Center for Bio-Optoelectronic Sensor Systems

Defense Advanced Research Projects Agency
University Opto Centers Program

PI Meeting

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Status of Bio-Sensing Techniques

Limitations of current techniques

- Discrete bulky and expensive components
- Highly trained operation personnel
- Specialized sample labeling procedures
- Use in diagnostic laboratory
- Slow response time

Advantages of Optoelectronics sensors

- Enable compact, low cost, low power sensor systems
- Improved reliability through integration
- Reduced RMS noise levels compared to gas lasers
- Simple to operate
- Field deployable

BOSS Center Mission

“Integrated Optoelectronic Biological and Biochemical Sensor Systems”

Mission:

- **Detection and identification of chemical and biological threats through interaction between light and matter**
- **Leverage capabilities in compound semiconductor materials, engineered device structures, and integrated optoelectronics into light sources, sensors, waveguides, and spectrometers.**

Research Themes

Core Strengths

- Compound semiconductor materials
- Bandgap engineering
- Crystal growth
- Integration
- MEMS

Device Structures

- Laser diodes
- Superlattices, quantum wells, and quantum dots
- Waveguides
- Photo-detectors

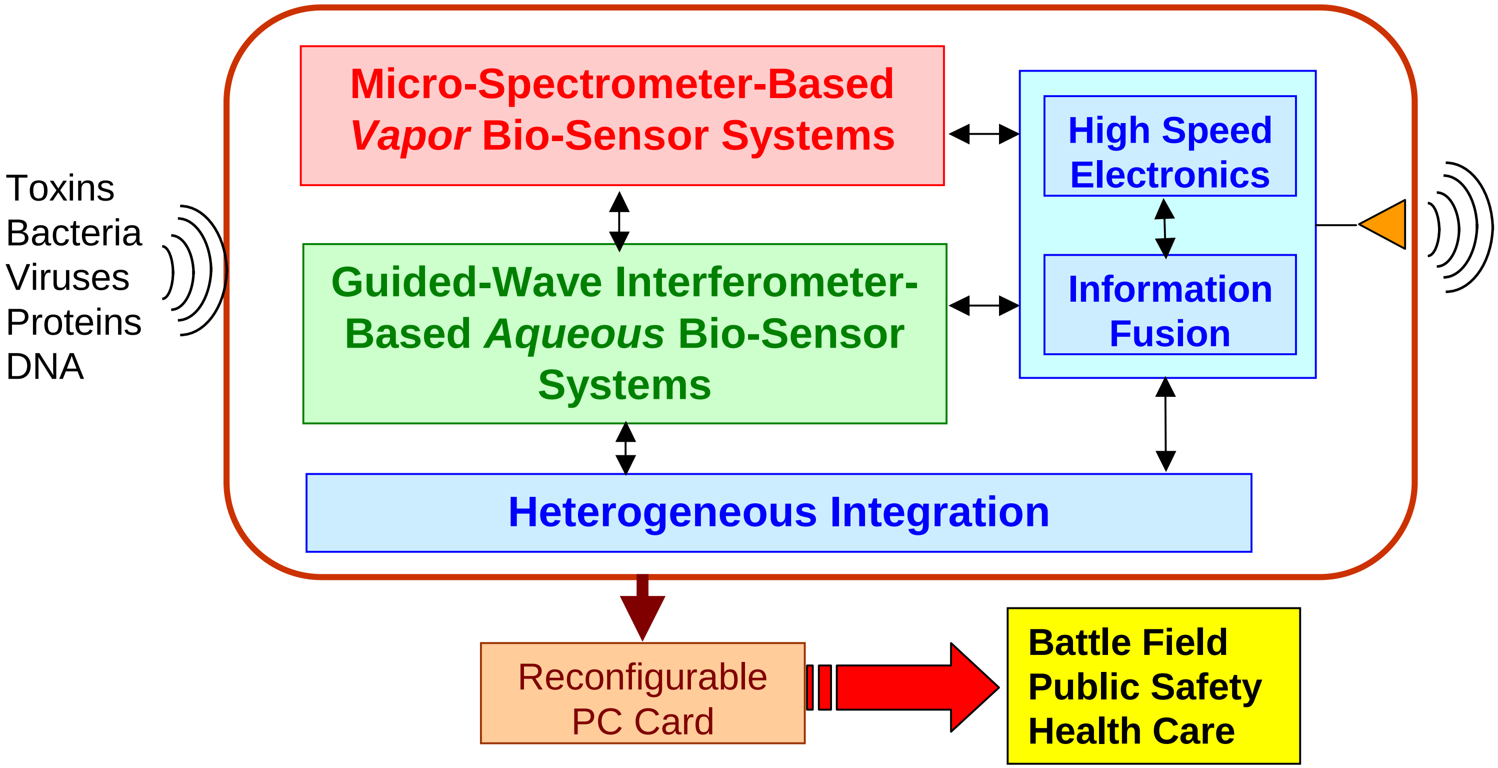
System Components

- Excitation sources
- Spectrometers
- Gratings
- Novel sensors

Integrated Bio-Optoelectronic Sensor Systems

- Miniature
- Low Cost
- Highly Sensitive
- Field Deployable

BOSS Approach to Bio-Sensors



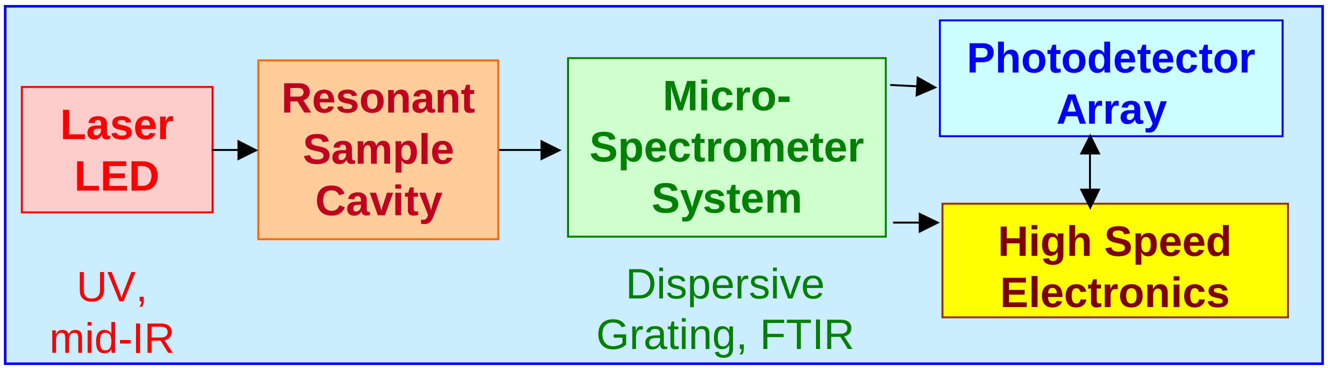
To develop in parallel two bio-sensor systems for

- Vapor phase agents using time- and wavelength-resolved FTIR-on-a-chip spectrometer and
- Aqueous agents using tunable DBR- or VCSEL-based interferometer

Institutional Contributions to Center Projects

Technical Barrier	Research Plan	Team Members	Task
Bio-sensor architecture	Bio-MEMS, interferometer waveguide	Georgia Tech, Illinois	1, 2
UV (300 nm) laser diodes	GaN-based UV laser diodes	Texas, Illinois	1
Room temperature CW operation mid-IR laser diodes	Sb-based quantum cascade laser diodes, Ordered InGaAsSb lasers	Columbia, Illinois	1
Wide frequency range optical spectrometer system	Re-configurable MEMS spectrometers FTIR-on-a-chip, opto-MEMS	Berkeley, Illinois	1
Integrated guided-wave interferometer systems	DBR lasers with intracavity sampling Tunable VCSELs with intracavity sampling Micro-fluidic photonic bandgap waveguide	Georgia Tech, Colorado State Michigan	2
System integration	Heterogeneous integration Information fusion	Georgia Tech, Illinois & All Illinois	1, 2, 3

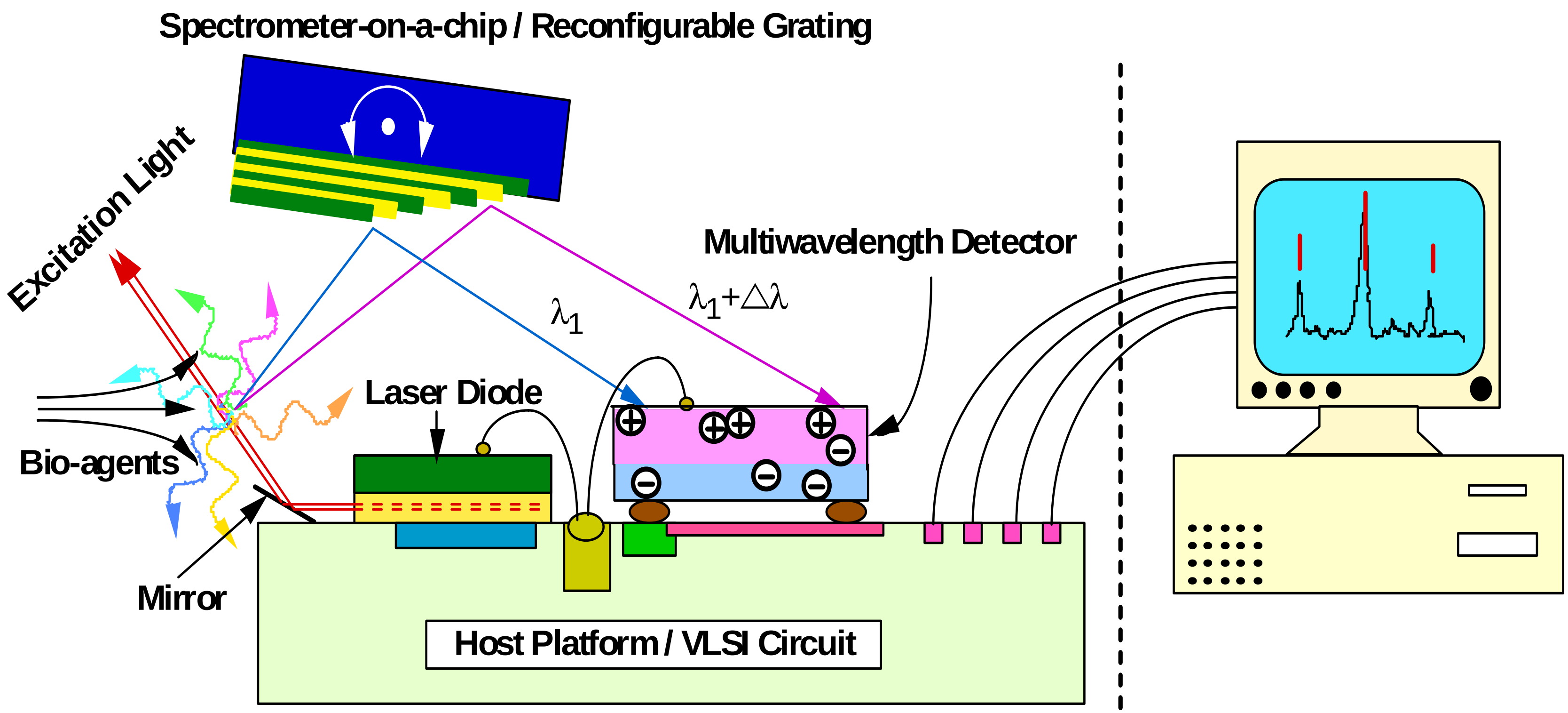
Micro-Spectrometer-Based *Vapor* Bio-Sensor Thrust



Barrier issues:

- UV laser diodes (< 300 nm).
- RT operation mid-IR laser diodes.
- UV and mid-IR detector arrays.
- Wide frequency range optical spectrometer system.

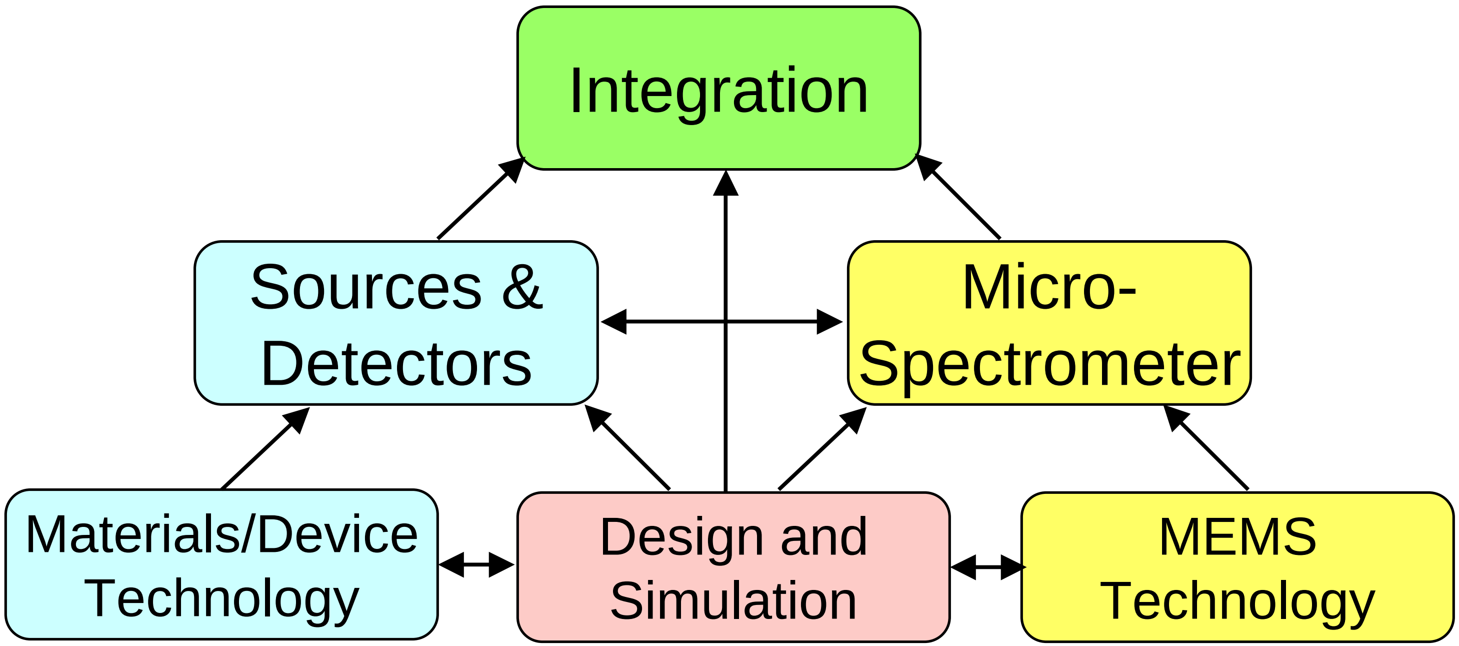
Bio-Sensor System-on-a-Chip



Material/Device Integration → **Information Fusion**

Projects Integration within Thrust: *Vertical Integration*

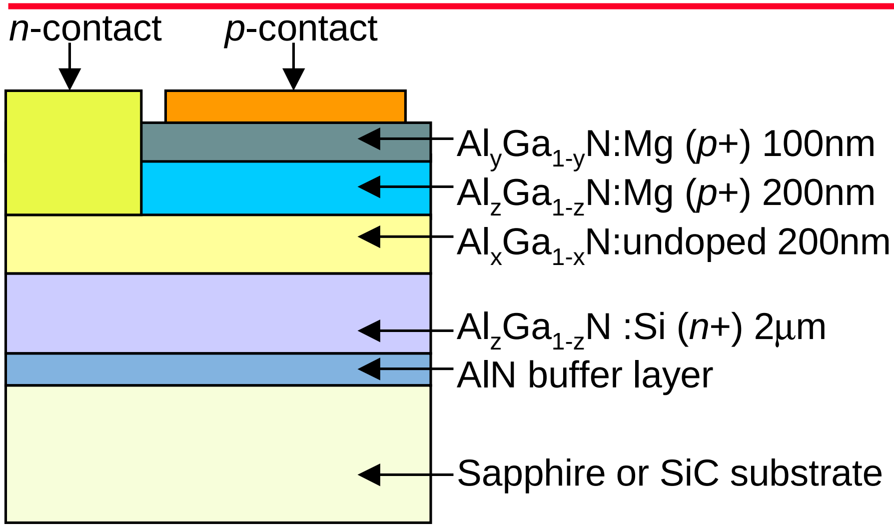
System Integration



Core Technologies

Nitride-Based UV Emitters

Russell D. Dupuis, UT-Austin; Nick Holonyak, Jr., UIUC



Objective

We will develop high-performance ultraviolet emitters based upon III-V nitride materials and heterojunctions. These devices will provide significant new capabilities for detection in a variety of DoD systems.

Approach

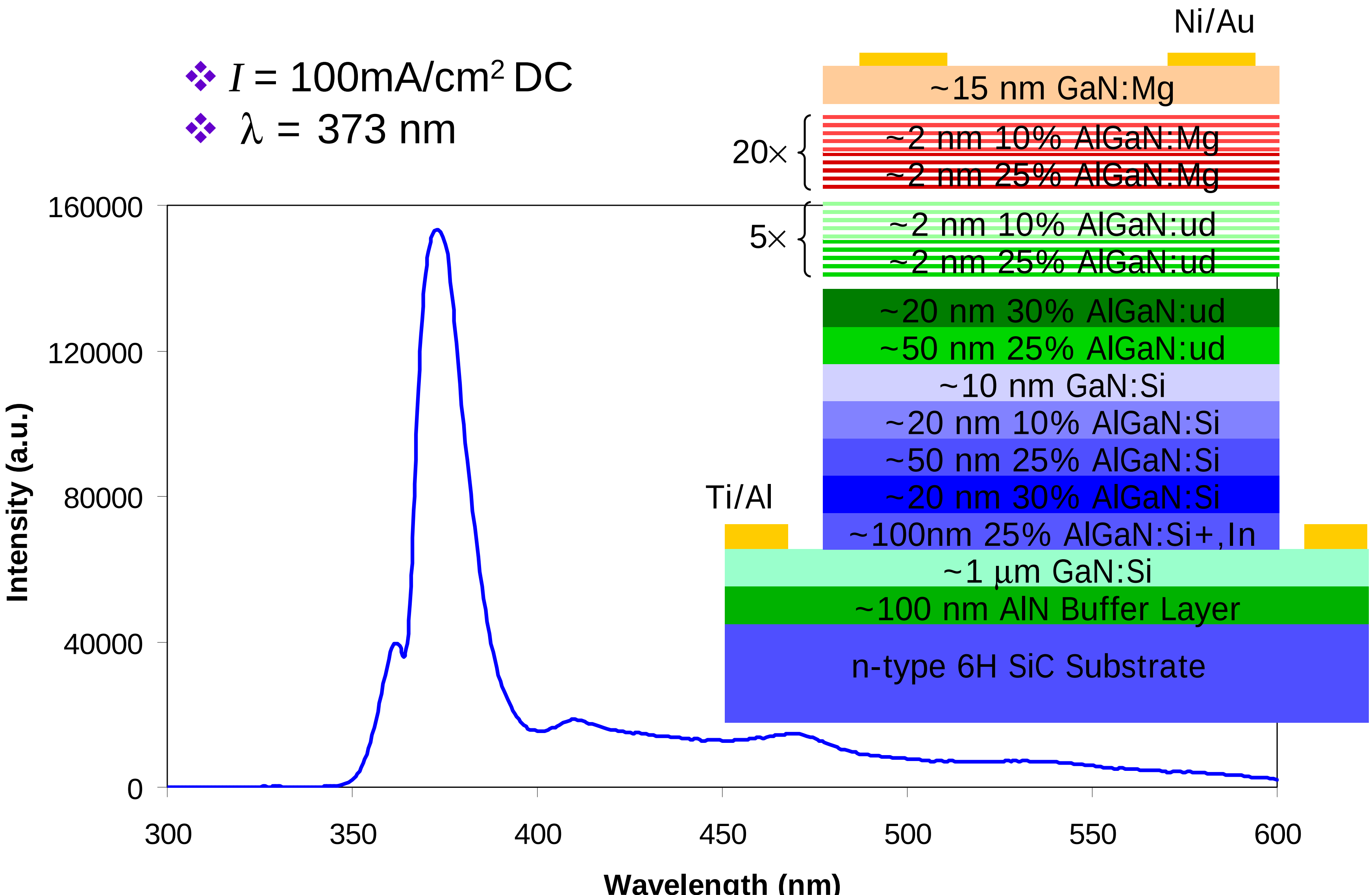
- MOCVD Growth of III-V nitride materials and heterojunctions
- Develop AlGaN epitaxy for superlattices, injection lasers, and light-emitting diodes
- Evaluate AlGaN/GaN heterojunctions for high-performance emitters
- Develop device processing technologies
  - Design and simulate optoelectronic devices
  - Process and test devices

Recent Accomplishments

- Grew and fabricated an AlGaN DH and SQW LED emitting at 323 and 373 nm at 300K, respectively;
- Demonstrated AlGaN:Si conducting buffer layer for *n*-type SiC substrates and Ohmic contacts
- Improved *p*-type doping using superlattices
- Developed facet-formation process for GaN film using dry and wet chemical etching

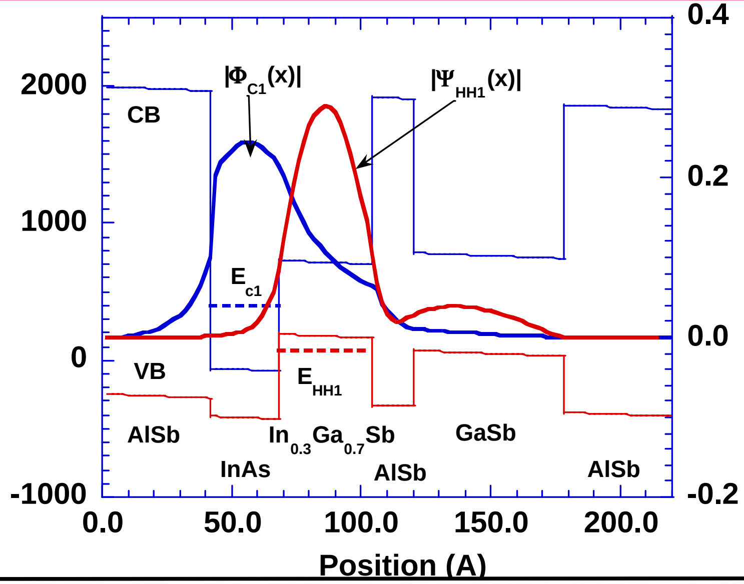
Electroluminescence Spectrum of AlGaN/GaN SQW LED (300K)

- *I* = 100mA/cm² DC
- λ = 373 nm



Sb-Based Mid-IR Emitter/Detector

W. I. Wang, A. Pinczuk, H. Stormer, Columbia,
S. L. Chuang and K. Y. Cheng, UIUC



Objectives

To design and fabricate near-IR (3-5 μm) and mid-IR (8-12 μm) lasers and detectors for the optical querying and determining information about gaseous bio-agents. The mid-IR lasers will be capable for high power, high quantum efficiency, low threshold current, and room temperature operation.

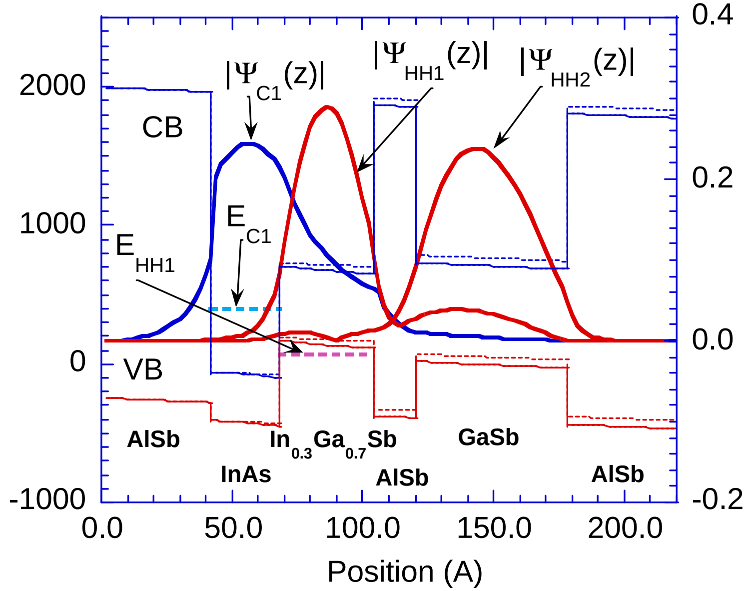
Approach

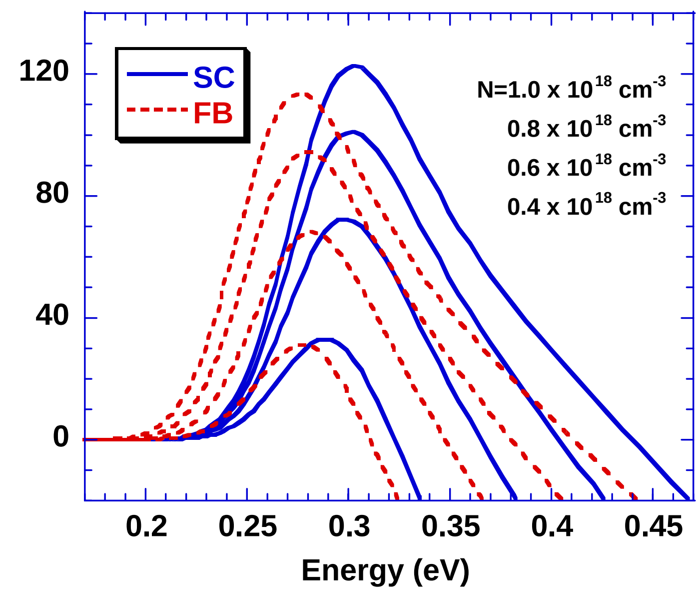
- Design, modeling, optimization, and fabrication of Sb-based IR lasers using type-II QW and cascade configurations.
- Utilizing long-range ordering in Sb-based III-V's to extend wavelength response range
- Develop compliant epitaxial layers for detector applications

Recent Accomplishments

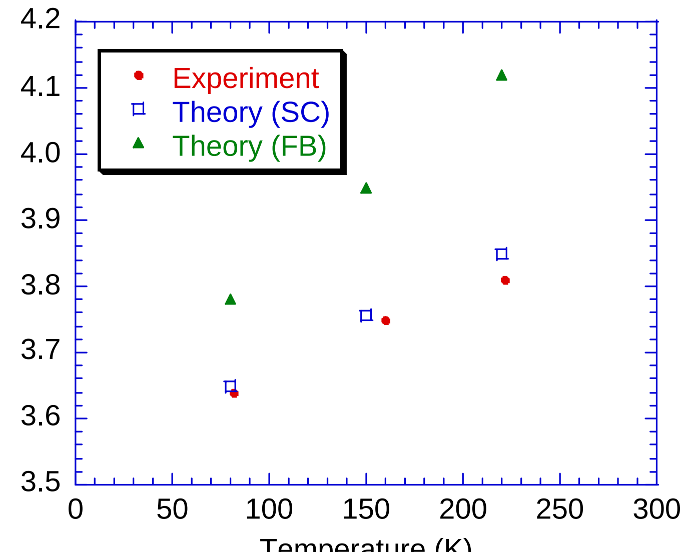
- Developed a self-consistent model for type-II interband QC laser for the first time, including carrier population dependent band structure and optical gain
- Demonstrated compliant epitaxy of InSb/AlInSb MQWs on (511) silicon-on-insulators (SOI) substrates with a low defect density.

Electronic Band Structure, Optical Gain, and Peak Wavelength

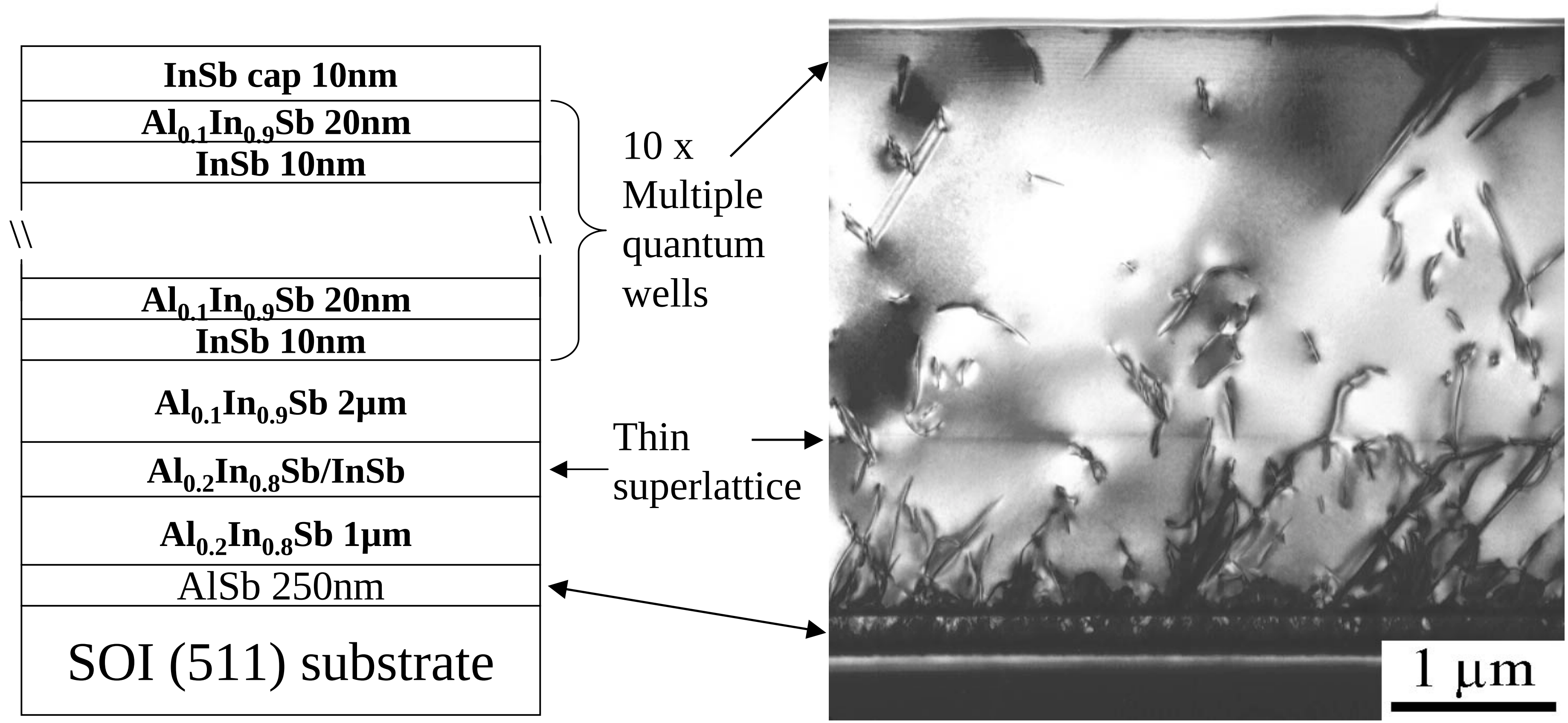




- We have developed a theoretical model to block-diagonalize the 8-by-8 Hamiltonian with the coupling between the conduction and valence bands taken into account.
- Band structure and wave functions are solved self-consistently since electrons and holes occupy different layers of a type-II quantum-well structure.
- The self-consistent (SC) solution is important to give a better agreement with experimental data than the flat-band (FB) model ignoring the electron-hole separation (screening) effects.



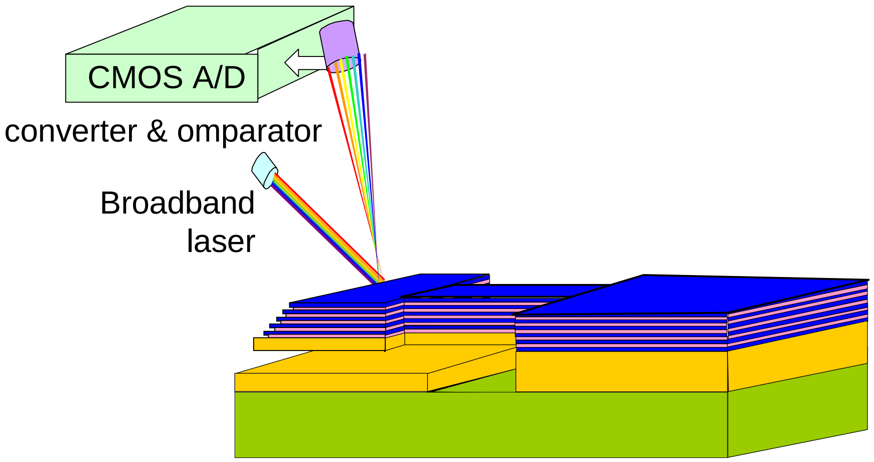
AlInSb/InSb/AlInSb Multiple Quantum Wells Grown on SOI



- InSb/$Al_{0.2}In_{0.8}Sb$ thin superlattice helpful in bending dislocations
- Dislocation density ~10^7 cm^{-2}

Reconfigurable Diffraction Gratings

M. Feng and S. L. Chuang, UIUC



Objective

Fabrication of integrated MEMS-based re-configurable diffraction gratings and filters for the preparation of optical querying and determining information about gaseous bio-agents.

Approach

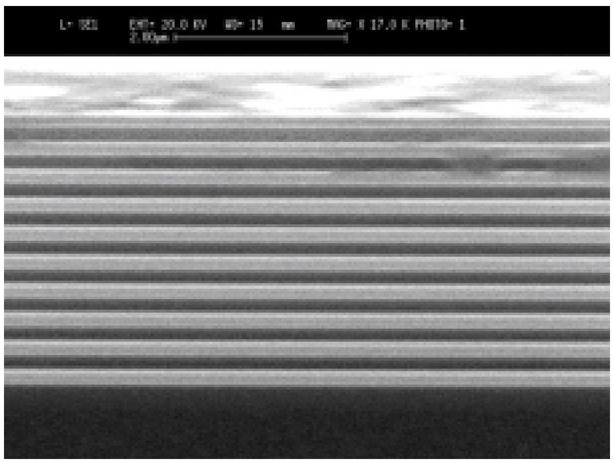
- Develop a reflection filter by using semiconductor superlattice structure to detect bio-agents;
- Develop a planar grating on the semiconductor substrate for chemical gaseous detection;
- The gratings are integrated with a MEMS rotation stage and recognition circuits.

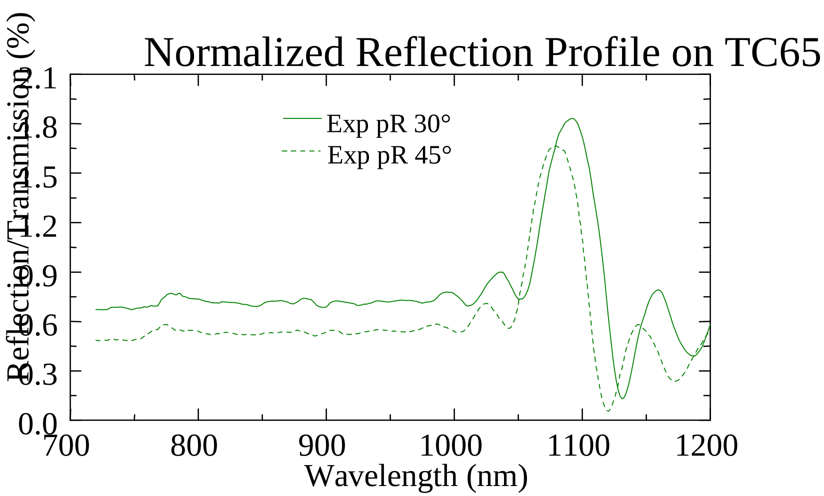
Recent Accomplishments

- Designed and fabricated planar superlattice gratings with reflection peak tunable as a function of light incident angles around 1 μm;
- Integration of a grating with a MEMS cantilevel switch has been designed for low voltage (~10 V) operation.
- Ridge optical grating for diffraction wavelength near 3.5 μm has been designed.

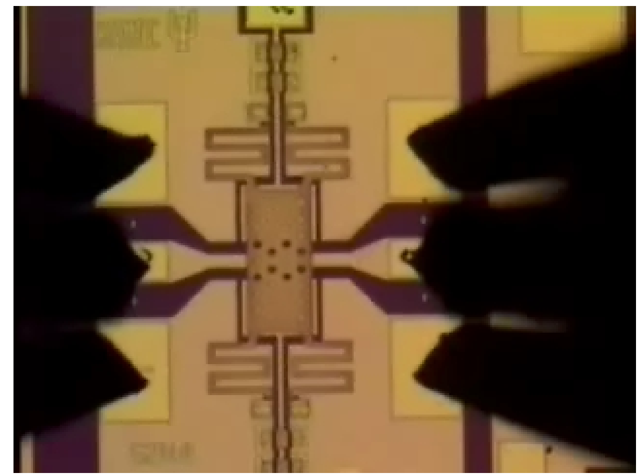
Re-configurable Reflection Filter and Diffraction Grating

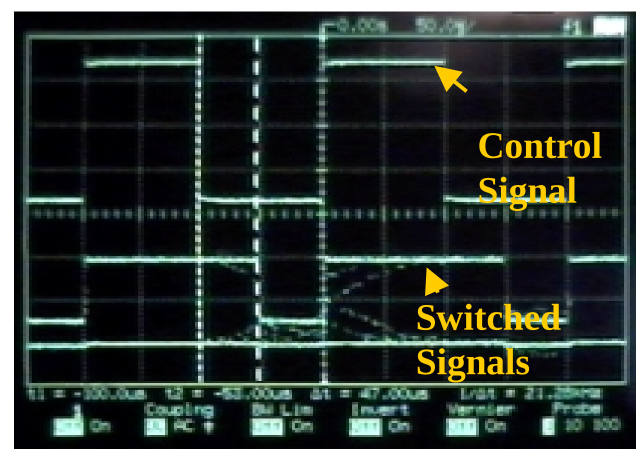
AlGaAs/GaAs (x10) SL reflection filter





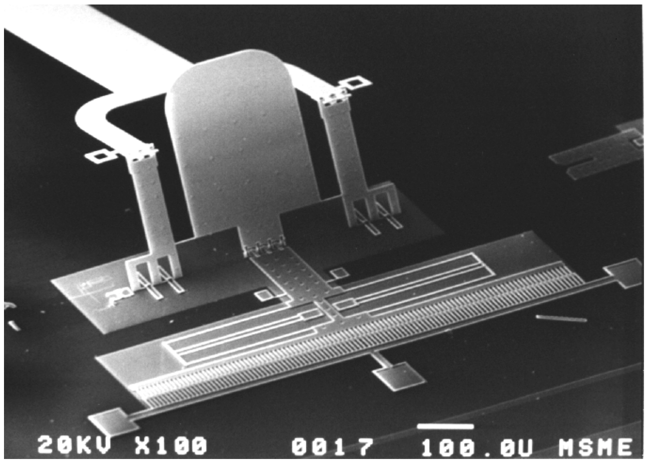
Voltage controlled rotation mirror





Micro-Spectrometer Development

C. Chang-Hasnain and K. Y. Lau, UC-Berkeley



Objective

- Build MEMS-based compact optical spectrometers to identify chemical gases or biological agents accurately in real-time.
- First time- and space- resolved spectrometer-on-a-chip
- Ultra-wide spectral range Dl/l_s=30-50%

Approach

- Evaluation of single tunable detector (with option of lock-in detection)
- Establish a close collaboration in Bio-engineering to understand the application needs
- Start with GaAs-based tunable detector array at 0.7-1 μm
- Design and fabricate detector array for other wavelength regime of interests: 1.3-1.8μm, 2-3μm, 8-10μm

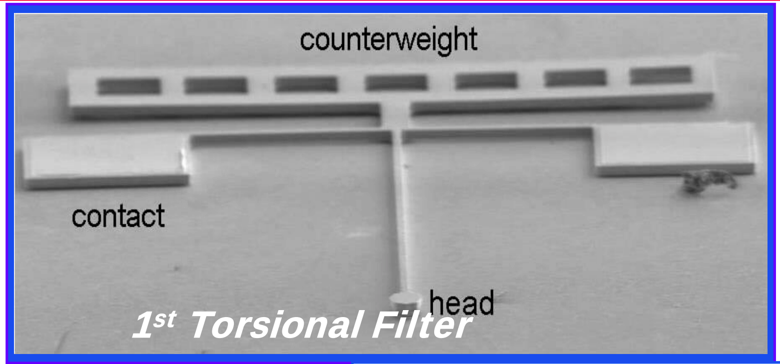
Recent Accomplishments

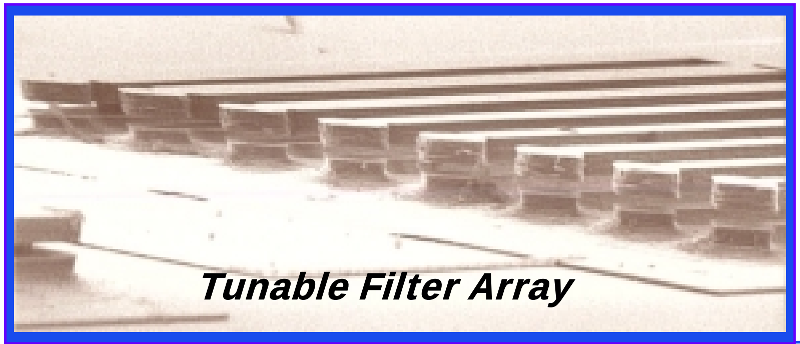
- Fabricated tunable filter array with torsion structure. It has a center wavelength at 1.55 μm, and is ready for characterization
- Designed silicon micromoters for micro-spectrometer applications.The design has been submitted to Sandia National Lab for fabrication.

Spectrometer-on-a-Chip

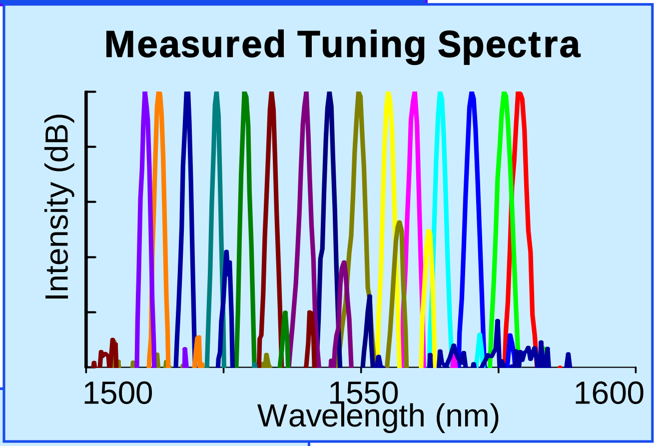
Approaches

- Time- and space- resolved spectrometer-on-a-chip using tunable detector arrays
- Ultra-wide tuning torsional optical filter



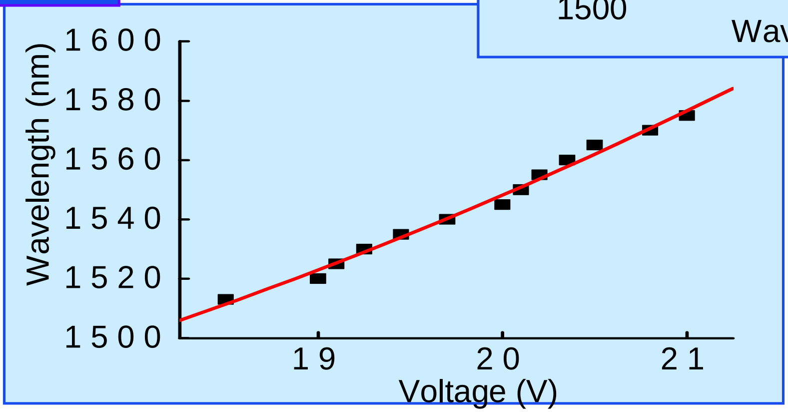


Wide (100nm) Continuous Tuning with Small Voltage (3V).

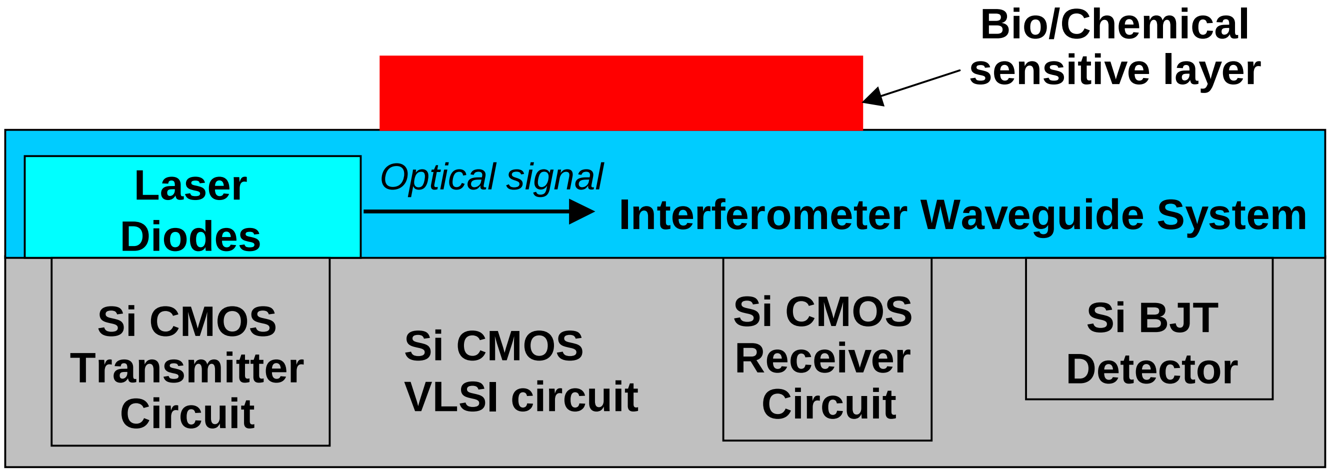


Progress-to-date

- Fabricated tunable filter array and ready for characterization
- Achieve 1500-1600nm tuning and 2X improvement with torsion structure

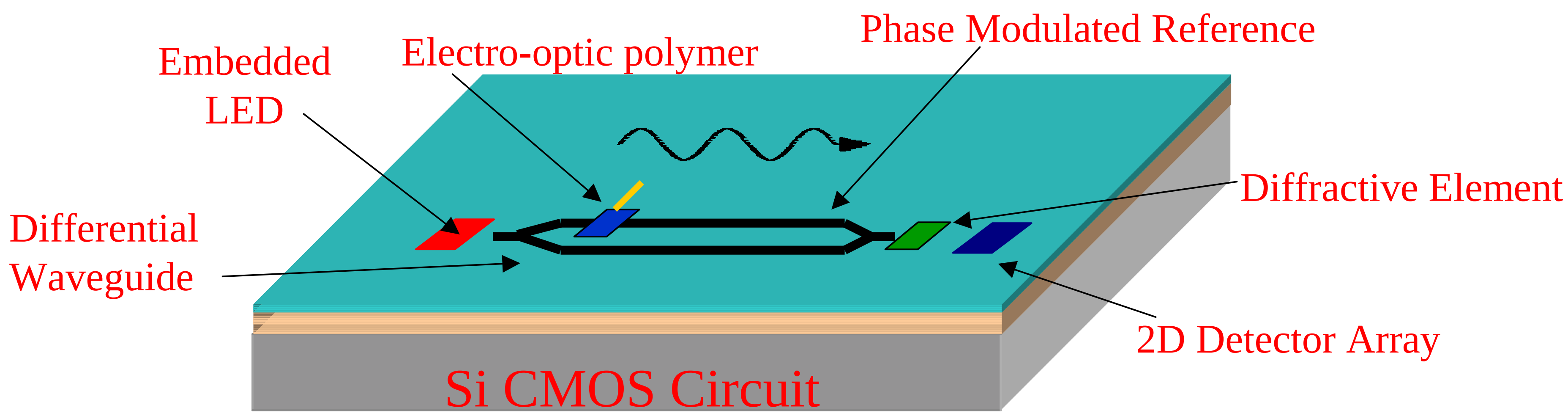


Integrated-Interferometer-Based *Aqueous* Bio-Sensor Thrust



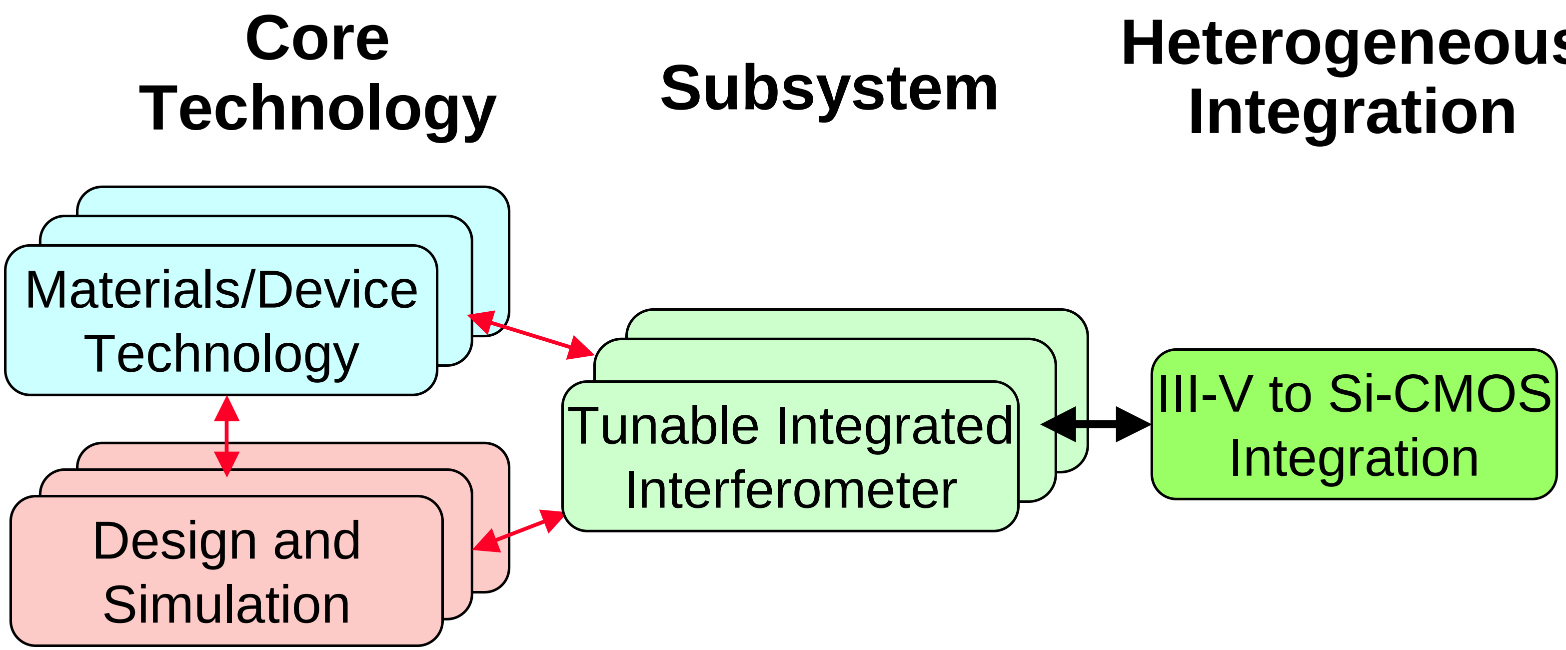
- Tunable laser diode-based interferometry.
- Utilizing passive or active bio/chemical surface sensing layer.
- Detecting index of refraction change as small as 10^{-6}.
- Integrated with silicon-based electronics and photo-receiver circuits.

Bio-Sensor System-within-a-Chip



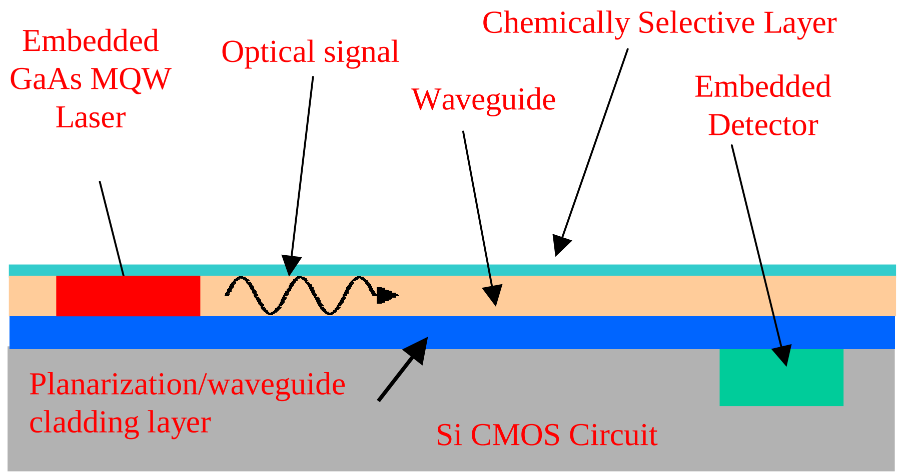
- On-Chip phase modulation allows phase sensitive detection and increased sensitivity
- Embedded broadband source coupled into waveguide interferometer
- Spectrally identify bio/chemical agents using a multi-agent sensitized layer
- 2D detector array
  - Transverse image of large waveguide width insures multiple absolute phase
  - Dispersed spectrum allows interferometric spectroscopy

Projects Integration within Thrust: *Lateral Integration*



Integrated Interferometric Bio/Chem OEIC Sensors

N. Jokerst, M. Brooke, S. Ralph; Georgia Tech



Objectives

To design and fabricate interferometric biological/chemical sensors using heterogeneously integrated GaAs-based emitters and waveguide differential sensors integrated in three dimensions (3D) on top of Si CMOS VLSI detector and signal processing circuitry.

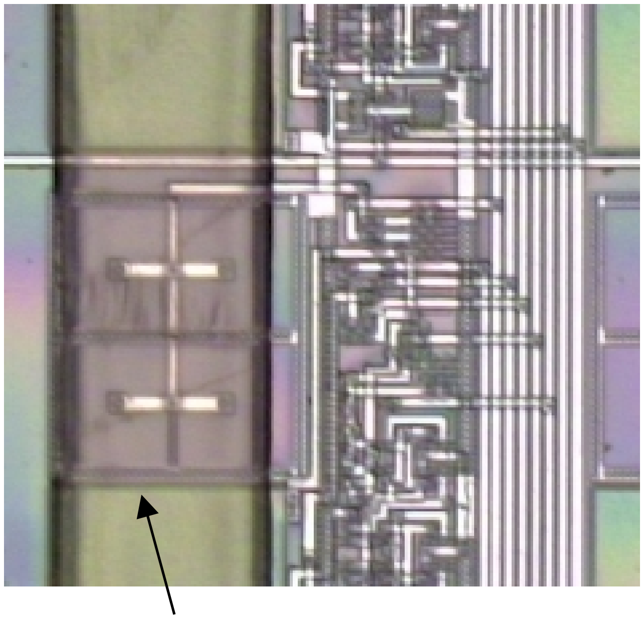
Approaches

- Fabricate edge emitting lasers and LEDs; bond to Si CMOS circuits; embed into planar waveguide interferometric sensors
- Design waveguide sensor for System on a Chip (Si CMOS) implementation
- Use Si VLSI signal processing to analyze sensor signals on the chip

Recent Accomplishments

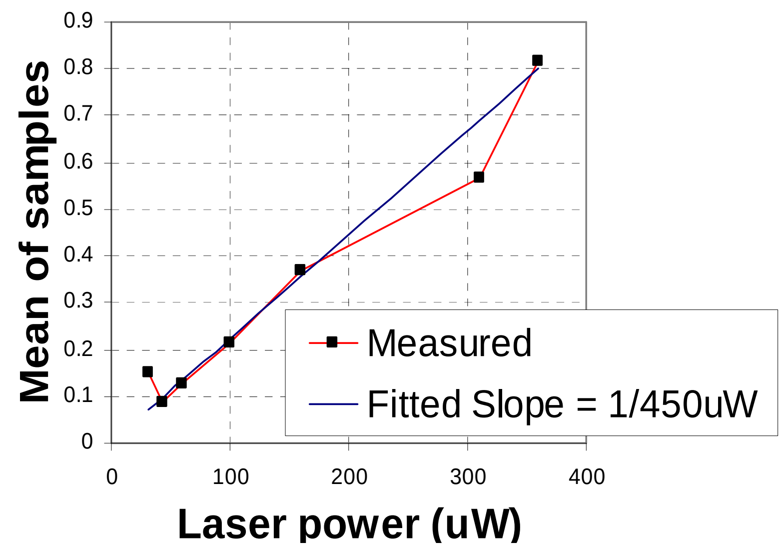
- Si ICs including detector, ADC and waveguide fabricated and tested
- Waveguides fabricated on Si ICs and optimized
- 3D Electromagnetic modeling established
- Advanced spectral interferometry concept identified
- Embedded photodetector and Si CMOS circuits fabricated and tested

Integrated Sensor Si CMOS Circuit (ADC + PD + Waveguide Circuit)



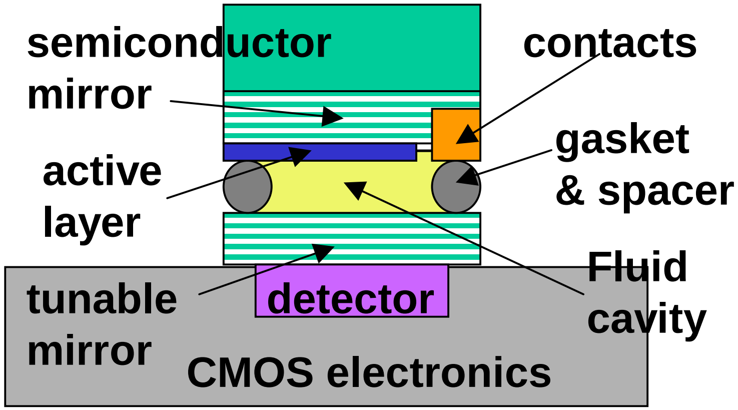
Channel waveguide

- Optical signal (He:Ne) butt coupled in to Si CMOS chip from one edge of chip
- End of waveguide at right hand side (bright spot)
- Some reflection from discontinuities/metallization on Si CMOS IC
- Embedded photodetectors addressed by waveguide



Intracavity Fluidic VCSEL Sensors

K. Lear & C. Wilmsen, Colorado State University



Objectives

The development and application of laser diodes that admit intracavity liquid biological or chemical analytes provides the potential for high sensitivity detection and identification of important battlefield and environmental agents.

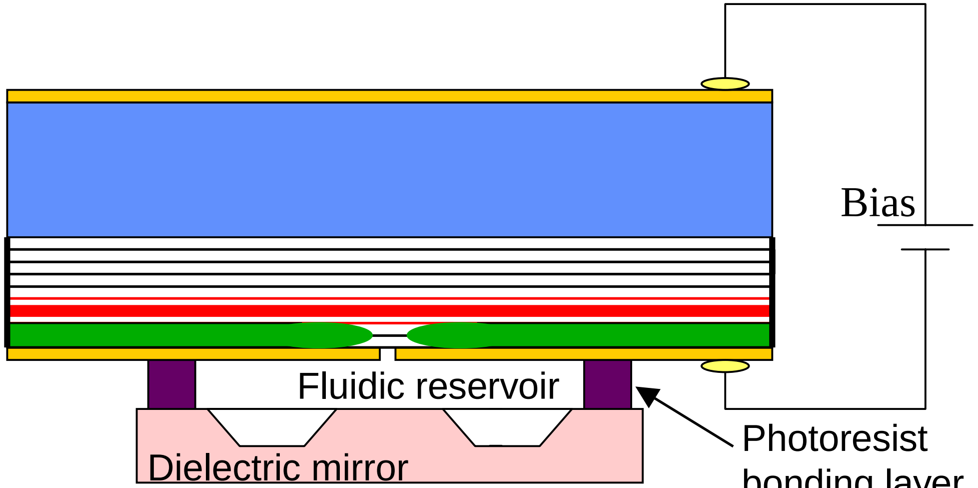
Approaches

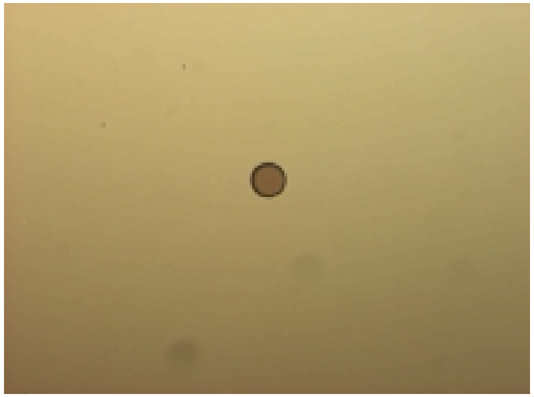
- Develop laser cavity model based on optical properties of cells
- Fabricate fluidic cavity laser diodes
- Evaluate devices as differentiated cell detectors
- Apply devices to cellular diagnoses
- Implement & evaluate full assembly process
- Evaluate laser response to fluids and inert artificial cells

Recent Accomplishments

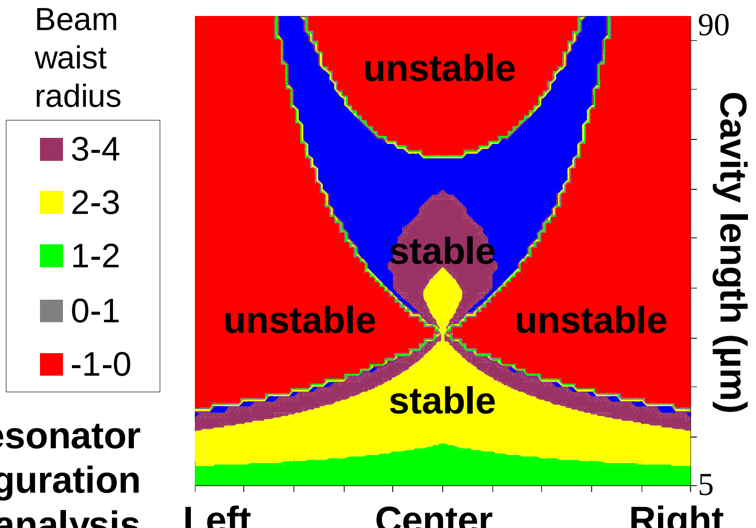
- Designed mask set for fluidic cavity VCSELs
- Fabrication process developed
- Fabricated fluidic cavity VCSELs
- Fluidic cavity VCSEL mode structure modeled.

Intracavity Fluidic VCSEL Sensors

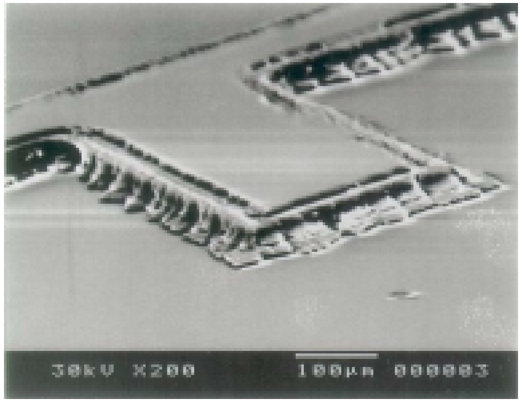




Photoresist mask after implantation



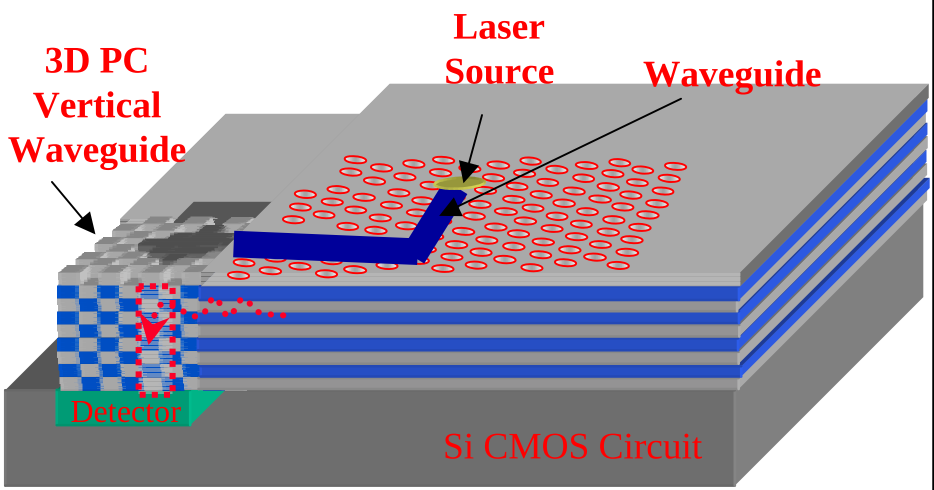
Micro-resonator configuration analysis



Etched reservoir

Microfluidic Photonic Crystal Sensors

P. Bhattacharya, University of Michigan



Objectives

Design and fabrication of micro-fluidic sensor to detect bio-fluids based on their refractive index using photonic crystal waveguides.

Approaches

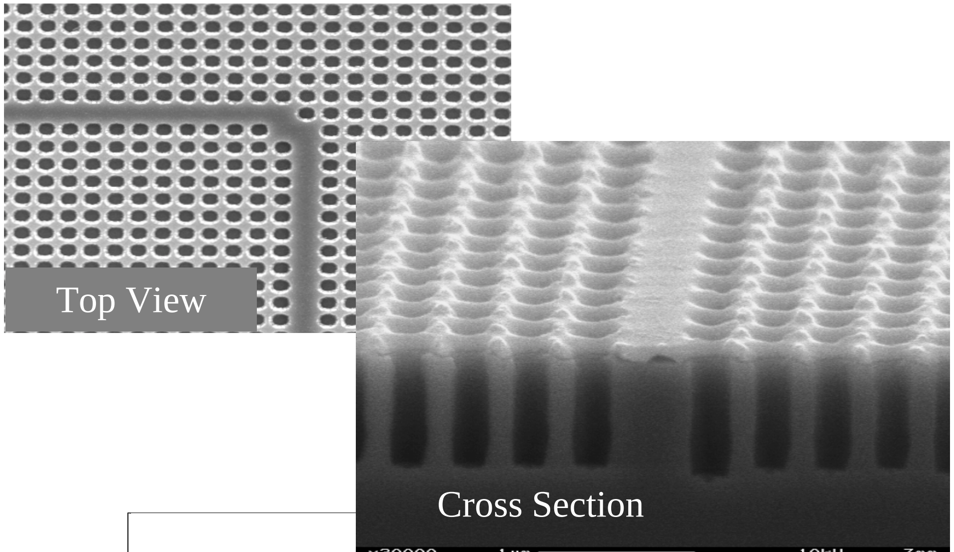
- Develop sensor components using photonic crystal structures
  - single channel and multi channel Photonic Crystal Waveguide
  - QD photonic crystal defect microcavity light source
  - Embedded detector
- Integrate above mentioned components into an integrated bio-sensor system

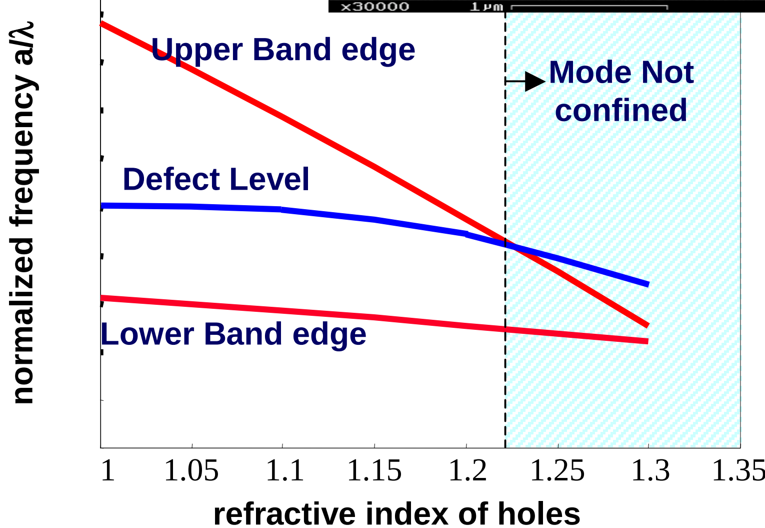
Recent Accomplishments

- Theoretical photonic band structure and defect mode level determined
- 2D photonic crystal waveguides fabricated
- Multi channel photonic crystal waveguides designed
- Demonstrated 1.04 µm quantum dot photonic crystal vertical micro cavity light source.

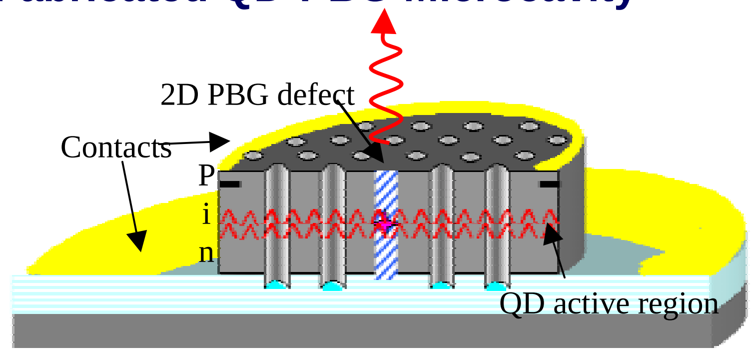
Fabrication of PC Sensor Structures

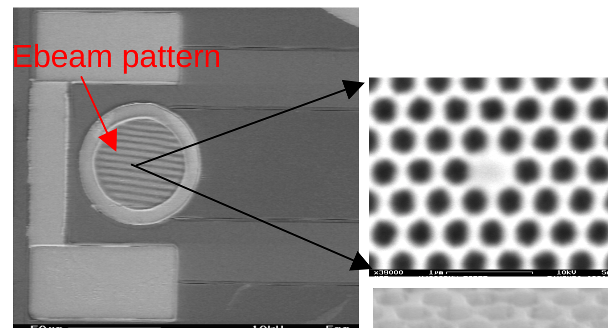
Final 2D PBG after Deep etching





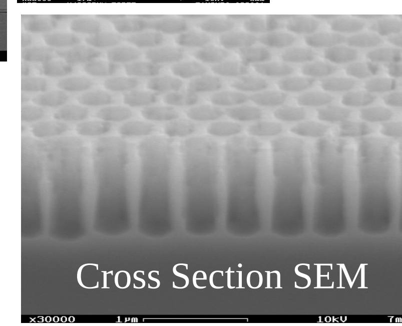
Fabricated QD-PBG Microcavity





Quantum Dots in microcavity:

- Incorporating quantum dots provide optical and carrier confinement
- 1.04mm InGaAs QD active region
- I-cavity with bottom DBR and oxide confinement



BOSS / Industry Interaction:
Current Status

- **Strong interactions at device / component level**
  - Fabrication and characterization
    - Sandia National Lab - VCSEL, MEMS motors
    - ARL and LumiLED - UV emitter
    - SRU Biosystems - system characterization
  - Provide specific device structures
    - Bell Labs - QC lasers
    - Maxion Technologies - type II lasers
- **Seeking system level collaborators**
  - Strategic system research planning
    - PhotonicSensors Inc.
    - SRU Biosystems
  - Providing testing environment

Summary

- **Research**
  - Established system focus - vapor and aqueous bio-sensors
  - Strong interactions within thrusts
  - Significant progress on devices and subsystems
- **Industrial Interactions**
  - Collaborative research activities
  - System perspective input from industry
  - Support through cash and in-kind gifts