97% transparent
  - Substrate release following bonding
    - Aided by forming mesas prior to bond
  - III-V cell processing following the bond



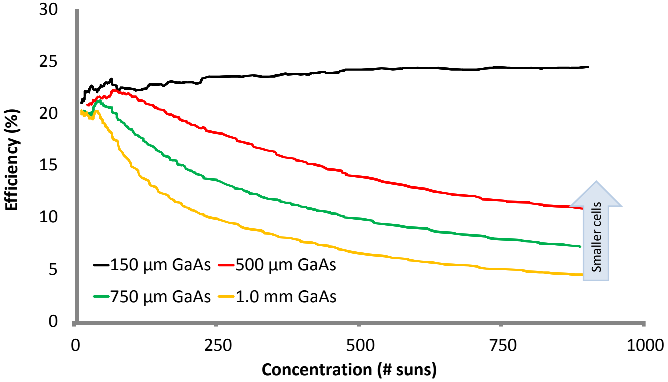
IR camera image of GaAs wafer bonded to Si

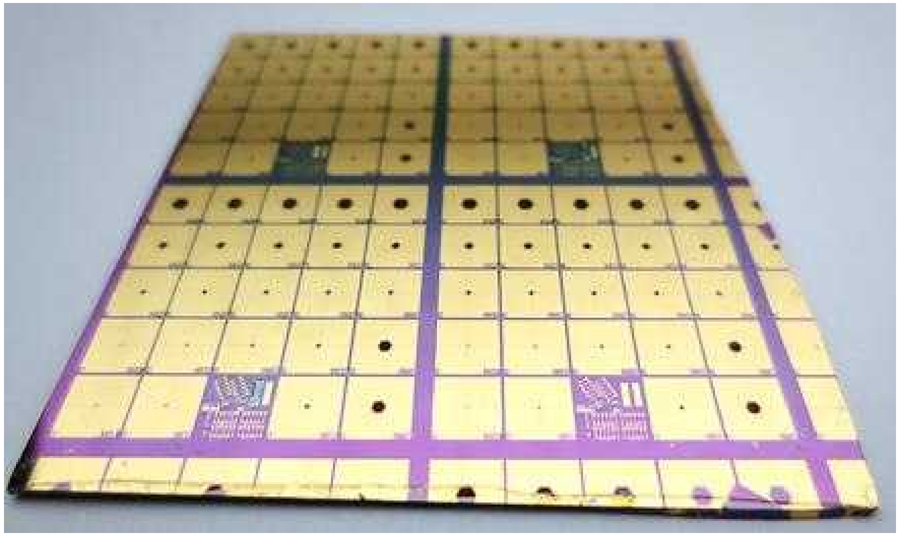
GaAs cells on Si

- Demonstrated efficiency of 20.7%

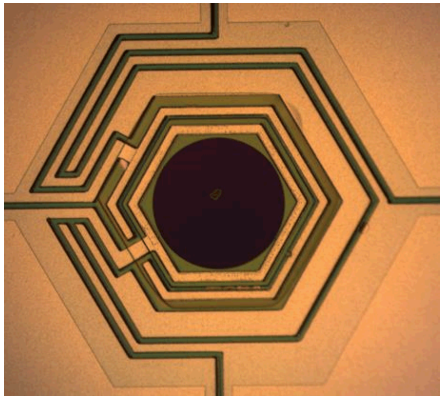


- Smaller cells are optimal at higher concentrations





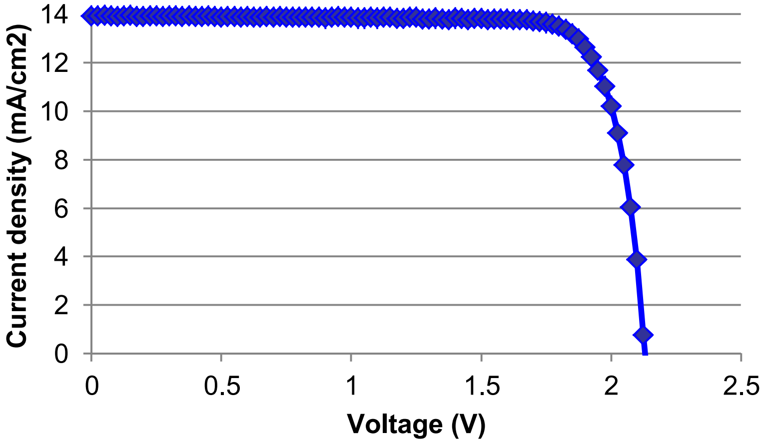
Array of bonded GaAs cells

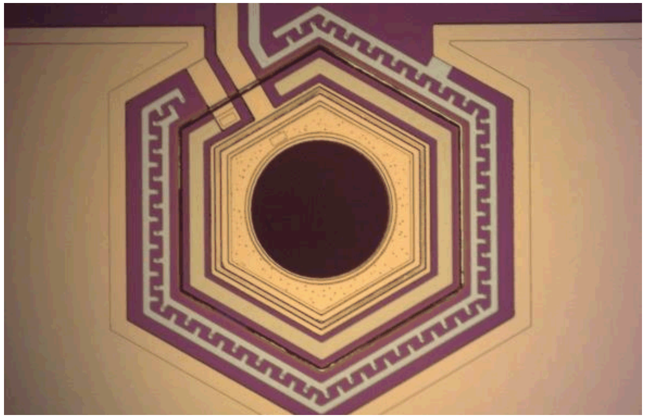


Detail of bonded cell

InGaP/GaAs Bonded Cells

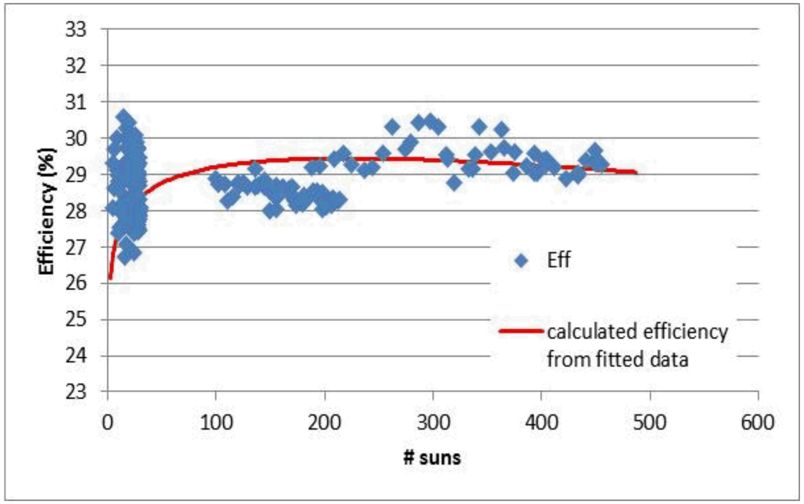
- Demonstrated efficiency of 26%





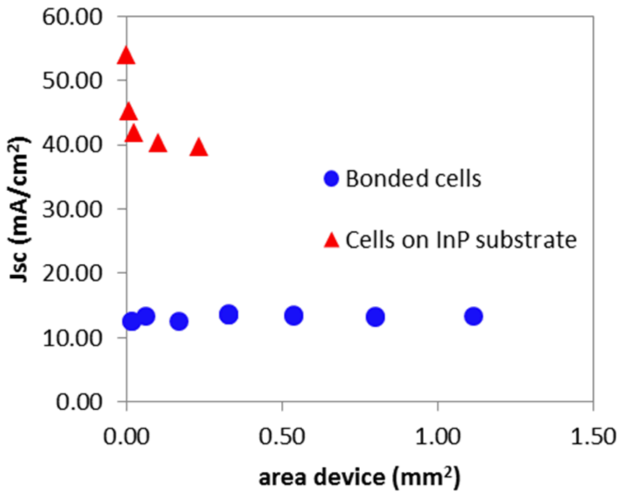
InGaP/GaAs cells bonded to Si

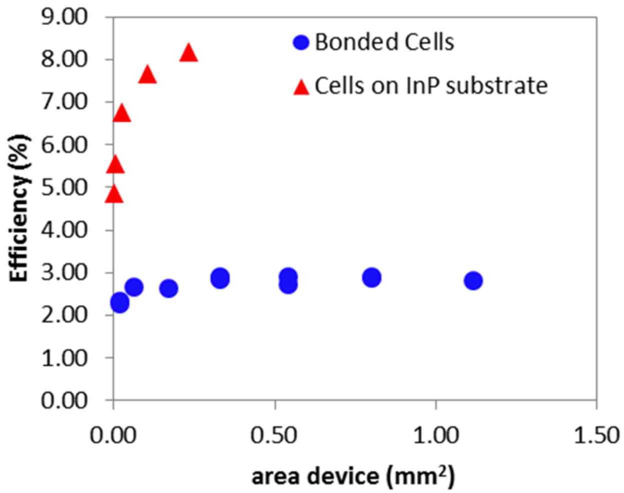
- Maximum efficiency of 29.5% with 200 sun concentration

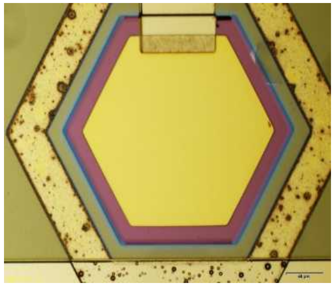


2.9% Efficient InGaAs Cell with no Observed Performance Degradation due to Bonding

- Performance of bonded cells
  - 2.9% efficient 'bottom' junction
    - Light above 1.1 eV is filtered by the Si wafer
    - Theoretical maximum of 6%
  - Maximum short circuit current is within 97% of theory
- Comparison to on substrate devices
  - Higher efficiency and short circuit current
    - Due to lack of Si substrate to filter the light
  - Similar open circuit voltage and fill factor
    - No observed degradation in device performance due to bonding

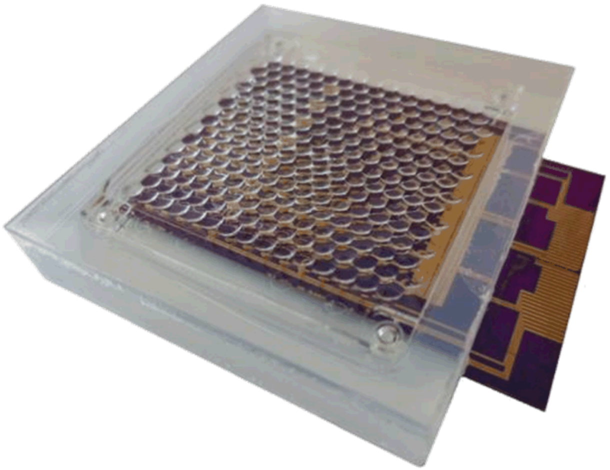


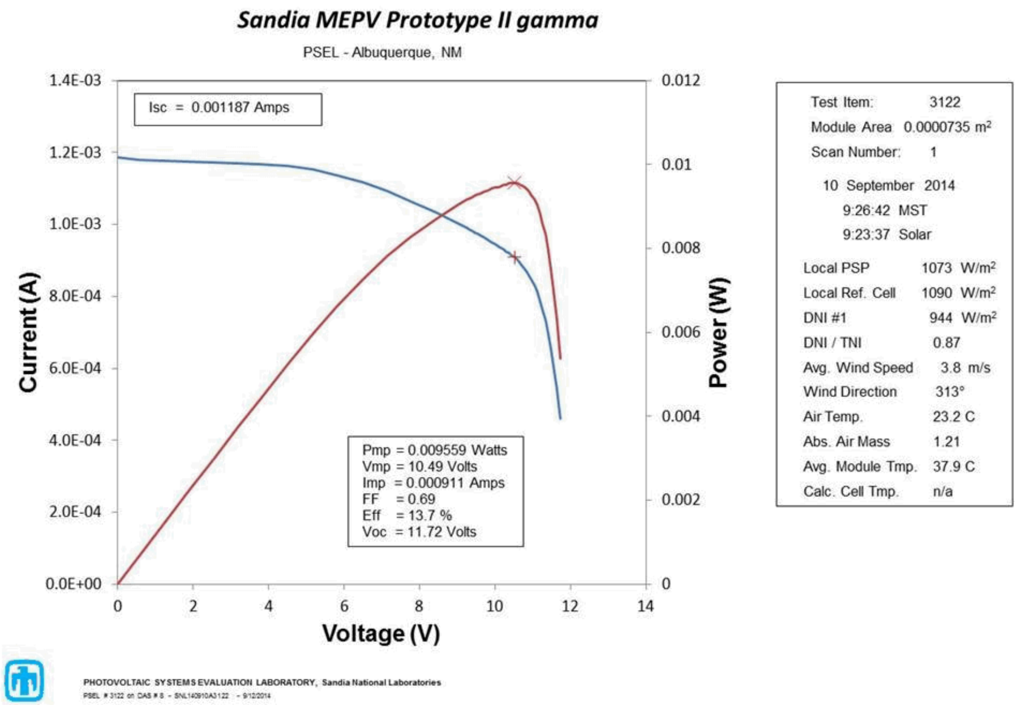




MEPV bonded InGaAs solar cell

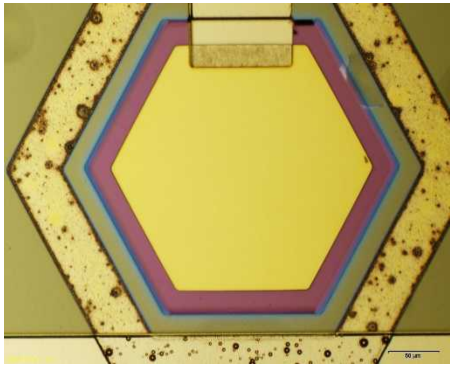
Outdoor Characterization

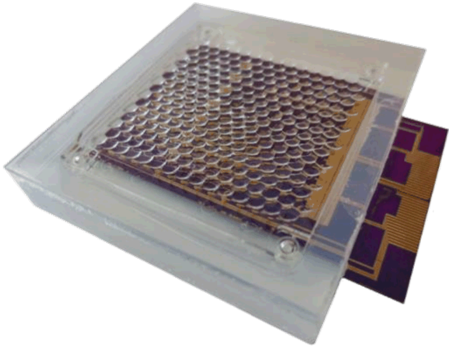


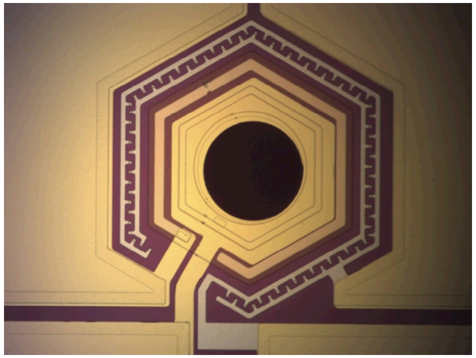


Conclusions

- A path to multi-junction cells free from lattice-matching and current-matching constraints has been shown using wafer bonding
  - Bonding of processed wafers gives increased flexibility
  - Applications in other areas of integrated photonics
  - Scaling is still an issue
- No degradation in performance observed due to bonding
- III-V cells show efficiencies typical of unbonded cells
  - Bonded InGaP/GaAs efficiency of 26% at 1 sun (29.5% at 200 suns)
  - Bonded InGaAs efficiency of 2.9% at 1 sun
- MEPV modules are shown with flat plate form factors
  - Has the potential to change the BOS costs of concentrated PV







Exceptional service in the national interest

Sandia National Laboratories

Thank You

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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