Boron Gallium Arsenide Alloys for Photodetectors on Silicon

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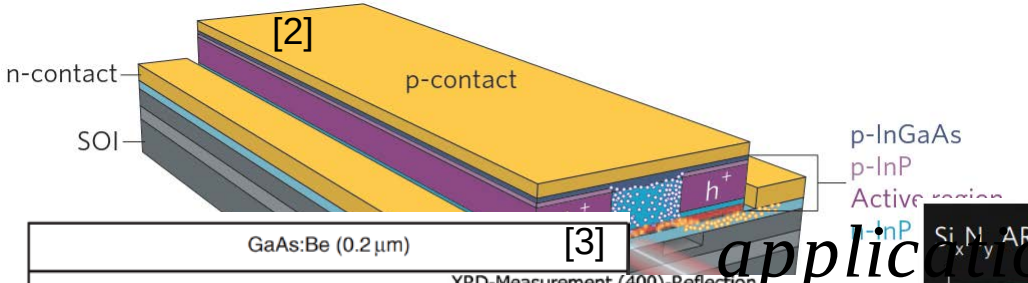
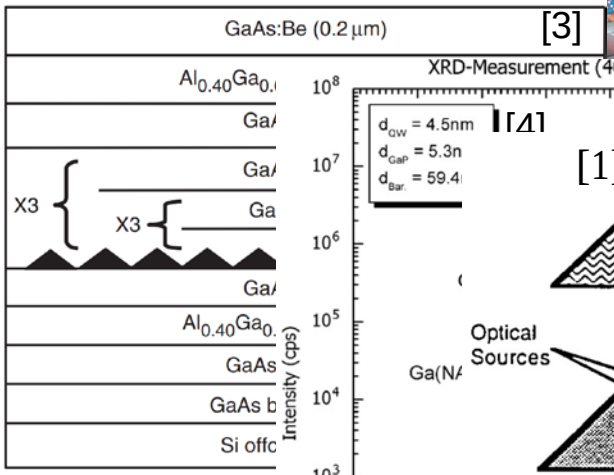
Laboratory for Advanced Semiconductor Epitaxy

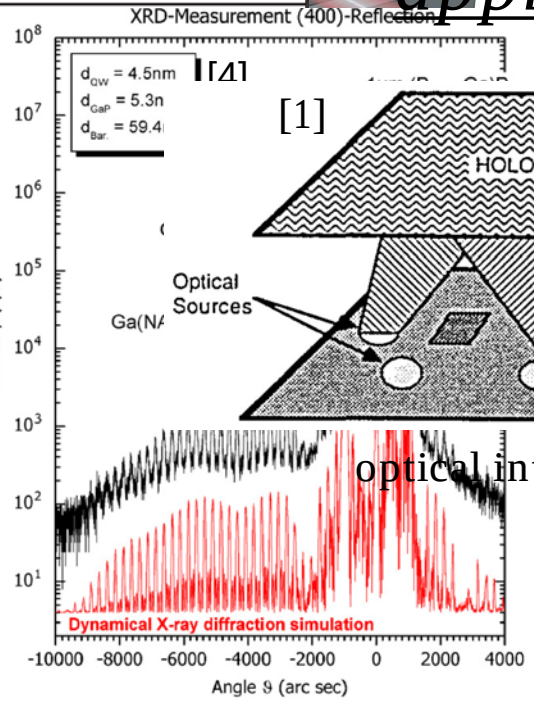
LASE

Challenge: direct-gap materials on silicon

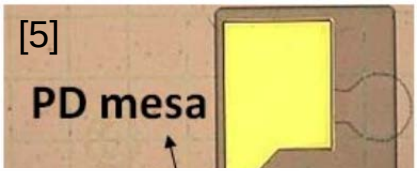
emitters



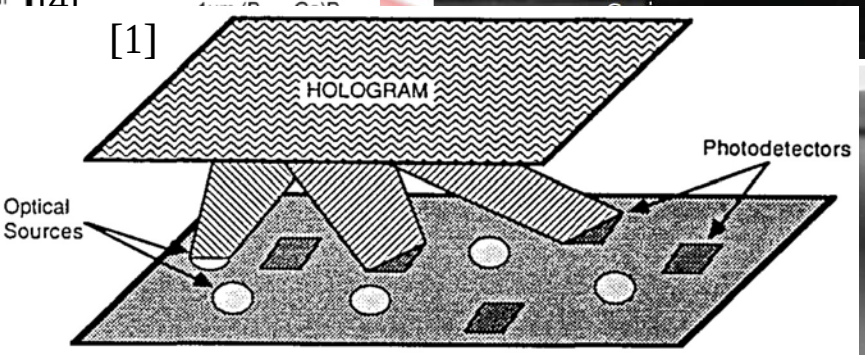




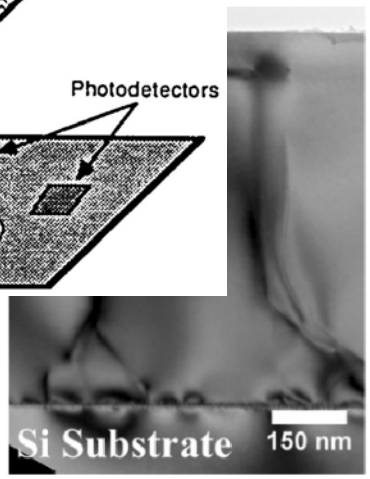
detectors



applications

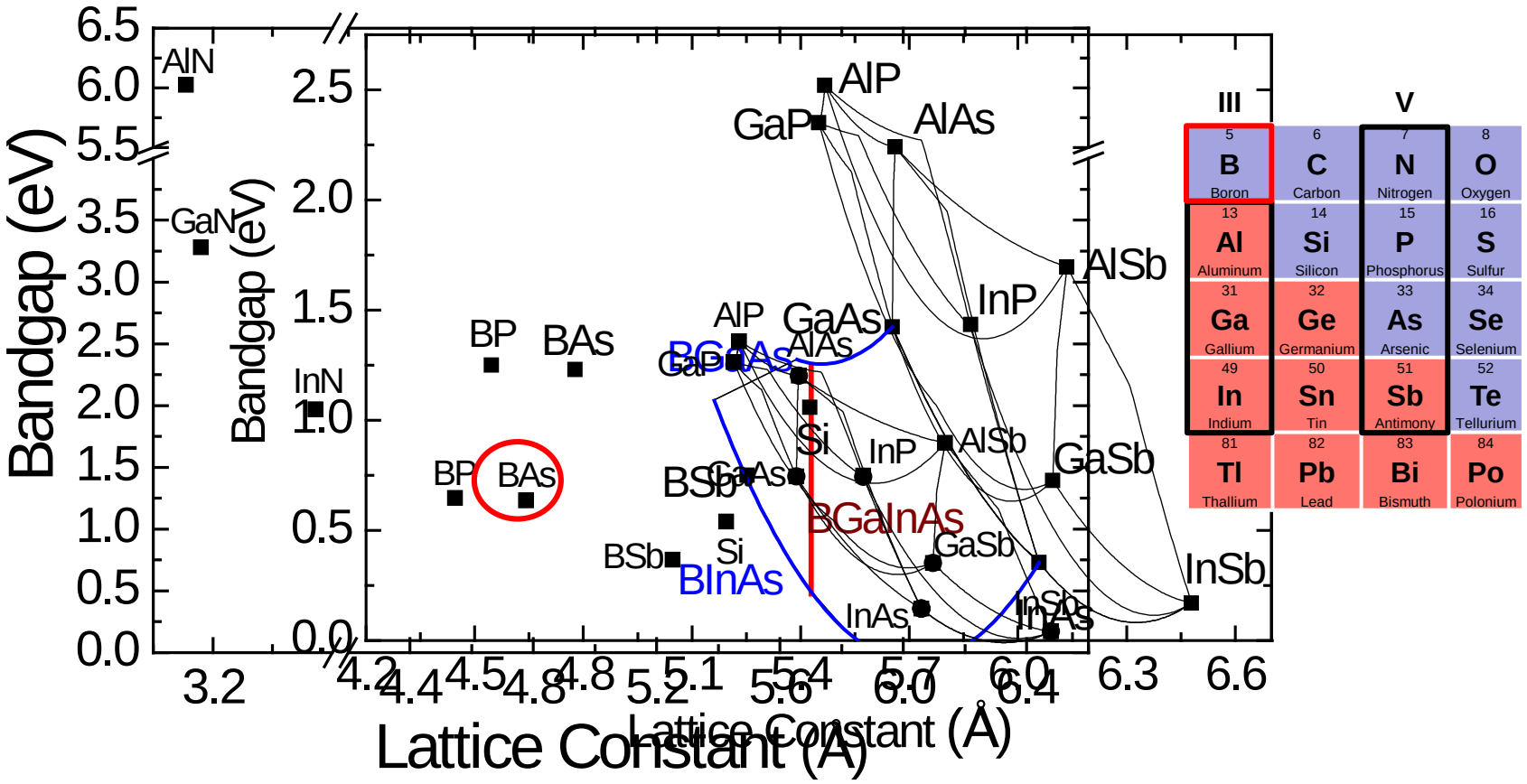


optical interconnects



[1] M.R. Feldman, Appl. Opt. (1988)
[2] Fang et al., Opt. Express (2008)
[3] Mi et al., Electron. Lett. (2005)
[4] Kunert et al., J. Cryst. Growth (2008)
[5] Beling et al., IEEE J. Quantum Electron. (2015)
[6] Kang et al., Nature (2008)
[7] Conley et al., Opt. Express (2014)

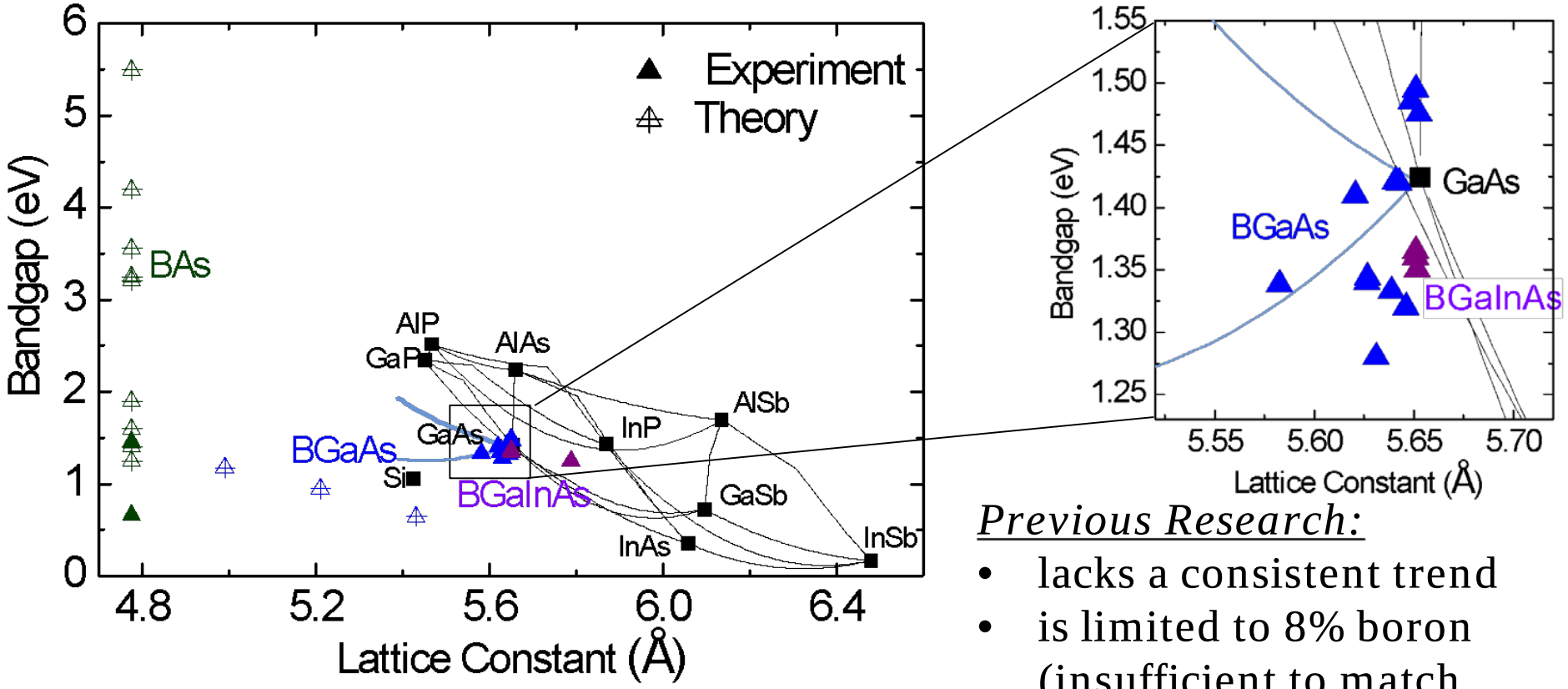
‘New’ III-V material to lattice-match silicon



- No *good* previous approach to lattice-match direct bandgaps to silicon
- Small lattice constants → new strain engineering opportunities
- Lattice-matched direct gap alloys by incorporating boron

A Zaoui et al. J. Phys.: Condens. Matter 13 (2001)
S. Azzi et al. Solid State Communications 144 (2007)

Need for characterization of BGaAs



Previous Research:

- lacks a consistent trend
- is limited to 8% boron (insufficient to match silicon's lattice constant)
- is limited by growth constraints to relatively poor quality material
- devices have never been reported

S. M. Ku, *J. Electro. Soc.* 1966.
D. J. Stukel, *Phys. Rev. B*, 1970.
T. L. Chu et al, *J. Electro. Soc.*, 1974.
M. P. Surh et al., *Phys. Rev. B*, 1991.
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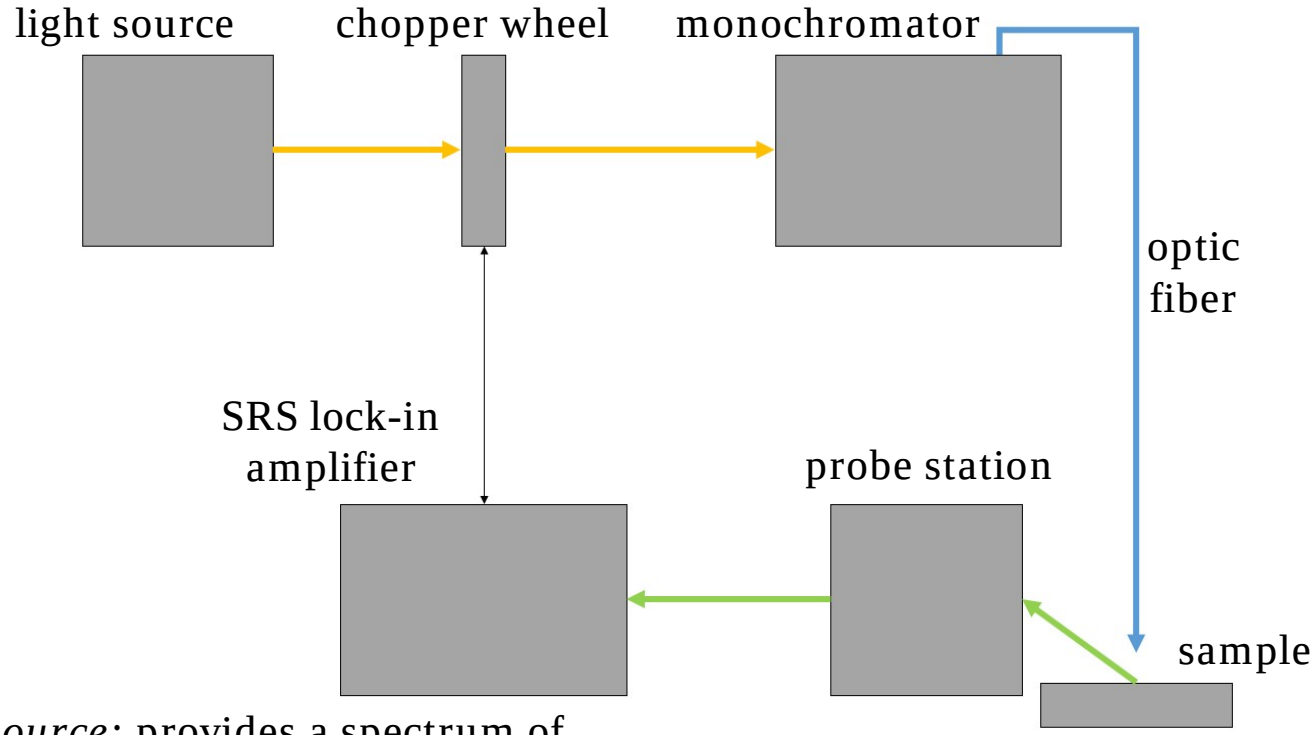
J. F. Geisz et al., *App. Phys. Let.*, 2000.
V. Gottschalch et al. , *J. Crys. Growth*, 2003.
W. Shan et al., *J. App. Phys.*, 2003.
F. Saidi et al., *Mat. Sci. Eng.: C*, 2006.
R. Hamila et al., *J. Lumin.*, 2009.
M. Guemou et al., *Phys. B*, 2012.
R. Hamila et al., *J. App. Phys.*, 2012.
S. Ilahi et al, *Physica B*, 2013.

Photocurrent measurement setup design



White Light Source: provides a spectrum of light (all wavelengths)

Chopper Wheel: chops incoming light at a certain frequency synced with the SRS

Monochromator: selects a single wavelength of light

Optic Fiber: transports light to the sample

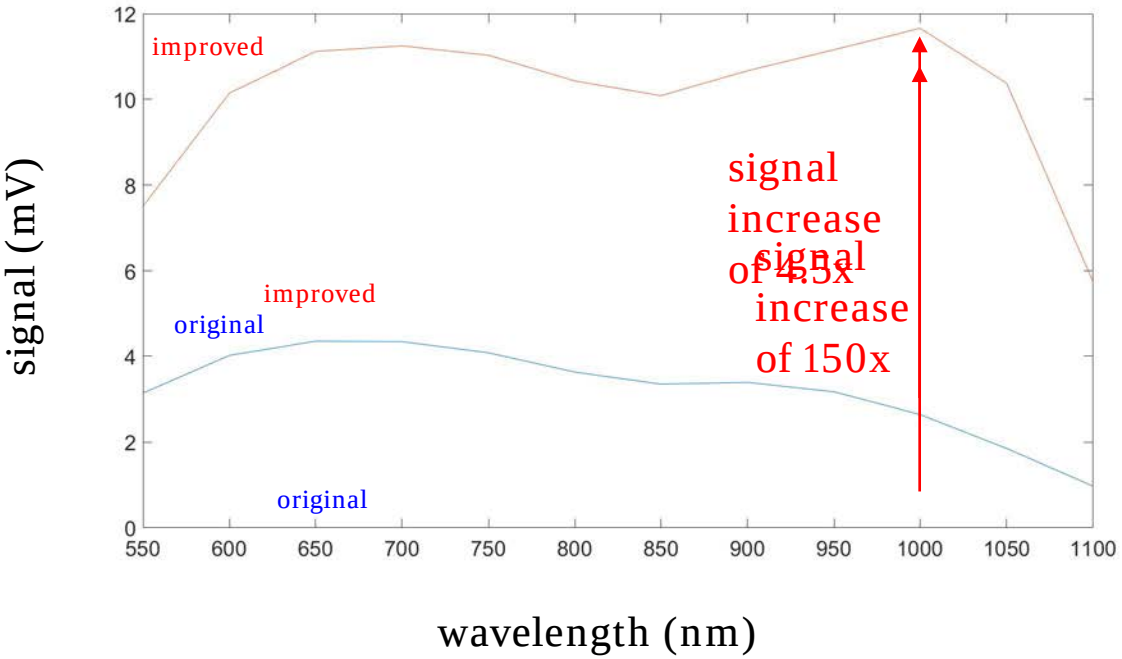
Sample: III-V semiconductor photodetectors

Probe Station: measures signal from photodetector electrodes

SRS Lock-In Amplifier: amplifies and measures the signal from the probe station

Photocurrent measurement setup results

At Monochromator Output:



Signal Increase due to Wider Aperture Optic Fiber Cable

Original Setup
- Max: 4.35 mV
- Min: 0.97 mV

Improved Setup
- Max: 1.66 mV
- Min: 0.95 mV

New White Light Source

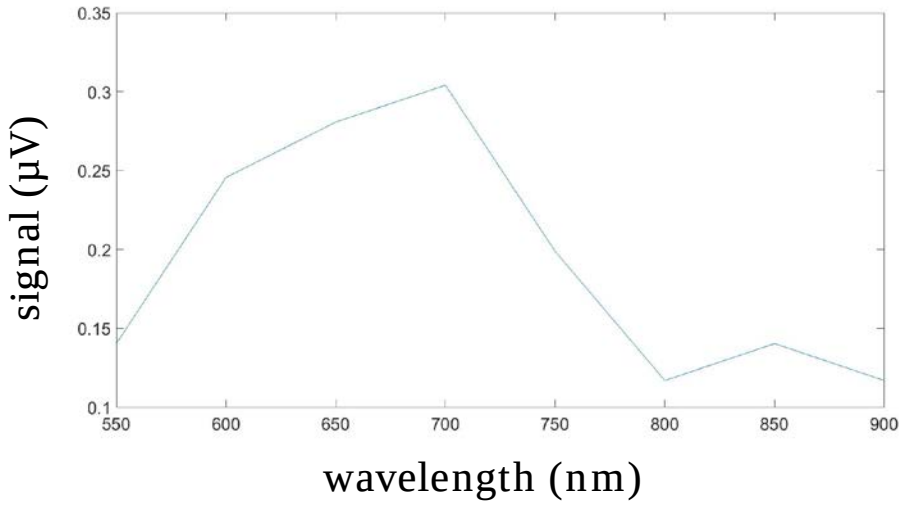
Original Setup
- Max: 0.97 mV
- Min: 0.001 mV

Improved Setup
- Max: 3.54 mV
- Min: 0.95 mV

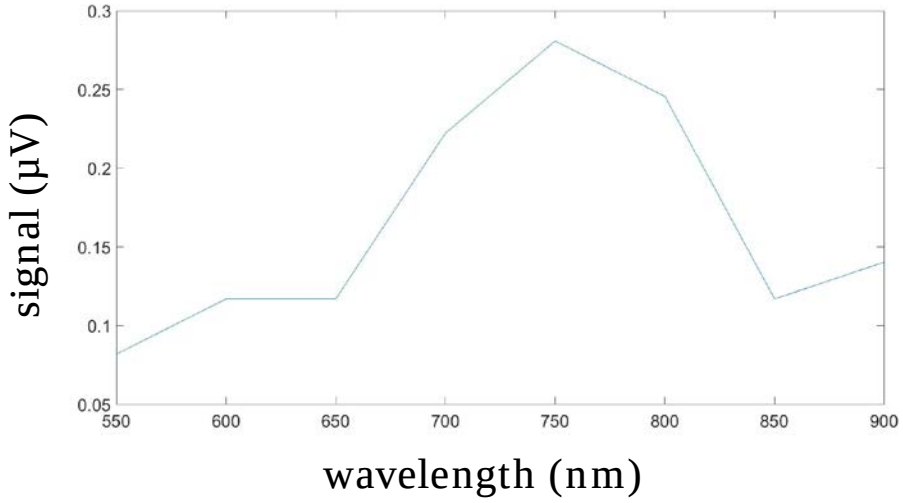
System Improvements:
- Tungsten lamp source -> Supercontinuum source
- Wider aperture fiber optic cable
- Focused optics

Thin film photocurrent results

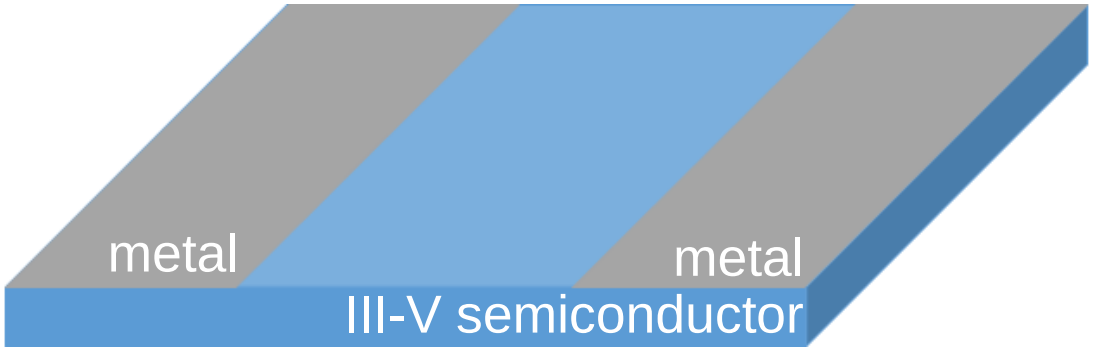
GaAs:



BGaAs:



Photodetector design optimization

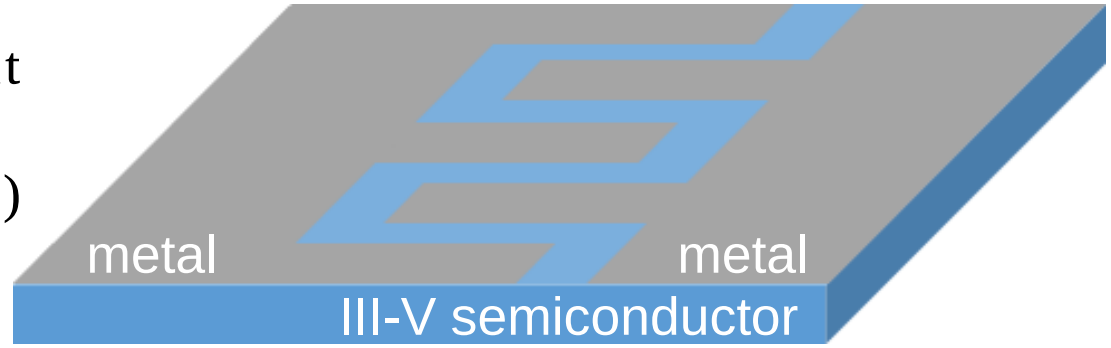


Old MSM Design:

- Higher capacitance
- Lower Shockley-Ramo current
- One step fabrication (metal deposition)
- Larger distance between electrodes

New MSM Design:

- Lower capacitance
- Higher Shockley-Ramo current
- Two step fabrication (lithography, metal deposition)
- Small distance (5-20 μm) between interdigitated fingers of electrodes



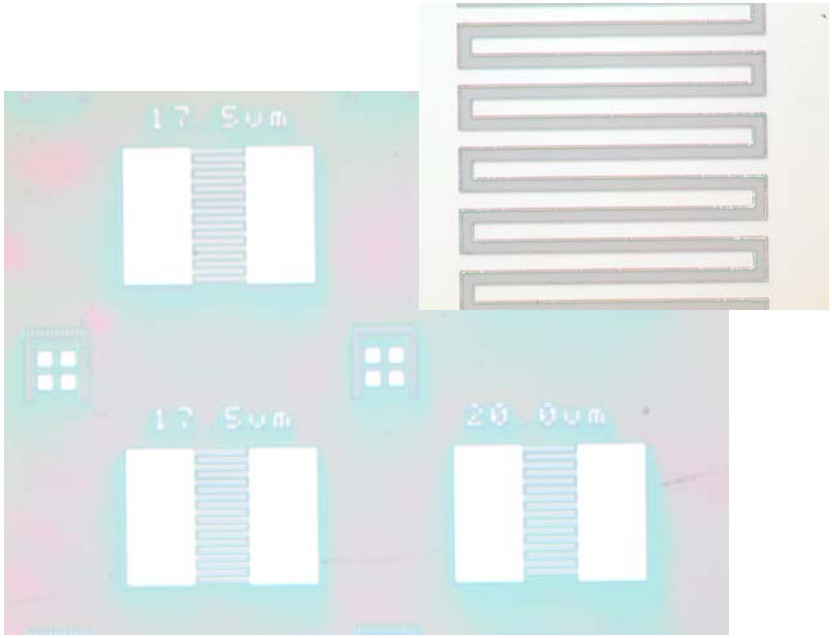
M. Sirkis and N. Holonyak, *J. Phys.*, 1966.

Conclusion and Future Work

A functioning photocurrent measurement setup for thin film devices was designed and assembled. It is one of the only reported photocurrent systems to utilize a supercontinuum source.

Further Work:

- **Investigation of new MSM photodetector design**
- Growth of thicker BGaAs films
- Testing of tunability of the material's bandgap
- Quantification of the material's detection and responsivity
- Doped BGaAs for PiN devices



Acknowledgements

This work is based upon work supported primarily by the National Science Foundation under Cooperative Agreement No. ECCS-1542159, who provided funding for this research.

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Questions?

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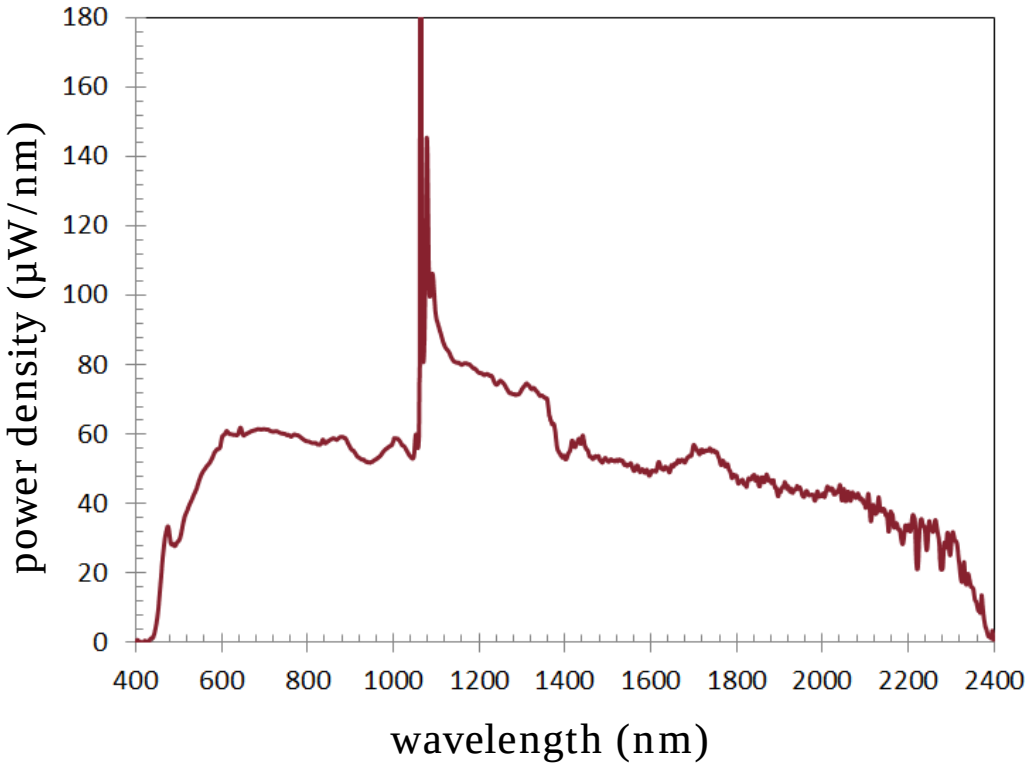
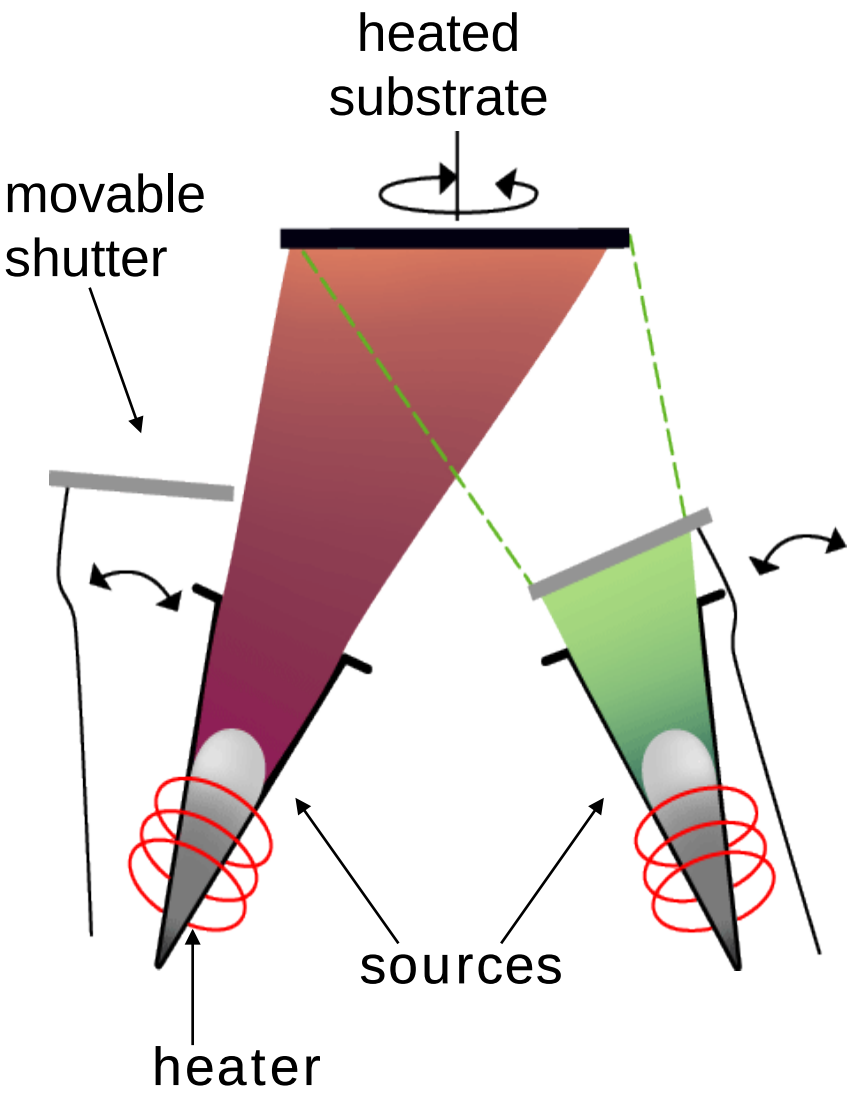
Supercontinuum light source



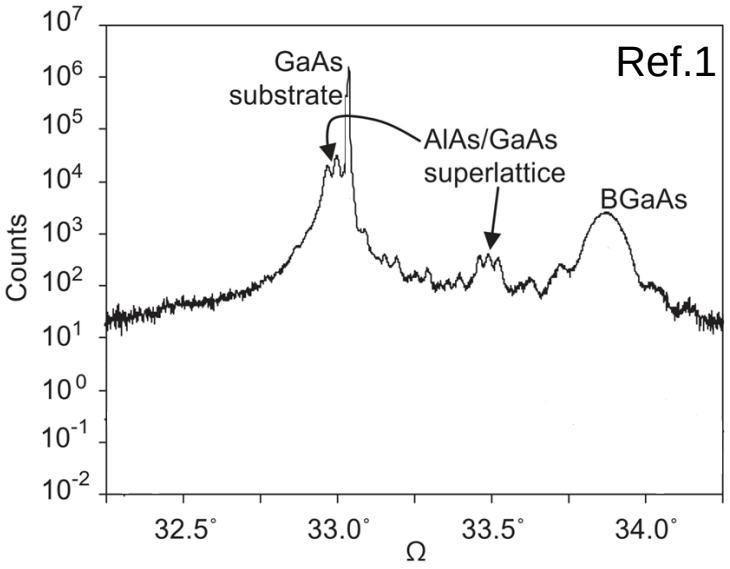
NKT Photonics

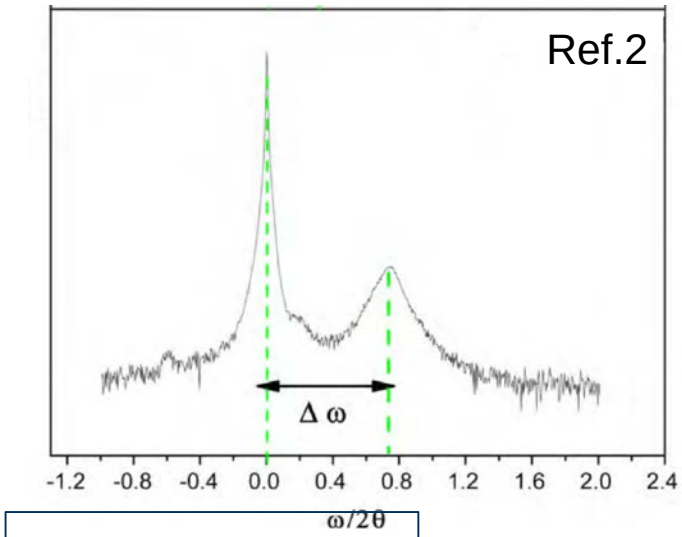
Molecular beam epitaxy



- Deposition controlled to sub-monolayer precision
- Ultra-pure materials
  - B: vertical e-beam evaporator
  - Group IIIs: SUMO effusion sources
  - Group Vs: Valved cracker sources
  - RE-Vs : High-temperature sources
- *In situ* Characterization
  - Reflection high-energy electron-diffraction (RHEED)
    - Real time monitoring of film quality, growth rate
- Growth Parameters
  - III:As ~10-200x BEP ratio
  - Substrate temp. room temp-700^{o}C
- Growth rates and alloy composition calibrated from high-resolution X-ray diffraction

B-III-V growth optimization





Current Record B concentrations ~8%

Key advancements:

- MBE
  - Low growth temperatures[1]
  - Large V/III flux ratio[1]
  - Fast growth rates[3]
  - Surfactant mediated growth[4]
- MOCVD
  - Low growth temperatures[5]
  - Large V precursor pressure[6]
  - Optimized precursor chemistry[7]

1 Groenert et al. *J. Cryst. Growth* (2004)
2 Hamilia et al. *J. Alloys Compd. (2010)*
3 Detz et al. *J. Cryst. Growth* 2017
4 Ptak et al. *J. Cryst. Growth* (2012)
5 Geisz et al., *J Cryst. Growth* (2001)
6 Gottschalch et al., *J. Cryst. Growth* (2003)
7 Geisz et al., *J. Elec. Mat.* (2001)

B-III-V: fundamental questions remain

What are the limits of B incorporation?

- Miscibility gap predicted[1], but unexplored

How does the band gap change with B composition?

- Increase or decrease in Eg with increasing B fraction?

Where does the direct to indirect transition occur?

- 30%[4] - 77%[7] B

What are the band alignments/offsets?

Dopant incorporation

1 Hart et al., *Phys. Rev. B* (2000)
2 Groenert et al. *J. Cryst. Growth* (2004)
3 Chimot et al., *Phys. B* (2005)
4 Gupta et al., *J. Elec. Mat.*, (2000)
5 Ilahi et al., *Phys. B* (2013)
6 Saidi et al., *Mat. Sci. Eng. C* (2006)
7 Guemou et al., Phys. B (2012)

Shockley-Ramo current

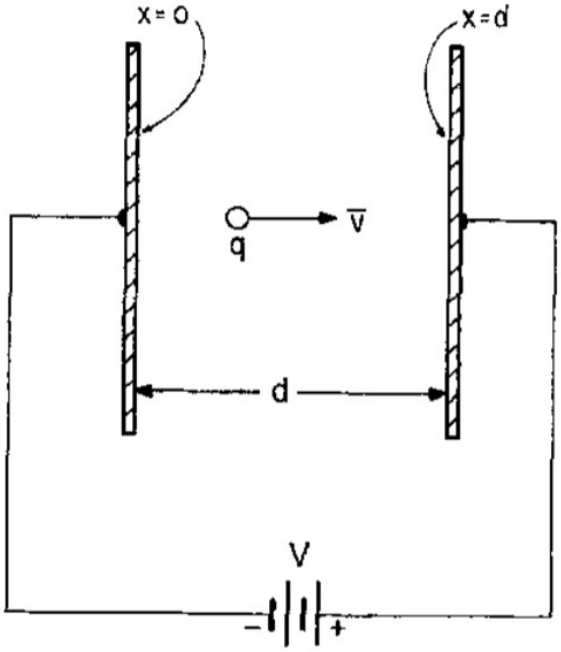


FIG. 2. A charge q moves with velocity $\mathbf{v}$ between parallel-plane electrodes.

$$I_2 = -q\mathbf{i}\cdot\mathbf{v}/d = -qv_x/d,$$

M. Sirkis and N. Holonyak, *J. Phys.*, 1966.