Micro-Spectrometer–Based Biosensor System

BOSS CENTER TASK 1:

A Strategic Thrust of the Center for Bio-Optoelectronic Sensor Systems

DARPA Optoelectronic Center Kickoff Meeting
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Presented by
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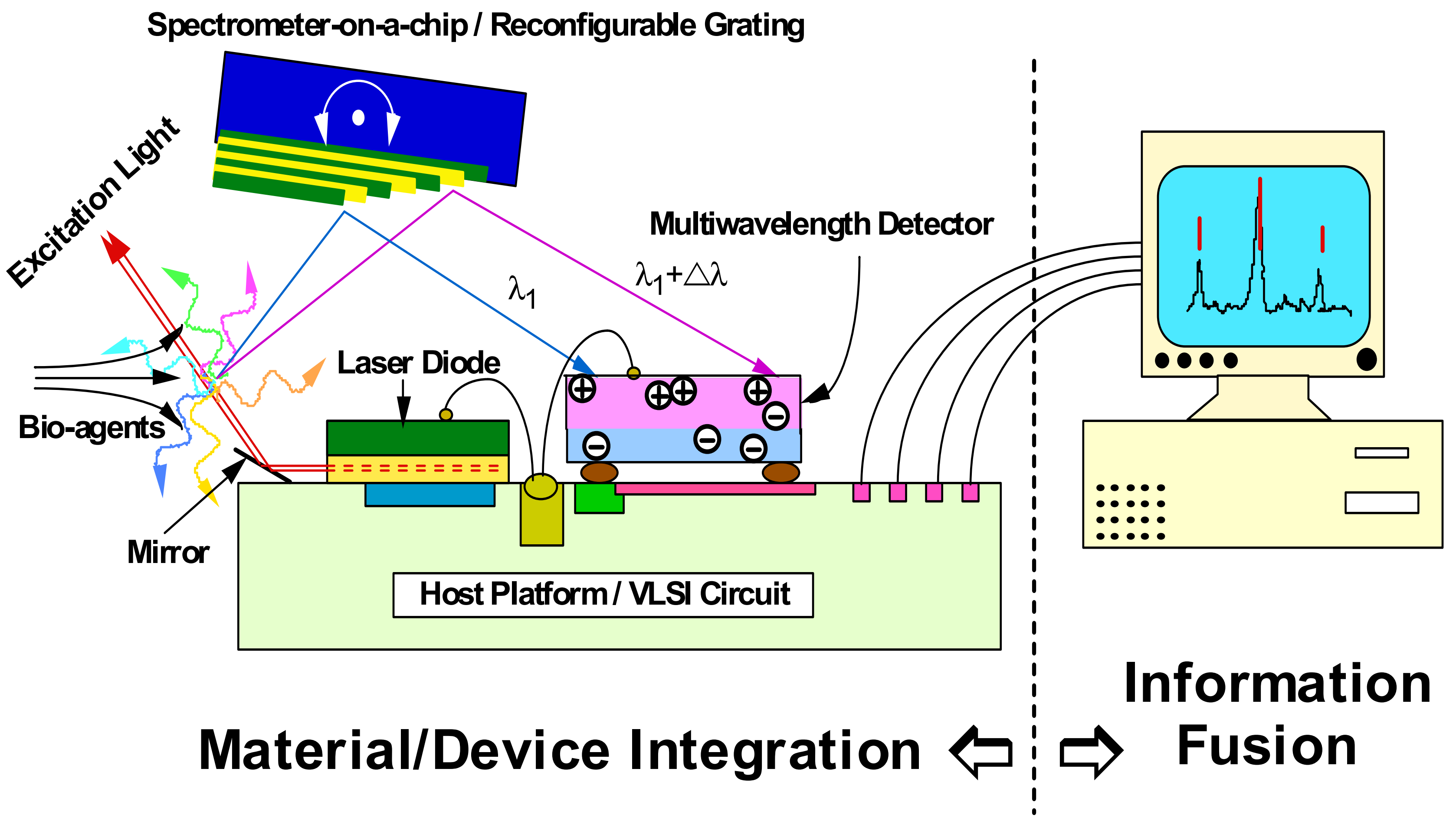
Task 1: Micro-Spectrometer – Based Biosensor System

Research Topics

- (1-1) Mid-IR quantum cascade Type II lasers and detectors based upon III-Sb compounds (Chuang, Cheng, Wang, Pinczuk, Störmer)
- (1-2) Near- and mid-IR emitters and detectors based upon ordered III-Sb materials (Wang, Pinczuk, Störmer, Cheng, Hsieh)
- (1-3) Mid-IR quantum cascade Type I lasers based upon III-N materials (Dupuis, Chuang)
- (1-4) Ultraviolet emitters using III-N materials (Dupuis, Holonyak)
- (1-5) Optical MEMs micro-spectrometer systems (Chang-Hasnain, Feng, Hsieh, Lau)

Biological/Biochemical Sensing System Device Integration

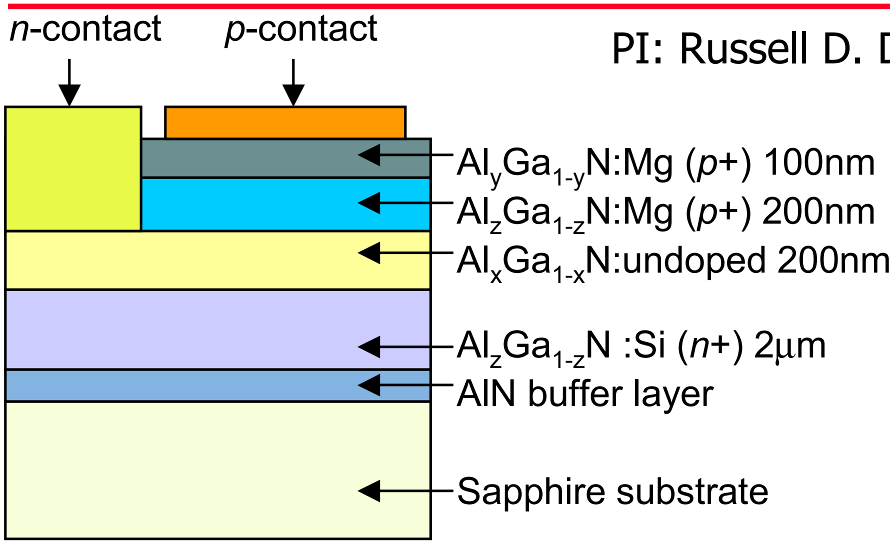


Task 1: Micro-Spectrometer – Based Biosensor System

Topic	Investigator	Institution	Approach
5	Chang-Hasnain	UC Berkeley	Micro-FTIR spectrometer, optical MEMs
1,2	Cheng	UIUC	Sb-based mid-IR sources & detectors
1,3	Chuang	UIUC	Modeling & design of mid-IR sources
3,4	Dupuis	U. Texas	Nitride materials growth & characterization
5	Feng	UIUC	MEMs-based gratings and optics
1,	Holonyak	UIUC	III-N light source design & fabrication
2,5	Hsieh	UIUC	Micro-spectrometer integration, TEM
5	Lau	UC Berkeley	Micro-FTIR spectrometer, optical MEMs
1,2	Pinczuk	Columbia	Micro-Raman spectroscopy of IR materials
1,2	Störmer	Columbia	Electronic characterization of IR materials
1,2	Wang	Columbia	Sb-based IR device growth & fabrication

Nitride-Based UV and IR Emitters Topics 3, 4

PI: Russell D. Dupuis, UT-Austin



Objective

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

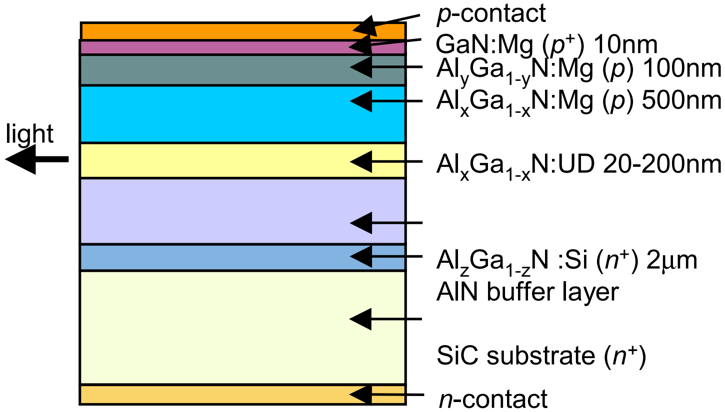
Approach

- 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

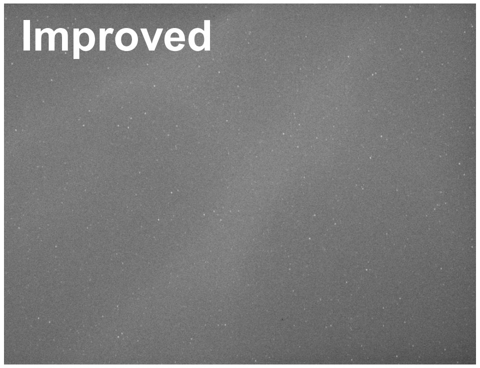
Recent Accomplishments

- Demonstrated high-quality GaN growth on SiC
- Growth of AlGaN *p-n* epitaxial structures
  - Demonstrated high-quality materials
  - Crack-free AlGaN *x*=0.45-0.60 films ~2μm thick
  - Demonstrated AlGaN *p-n* junctions
- Developed processing for AlGaN materials
- Growth of AlGaN/GaN and AlN/GaN SLs

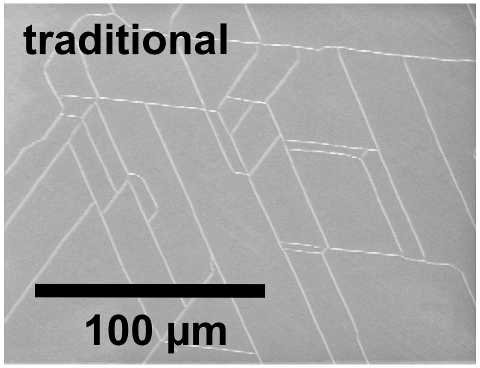
High Quality $Al_xGa_{1-x}N$ UV-Laser Structure Grown by Improved MOCVD



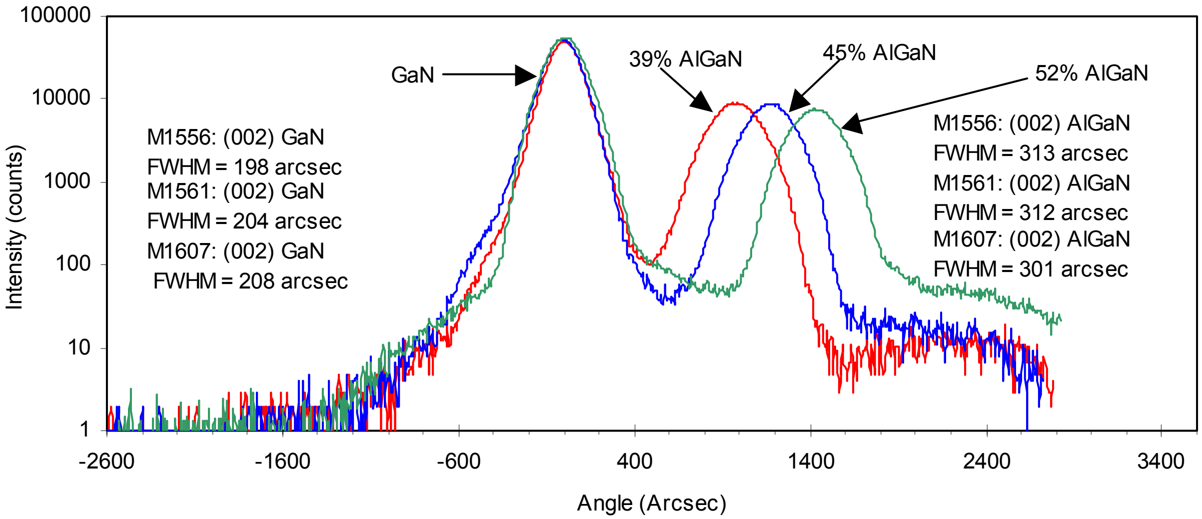
1 µm $Al_{0.5}Ga_{0.5}N/GaN$



0.2 µm $Al_{0.3}Ga_{0.7}N/GaN$

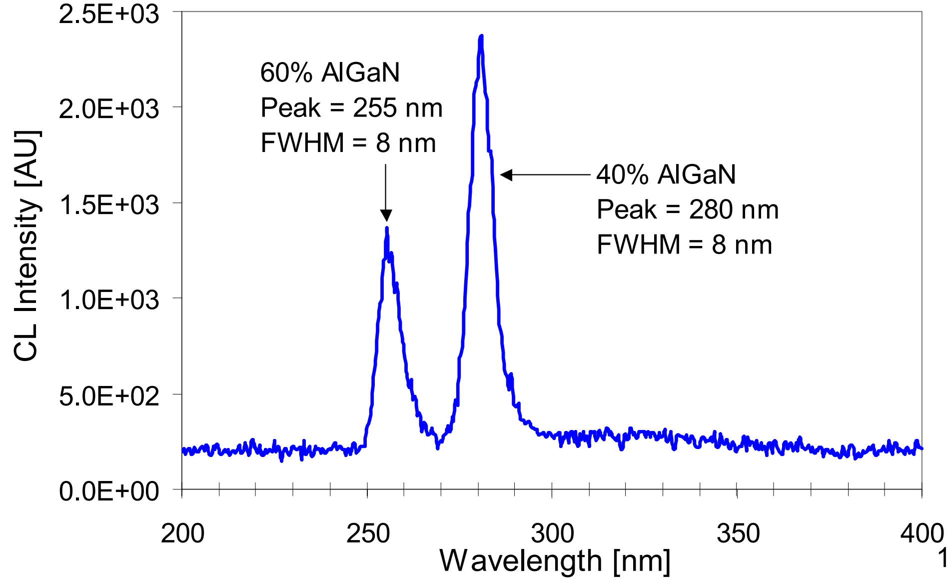


X-Ray Scan (002) Omega-2Theta



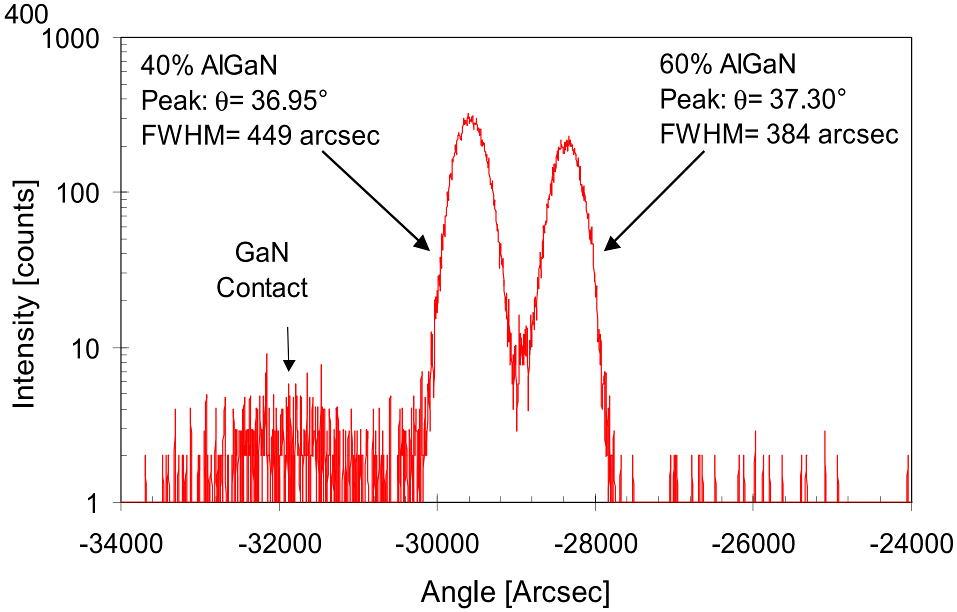
- High AlN-composition required to achieve $\lambda \leq 300$ nm
- Grown by an improved MOCVD method

AlGaN SH 4K CL Spectra and X-Ray Diffraction (004) ω-2θ Scans

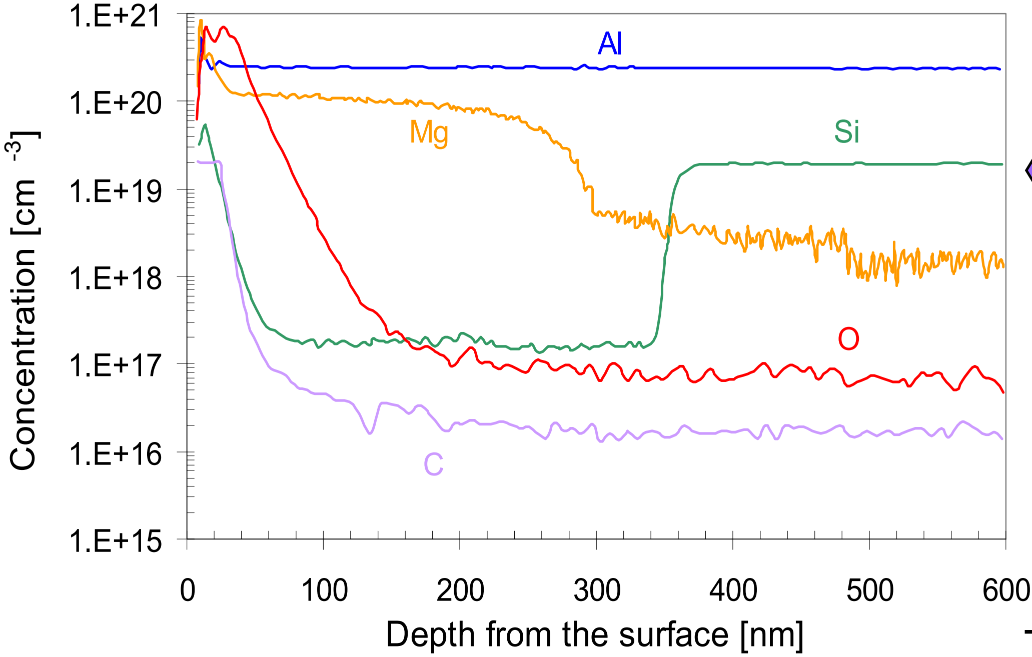


- 4K cathodoluminescence characteristics for AlGaN *x*=0.40/*x*=0.60 single heterostructure

- (004) X-ray data for AlGaN *x*=0.40/*x*=0.60 single heterostructure

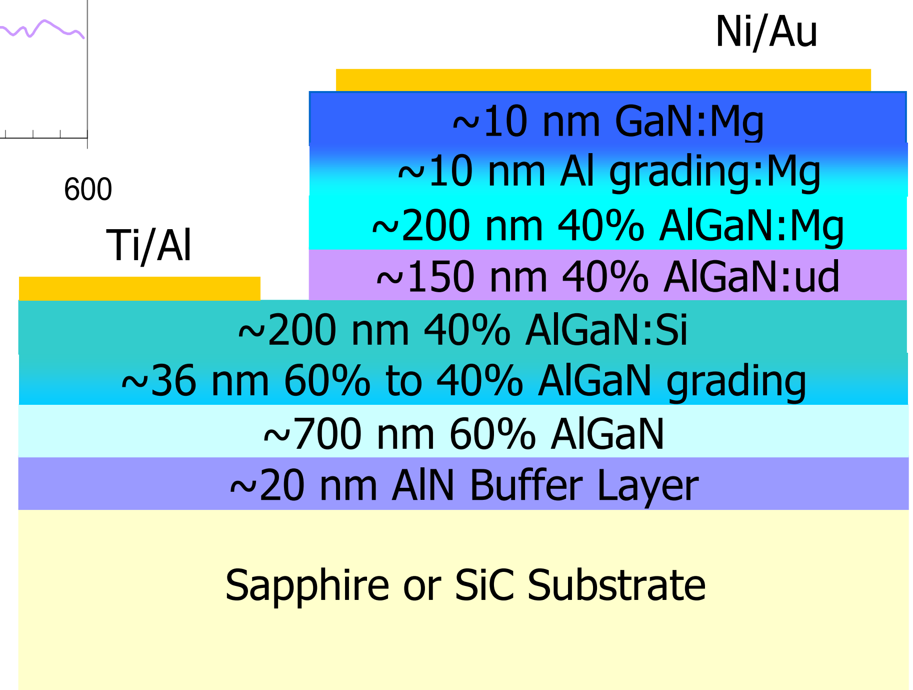


AlGaN Light-Emitting Diode Structure and SIMS Data

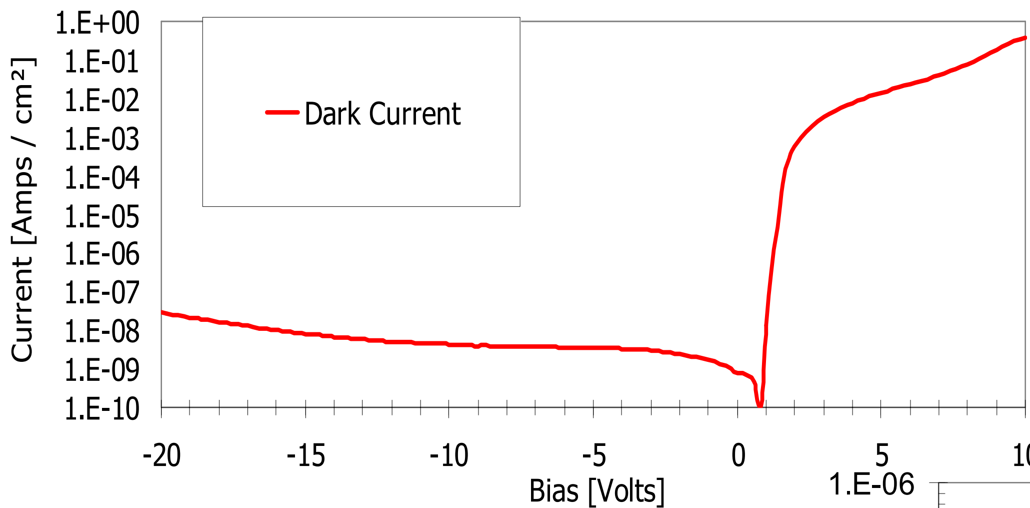


- SIMS data for AlGaN *x*=0.40 *p-n* junction grown on an *x*=0.60 cladding layer

- Schematic diagram for AlGaN *x*=0.40 *p-n* junction with a *x*=0.60 single heterostructure

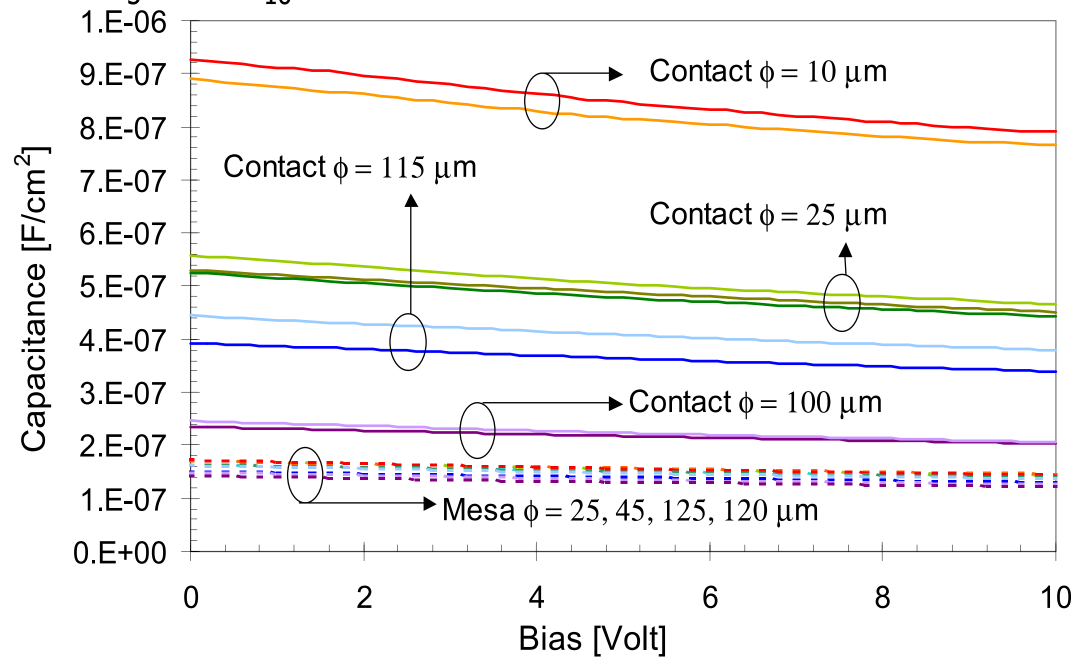


I-V and C-V Data for an AlGaN *p-n* Junction



- *I-V* characteristics for AlGaN *x*=0.45 *p-n* junction—low leakage current but high forward voltage

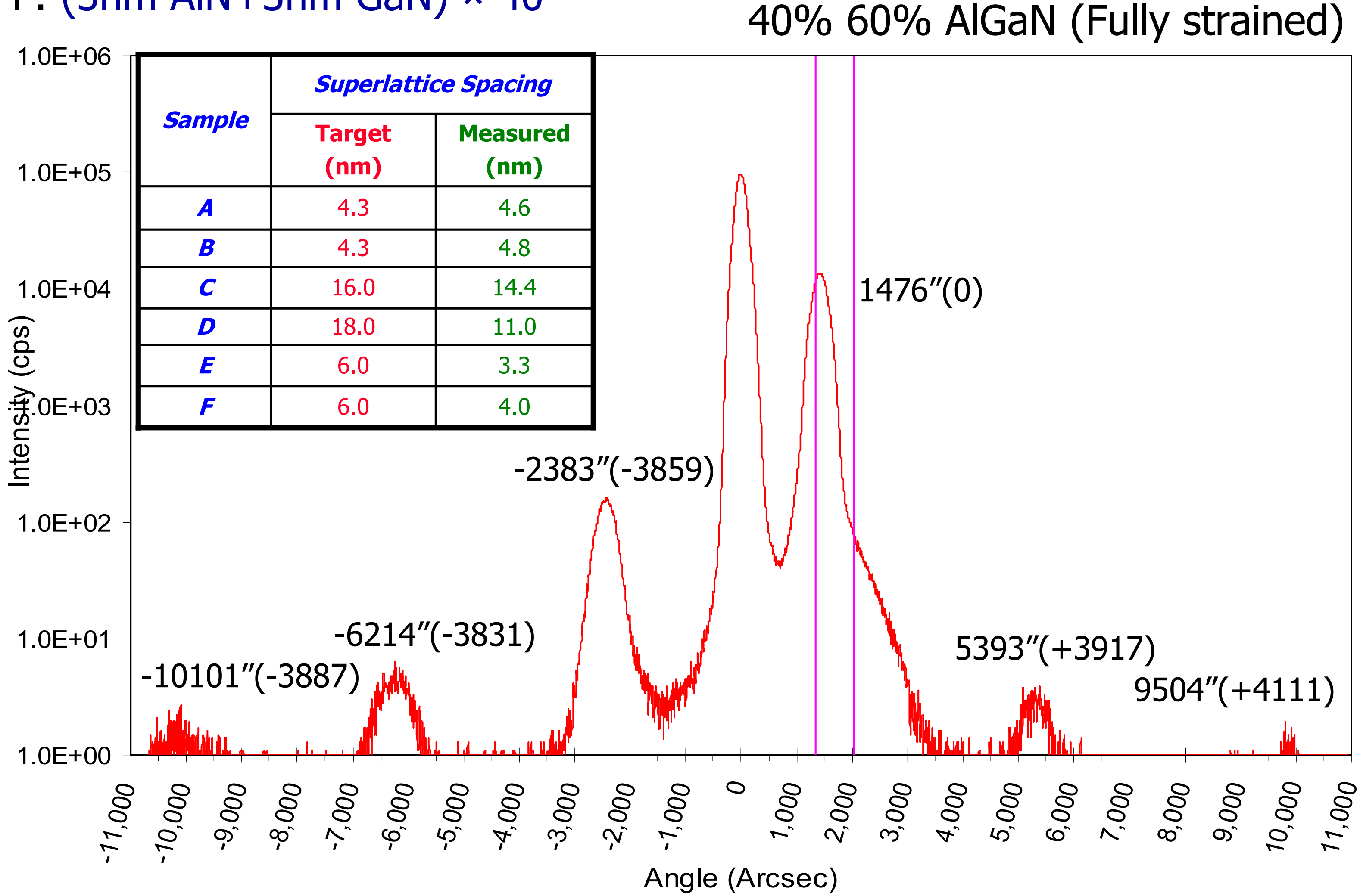
- *C-V* characteristics for AlGaN *x*=0.45 *p-n* junction—capacitance/area scales with mesa diameter, not contact diameter



AlN/GaN Superlattice Symmetric X-ray Scan (0002) ω-2θ

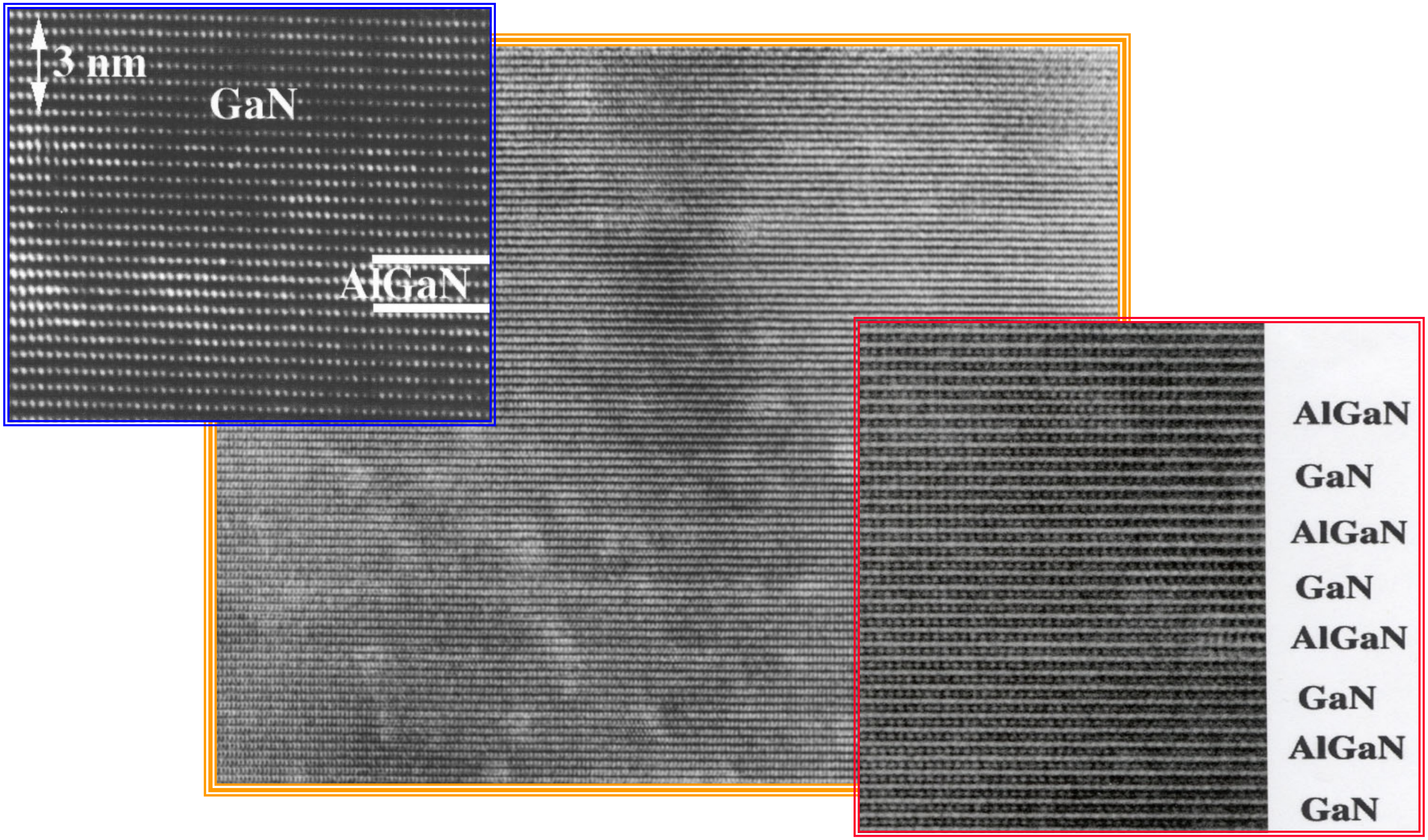
Sample F: (3nm AlN+3nm GaN) × 40

Sample	Superlattice Spacing	
	Target (nm)	Measured (nm)
A	4.3	4.6
B	4.3	4.8
C	16.0	14.4
D	18.0	11.0
E	6.0	3.3
F	6.0	4.0



AlGaN/GaN SL: High Resolution TEM Images

Sample B: (3.3nm 30%AlGaN+1.0nm GaN) × 20



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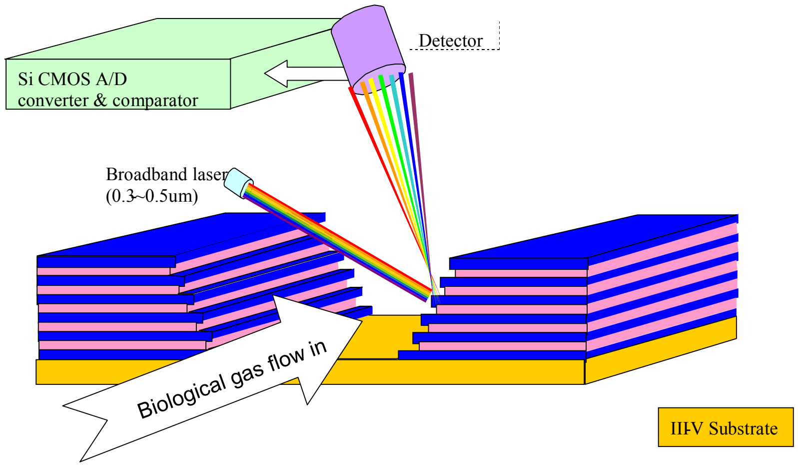
Optical Correlation Spectroscopy Using Re-Configurable Diffraction Gratings



Contractor: University of Illinois at Urbana-Champaign
POC: Dr. Elias Towe DARPA/MTO, (703) 696-0045
PI: Dr. K.Y. Norman Cheng, UIUC, (217) 333-6642
CoPI: Dr. Milton Feng, UIUC, (217) 333-8080

Objective:

- Fabrication of a re-configurable diffraction grating for the preparation of optical querying and determining information about gaseous bio-agents.

Approach:

- Develop a grating mirror in the vertical direction of the semiconductor superlattice layer structure for the detection of bio-agents, and a planar grating on the semiconductor substrate for chemical gaseous. The gratings are then integrated with MEMS rotation stage and recognition circuit.

- **Key Issues:**
- A low cost, mass production vertical optical grating in UV 0.3-0.5 μm wavelength range.
- Planar optical gratings in mid-IR 5-15 μm wavelength range.
- Hybrid Integration of optical gratings with rotation stages by the MEMS technology
- Si CMOS A/D converter and comparator for detection of bio-chemical agents.

Program Schedule:

Task 1: MEMS-based gratings and optics

FY00:*First iteration design and fabrication of 0.3-0.5 μm and 5-15 μm gating structure.

FY01:*Demonstrate of 0.3-0.5 μm and 5-15 μm grating structures and design of MEMS rotation stage

FY02:*Hybrid Integration of 5-15 μm grating with a MEMS rotation stage and A/D converter to demonstrate known chemical spectra

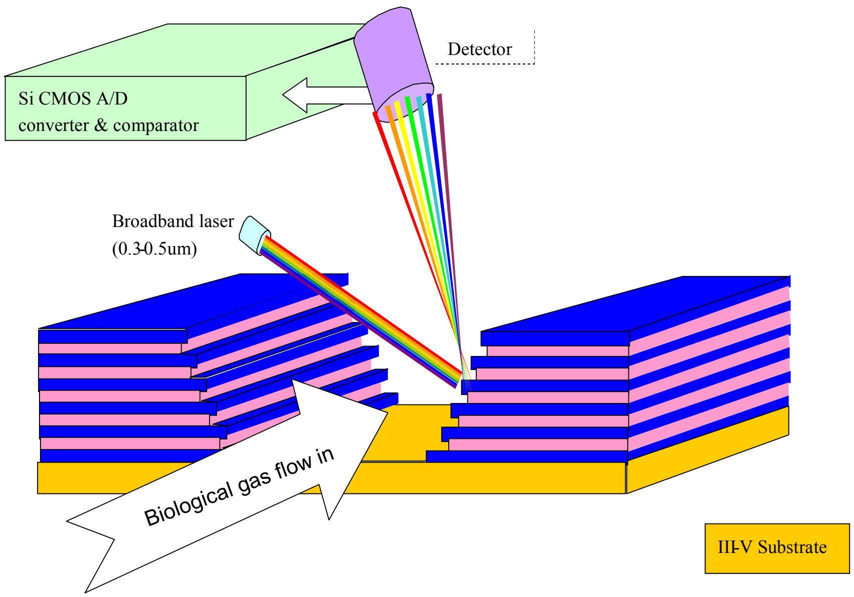
FY03:*Hybrid Integration of a 0.3-0.5 μm MEMS grating with rotation capability to demonstrate known biological agent spectra.

Micro-Spectrometer Development: Task 1, Topic 5 Goals

- Develop and fabricate a low cost, mass production vertical optical grating in UV wavelength range, λ=0.3-0.5 μm (FY00)
- Develop and fabricate a planar optical grating in mid-IR wavelength range, λ=5-15 μm (FY00)
- Hybrid integration of optical gratings with rotation stages by the MEMS technology (FY01-FY02)
- Develop a detection circuit to compare the detected signal with known bio-chemical spectra (FY02-FY03)
- Determination of detected bio-chemical agents (FY03)

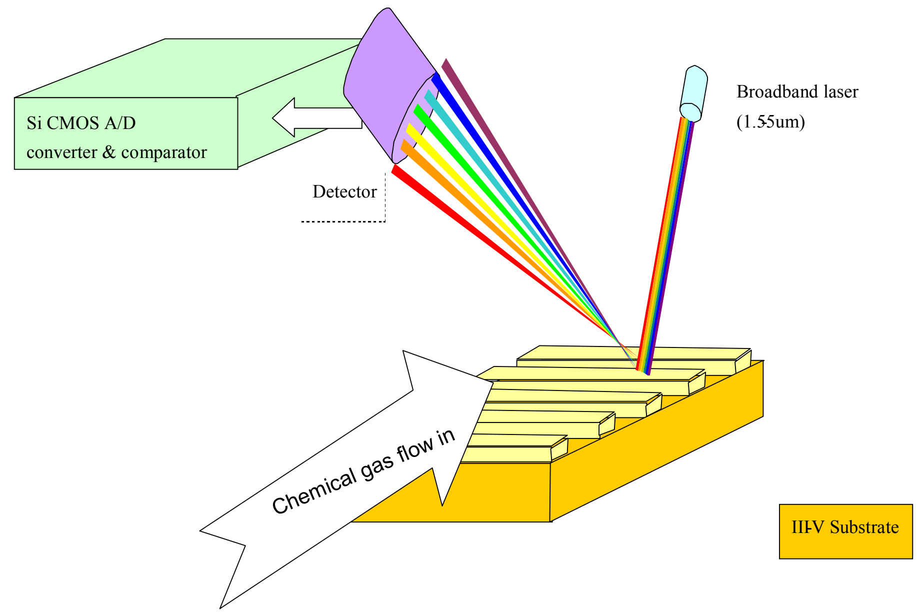
Re-configurable Diffraction Gratings

Vertical Optical Gratings in the UV 0.3-0.5 µm wavelength range



- The InGaP/GaAs or AlGaAs/GaAs superlattice structure is grown by MOCVD or MBE. The grating structure will be formed with different angles of undercut in different layers by reactive ion etching or selective wet etching

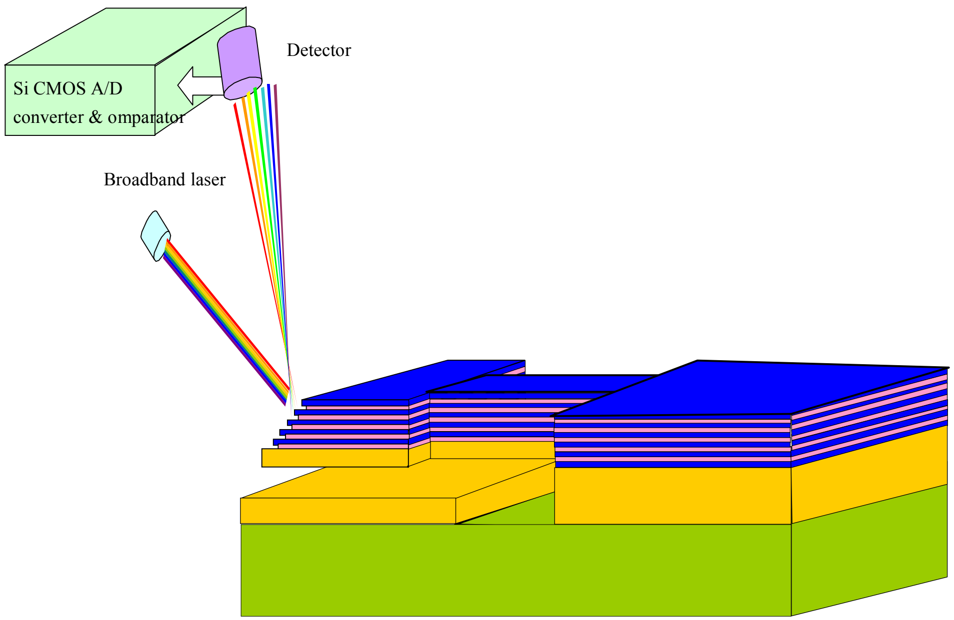
Planar Optical Gratings in the mid-IR 5-15 µm wavelength range



- Planar optical gratings are fabricated by optical lithography and then followed by reactive ion etching or wet etching.

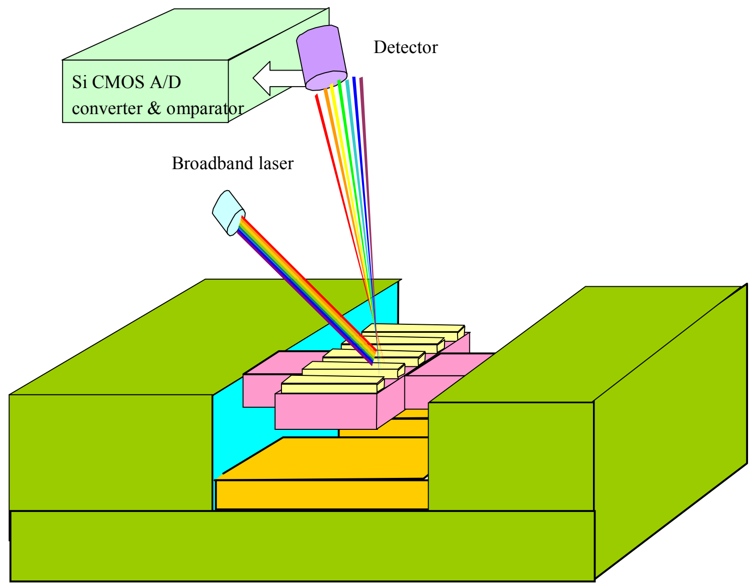
Voltage Controlled Rotation Mirror- Optical MEMS

Vertical Optical Gratings Integrated with Cantilever Structure



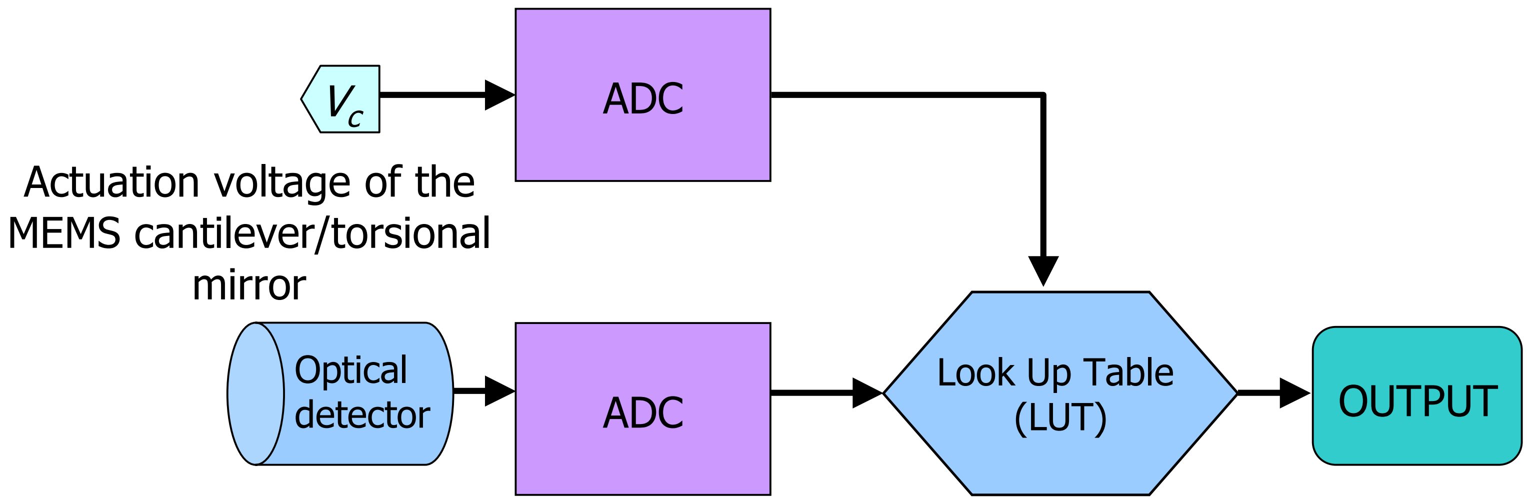
- The vertical grating is hybrid integrated on a conducting plate. The refraction angle of the optical beam is controlled by voltage between two conducting metal plates.
- The absorption spectrum detected is analyzed with known data through the detector array and A/D converter.

Planar Optical Gratings Integrated with Torsional Mirror



- The torsional mirror is first fabricated followed by a planar grating on top of the mirror.
- Similar to vertical gratings, the absorption spectrum is compared with known data and chemical species are identified.

Si CMOS A/D Converter and Comparator



- The actuation voltage of the MEMS cantilever/torsional mirror is related to the tilting angle of the grating mirror. Therefore the wavelength detected corresponds to the actuation voltage.
- The analog signal from the optical detector and the actuation voltage are converted to digital information. The digital data is then compared with known data through the Look Up Table (LUT).
- The bottleneck of the bio-chemical agent recognition time is the actuation speed of the MEMS cantilever.

Sb-Based Near- and Mid-IR Emitters and Detectors

Objective:
- Fabrication of a 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.

Approach:
- Design and fabricate 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.

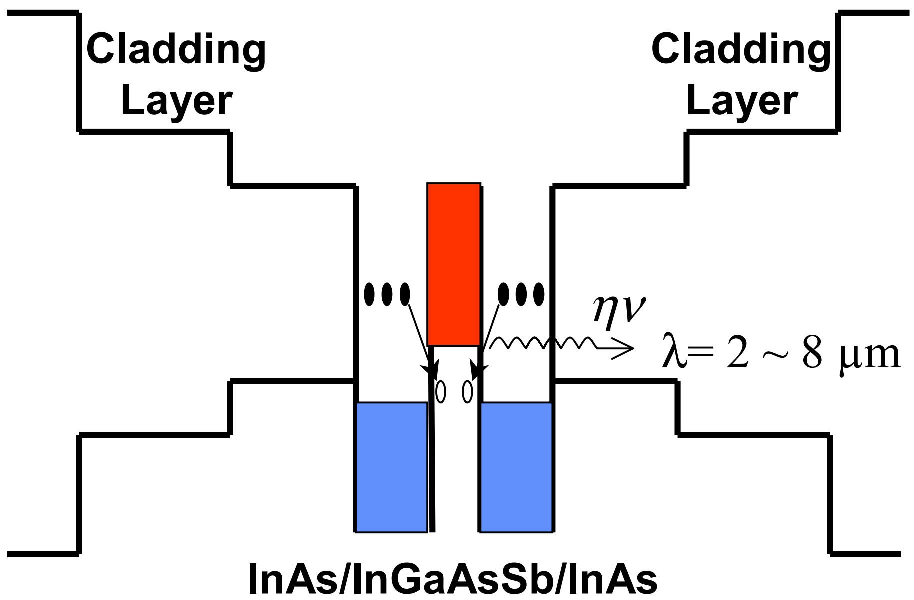
Key Issues:
- Develop a comprehensive theoretical model to optimize type-II QW and cascade device structures.
- Growth of Sb-based IR materials by molecular beam epitaxy.
- Develop Sb-based III-V IR materials using ordered GaInAsSb without cascade structures.
- Using strain-balanced short-period superlattice to extend the response range of Sb-based materials to 5 μm and beyond.

Program Schedule:
- FY01:*Demonstration of extended IR emission structures using ordered materials.
- FY02:*Demonstrate of near-IR emitters and detectors.
- FY03:*Demonstration of mid-IR lasers.
- FY04:*Optimization of near- and mid-IR lasers.

Sb-Based Device Program Tasks

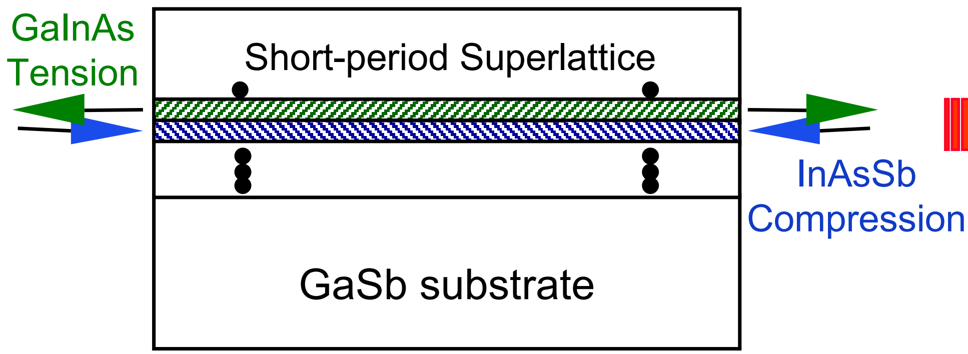
Institution	Investigators	Approach
UIUC	**K. Y. Cheng** **S. L. Chuang** **K. C. Hsieh**	• Theoretical modeling and device design • Quantum cascade lasers • SPS ordered long wavelength detectors • TEM micro-analysis
Columbia	**A. Pinczuk** **H. L. Stormer** **W. I. Wang**	• Type-II W-shape QW lasers • Ordered GaInAsSb long wavelength detectors • Micro-Raman characterization • Low-temperature electrical characterization

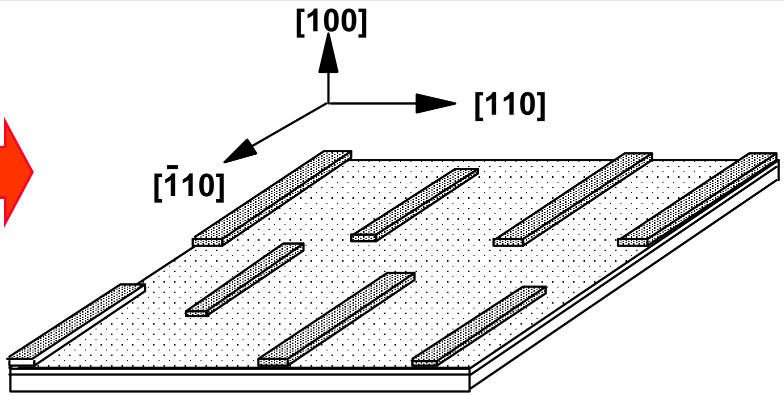
Band Structure Designs of Type-II W-Shape QW Mid-IR Lasers

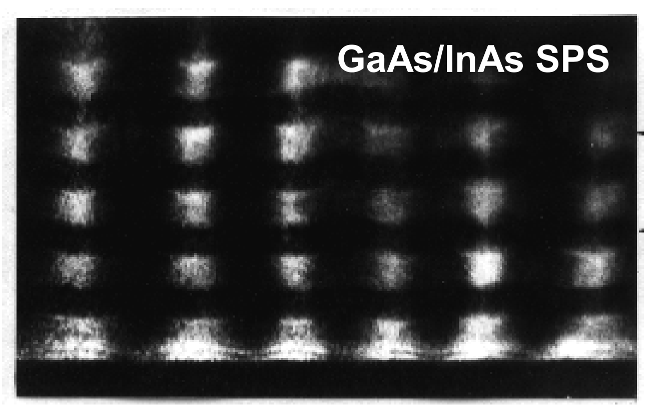


- MBE grown InAs/InGaAsSb/InAs type-II W-shape QW on GaSb
- Minimized Auger recombination loss
- Needs optimized active region design to enhance the lasing efficiency.

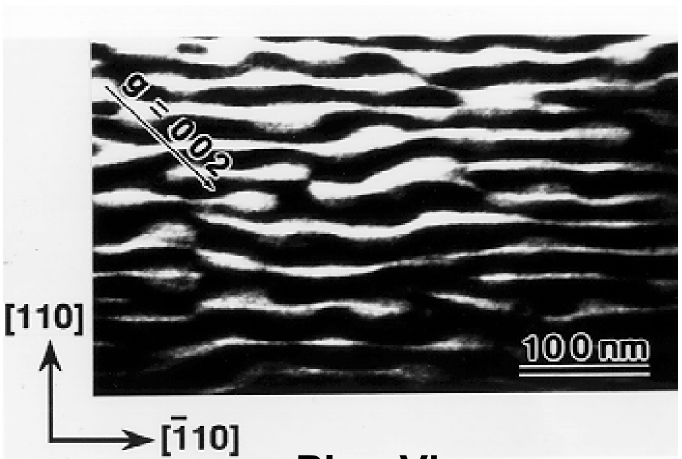
InGaAsSb Mid-IR Material with Extended Wavelength







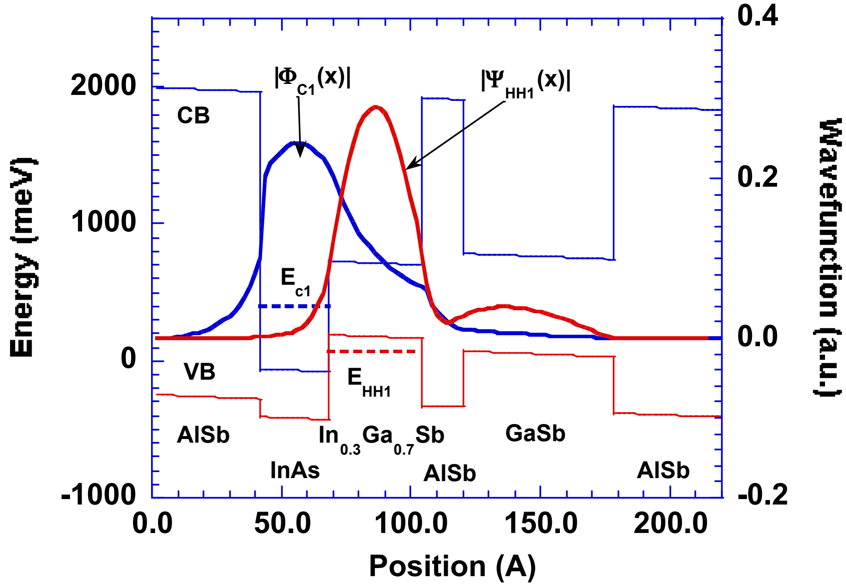
Cross-Section View



Plan-View

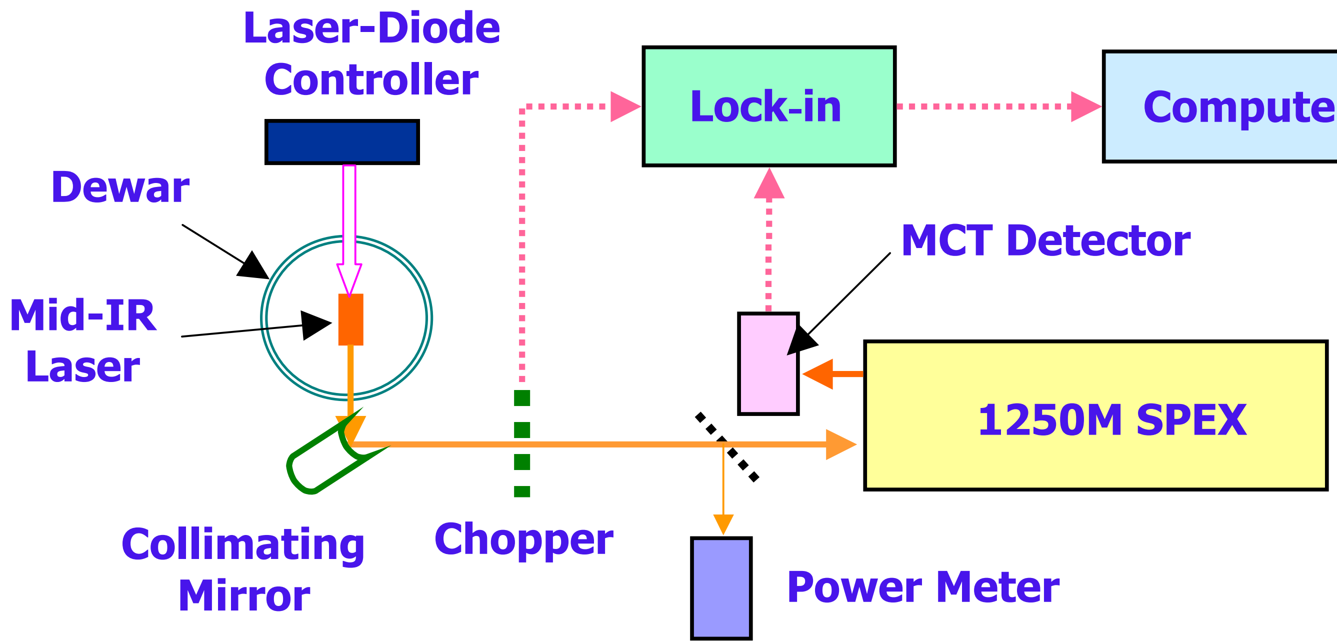
- Utilizing strain-induced ordering to extend wavelength range
- $\lambda \approx 5$ µm and beyond can be achieved in GaInAsSb quantum wires using strain-balanced (GaInAs)/(InAsSb) short-period superlattice (SPS).

Type-II QW:Sb-Based Mid-IR QC Lasers— S. L. Chuang



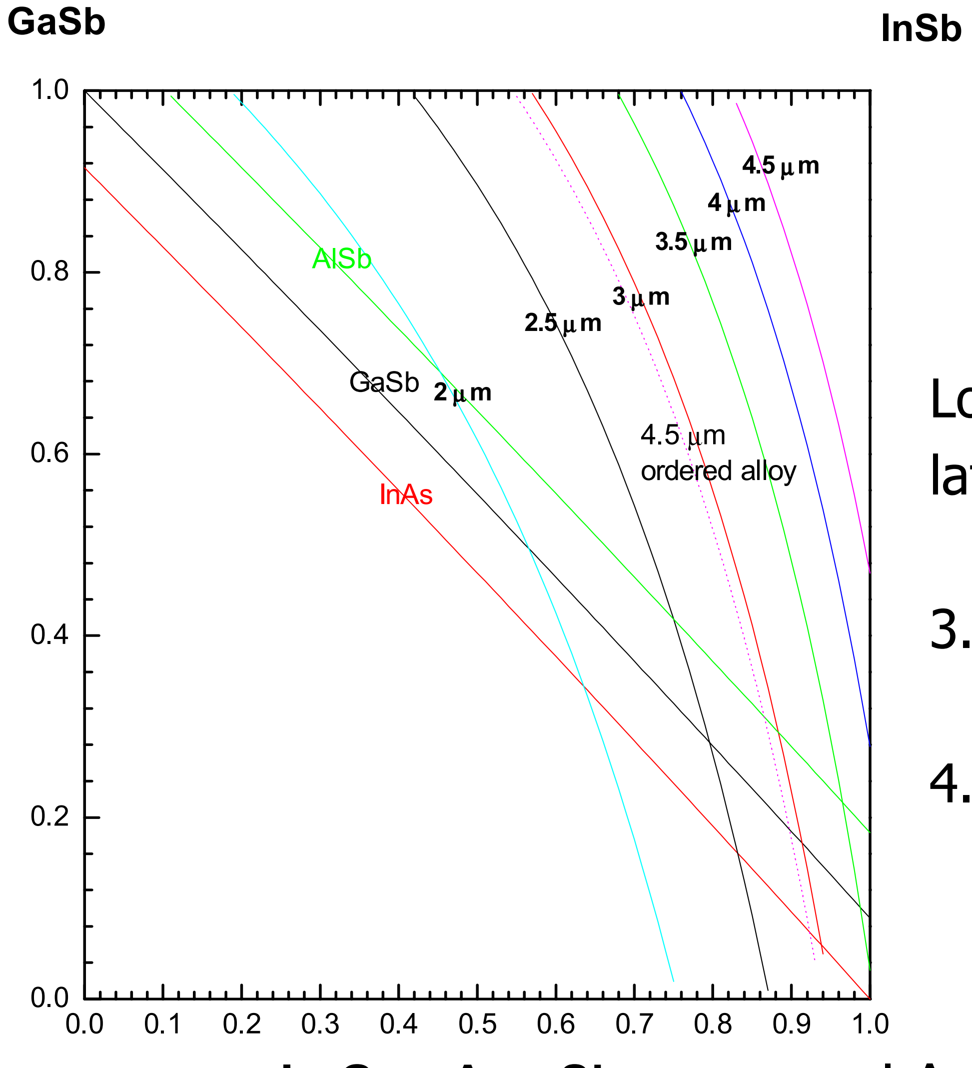
- The active region for one stage of a type-II Sb-based quantum-cascade laser is modeled.
- An 8×8 block-diagonalized Hamiltonian block-diagonalized into two 4×4 matrices with the coupling between the conduction and valence band is used.
- Band structures and wave functions are solved self-consistently.

Spectrum Measurements for Mid-IR Lasers—S. L. Chuang



- Experiment for measuring the spectra of mid-IR lasers is planned
- Mid-IR lasers from the Army Research Laboratory (ARL), the Naval Research Laboratory (NRL), and Bell Labs (Lucent Technologies) will be tested. The laser spectrum dependence on the current and temperature will be studied

Ordered InGaAsSb alloys for long wavelength lasers and detectors



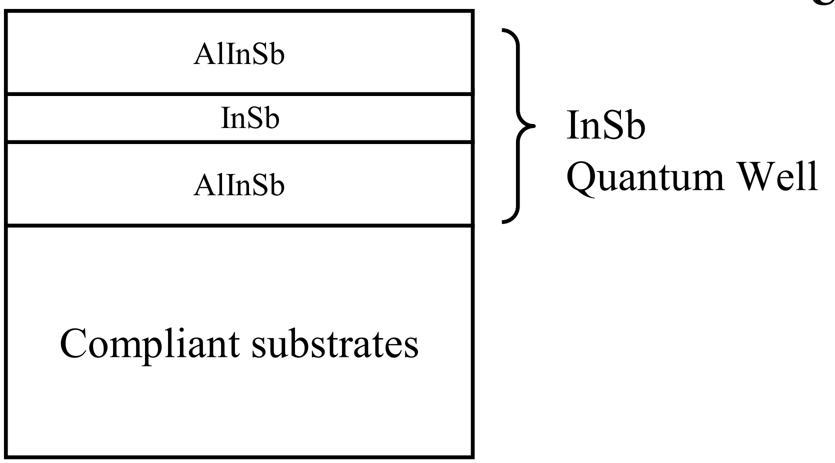
$In_xGa_{1-x}As_{1-y}Sb_y$

Longest wavelength of InGaAsSb lattice-matched to GaSb

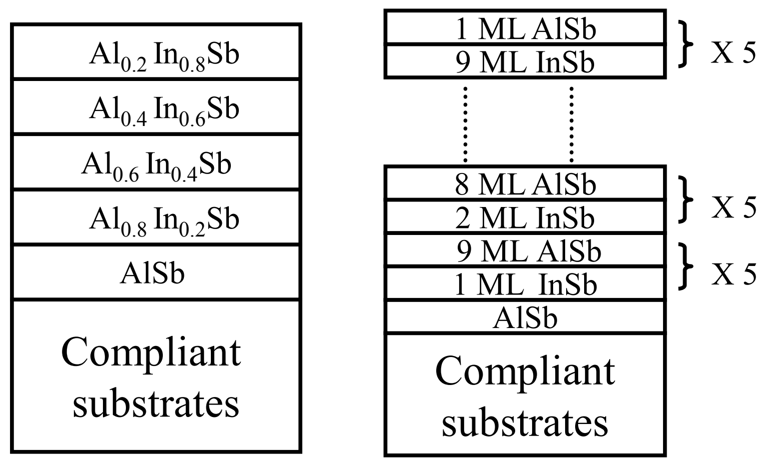
3.5 µm for disordered InGaAsSb

4.5 µm for ordered InGaAsSb (the dotted curve)

InSb Quantum Wells
for IR Sources and Detectors



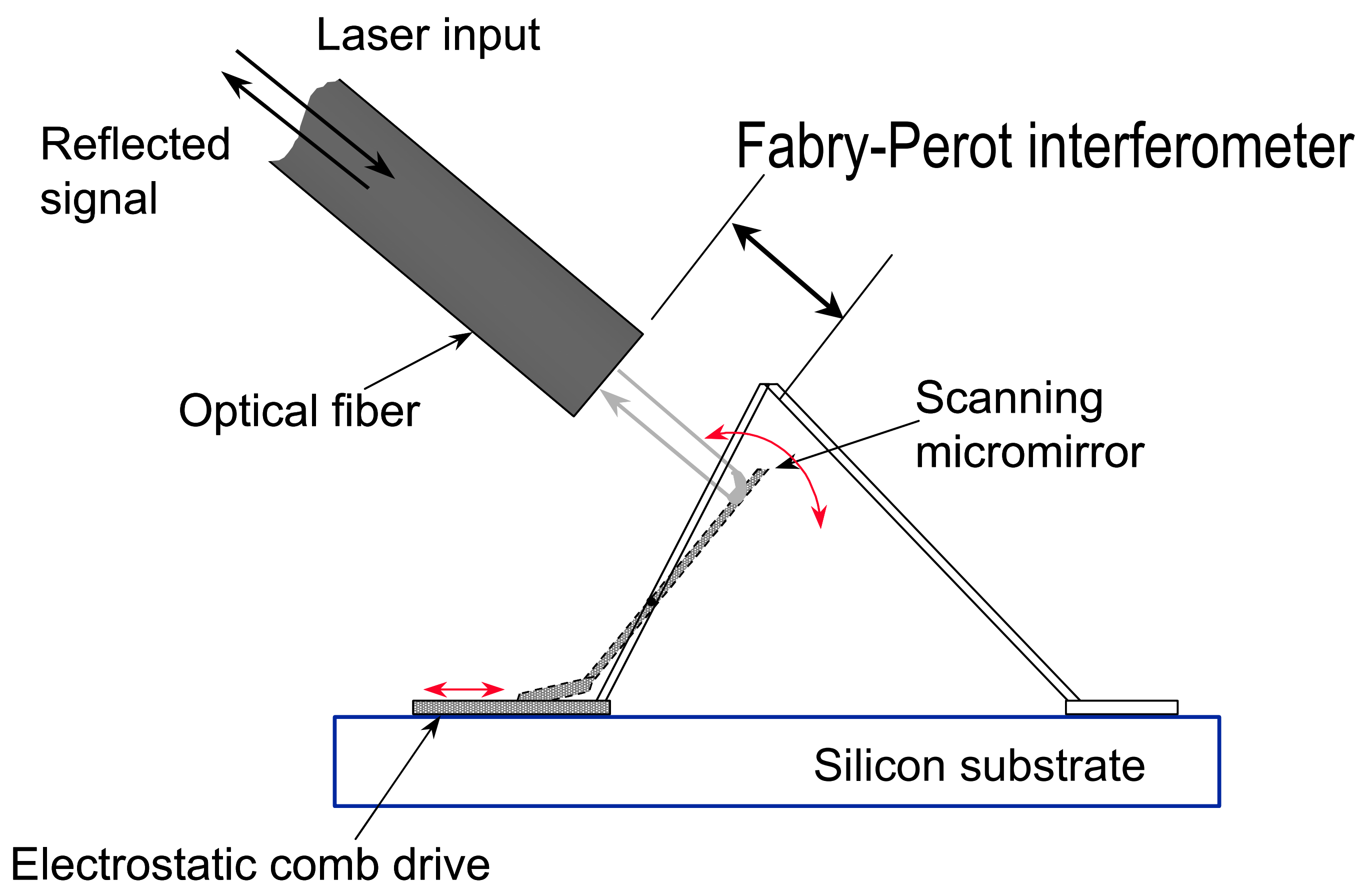
Use step grading (left) and digital (right) growth to achieve device quality AlInSb buffer



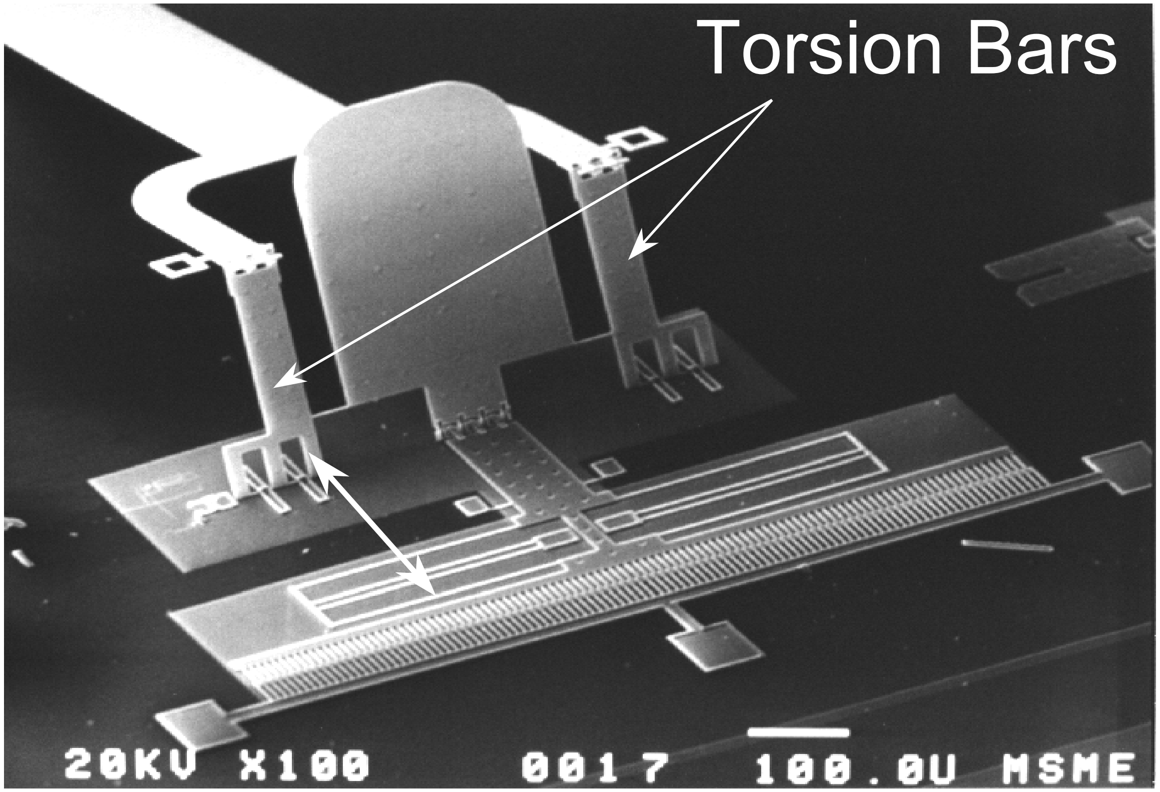
- Wen Wang - MBE growth and devices
- Aron Pinczuk - Optical characterizations
- Horst Stormer - Transport characterizations

Fast Scanning MEMS Spectrometer

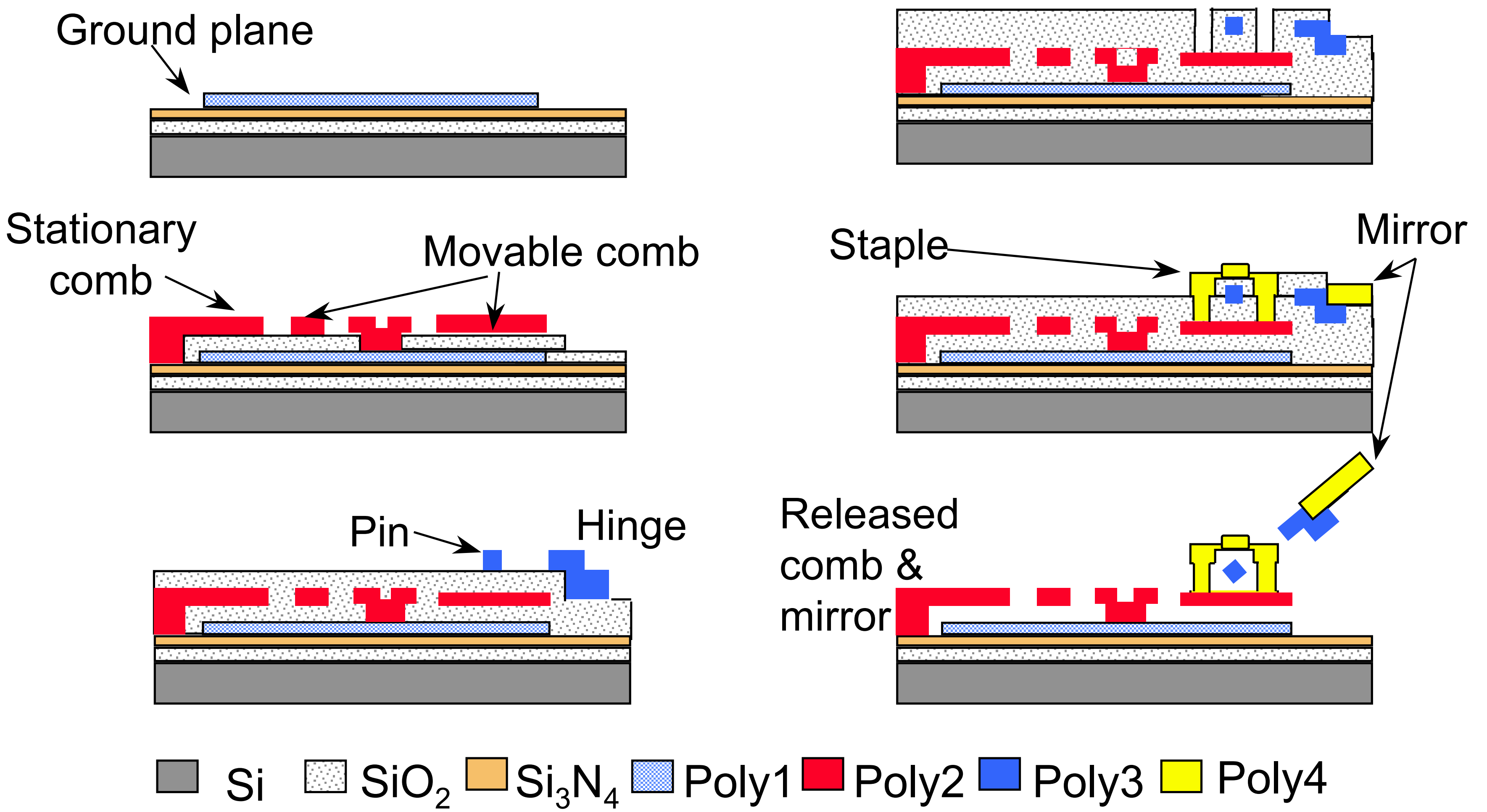
U.C. Berkeley – Kam Y. Lau



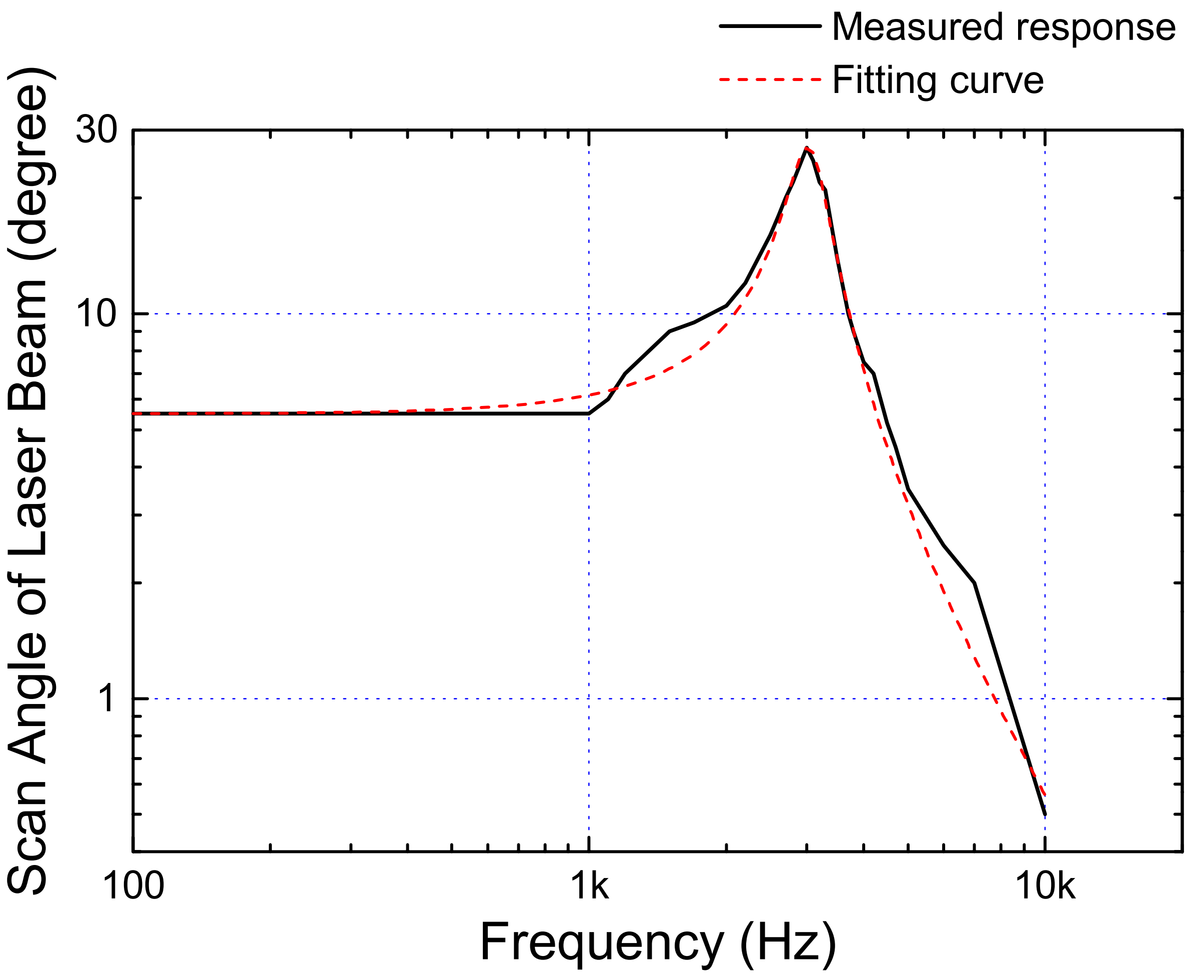
SEM Picture of Fast MEMS Scanner



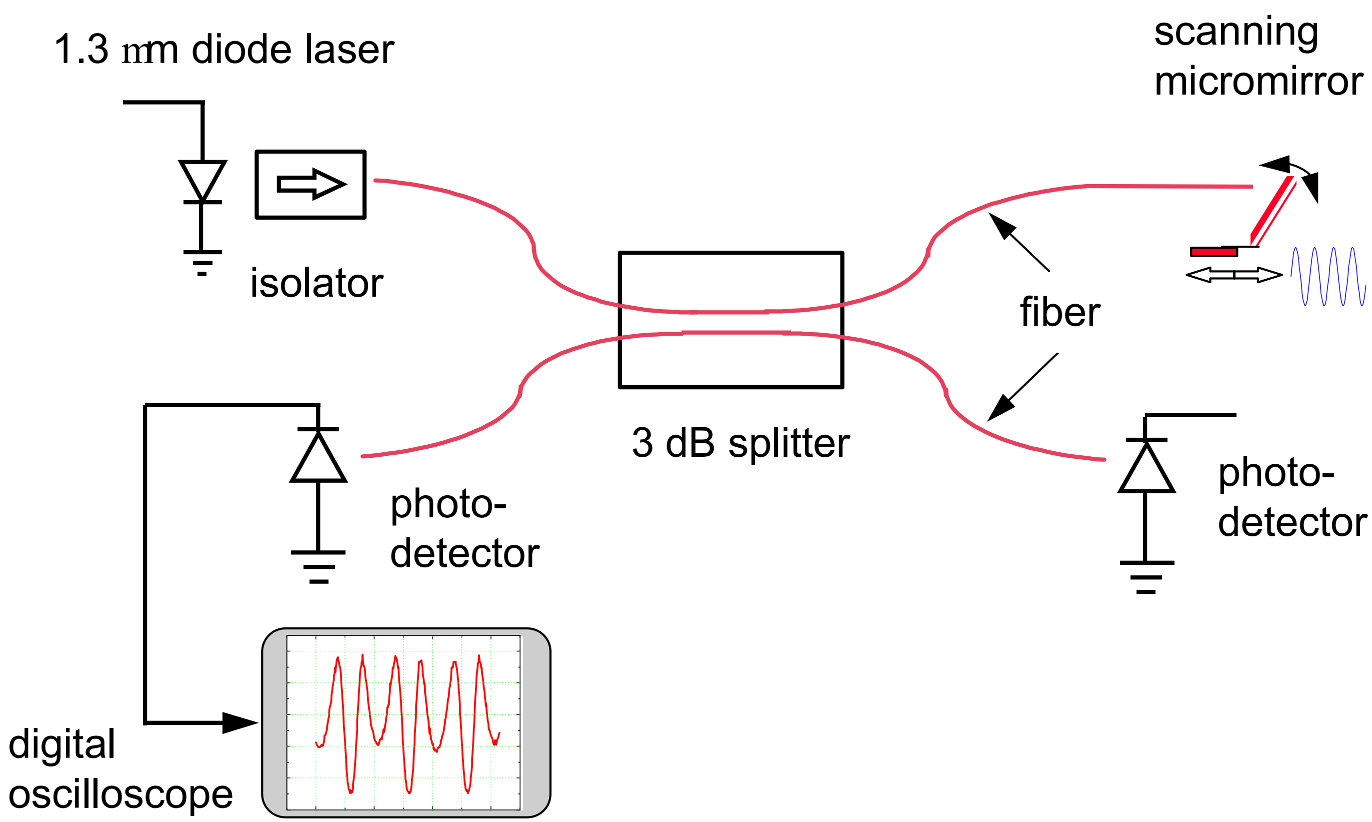
Fabrication Process of Fast MEMS Scanner



Frequency Response of MEMS Scanning Spectrometer

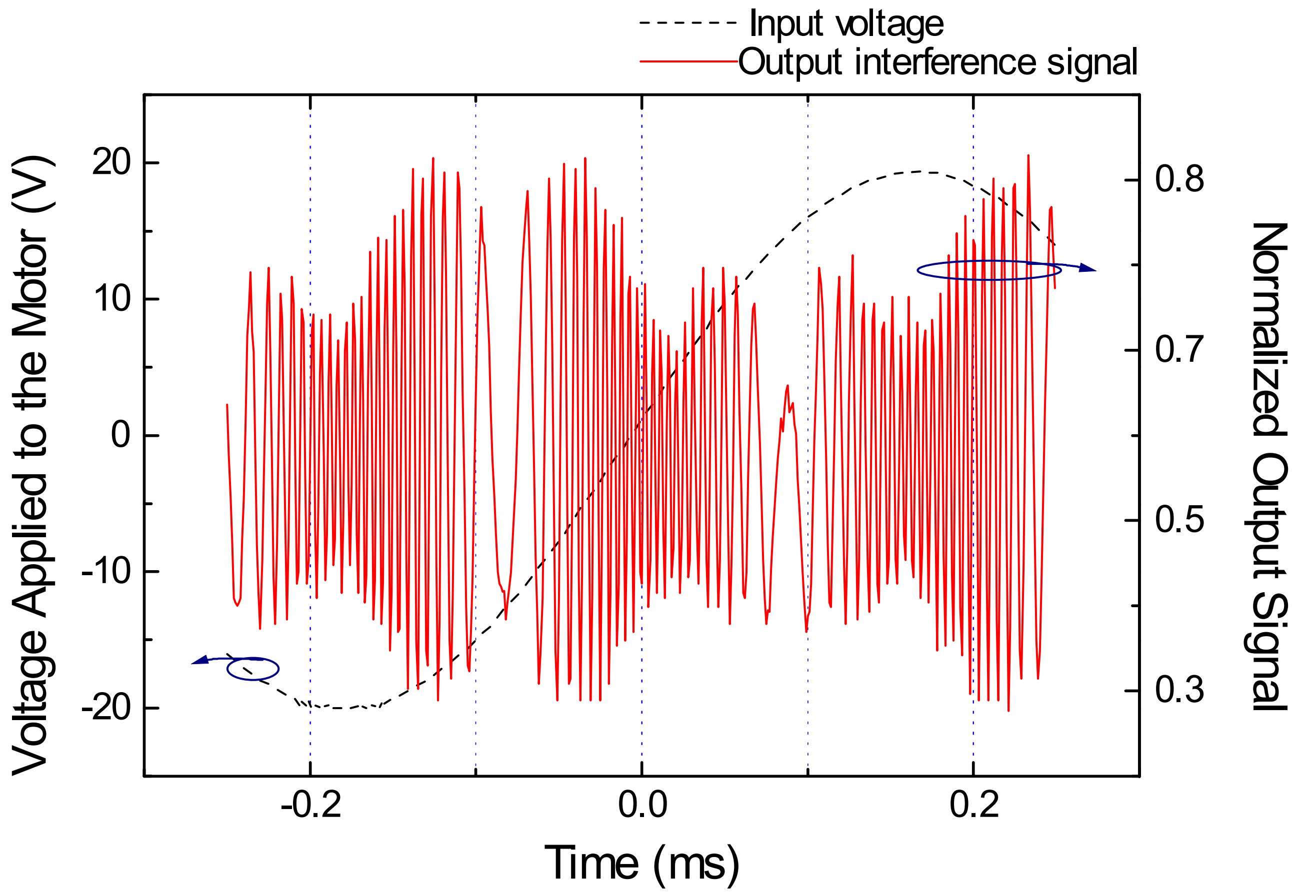


Experimental Demonstration of MEMS Scanning Interferometer



Measurement Results of MEMS Scanning Interferometer

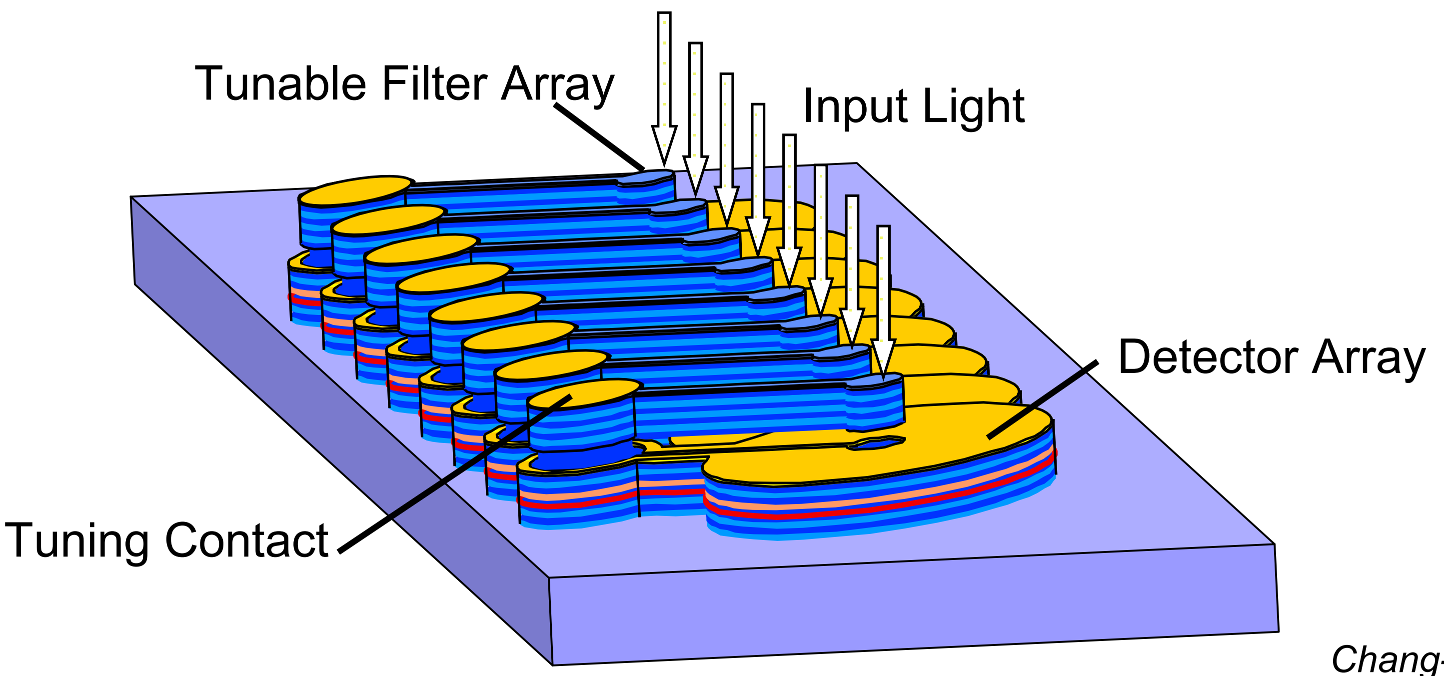
Interferometer scanning range – 8.5mm



Lock-in Spectrometer-on-a-Chip

Connie Chang-Hasnain

- Objectives
  - 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 $\Delta\lambda/\lambda_s$=30-50%
  - First lock-in detection on a chip



Chang-Hasnain Group

Technical Approach I

- Evaluation of single tunable detector (with option of lock-in detection)
  - Sensitivity and minimum detectivity with lock-in detection
  - High speed response
  - Dynamic range
  - Filter material of Choice: GaAs/AlAs, GaAs/AlOx, dielectric
  - Tuning range and spectral resolution tradeoff
  - On-chip wavelength calibration and referencing

- Establish a close collaboration in Bio-engineering to understand the application needs

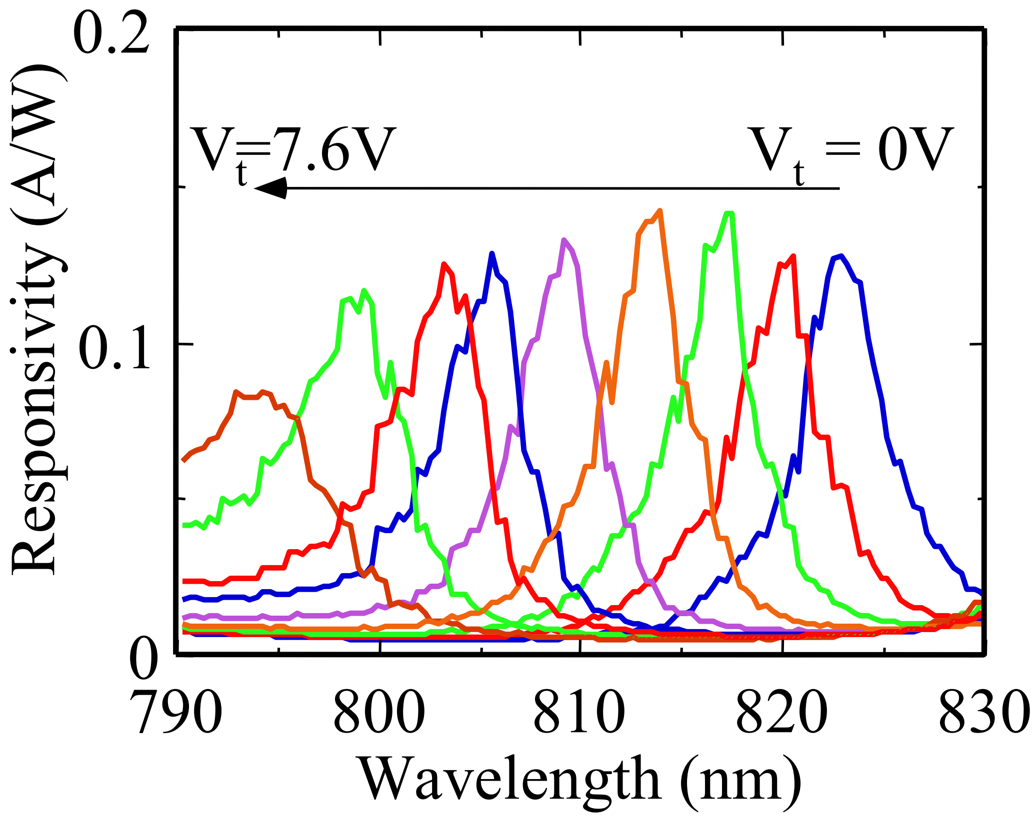
Technical Approach II

- Start with GaAs-based tunable detector array at 0.7-1 μm
  - Application:
    - Cancer cell study (collaboration with Luke Lee at UCB Bioengineering)
    - Explore new spectral finger prints: using the new capability of time-resolved and space-resolved spectra detection
  - First demonstration of the concept
  - Array related issues
    - Array size and density, electrical crosstalk, scalability
  - Wide spectra range:
    - Array of detectors with spatially-chirped center wavelengths to cover a wider range of spectra
  - Simplicity vs. versatility
    - One tuning electrode vs. N tunable electrodes

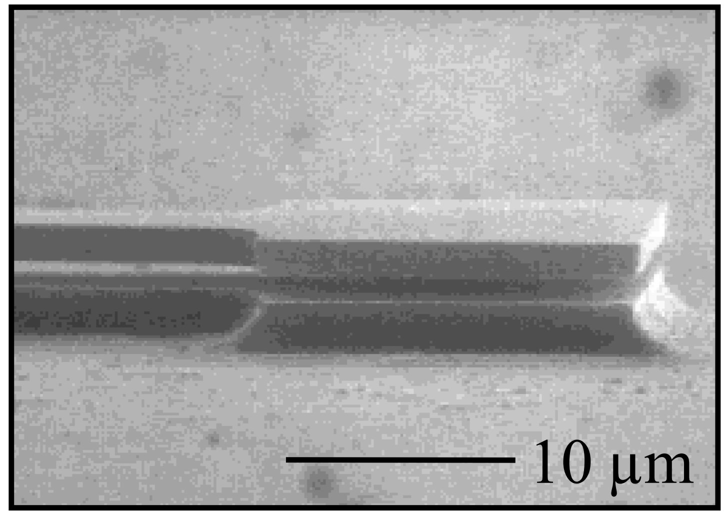
Technical Approach III

- Design and fabricate detector array for other wavelength regime of interests: 1.3-1.8um, 2-3um, 8-10um
  - Detailed understanding of applications
  - Establish test and measurement capability to extend towards other wavelengths of interest
  - Establish design and fabrication capability to extend towards other wavelengths of interest

Single Tunable Detector



Filter close-up



- 30 nm continuous tuning achieved ($\Delta\lambda/\lambda$ = 3.7 %)
- Responsivity of 0.14 A/W with σ = 10 % achieved
- 20 % quantum efficiency is achieved

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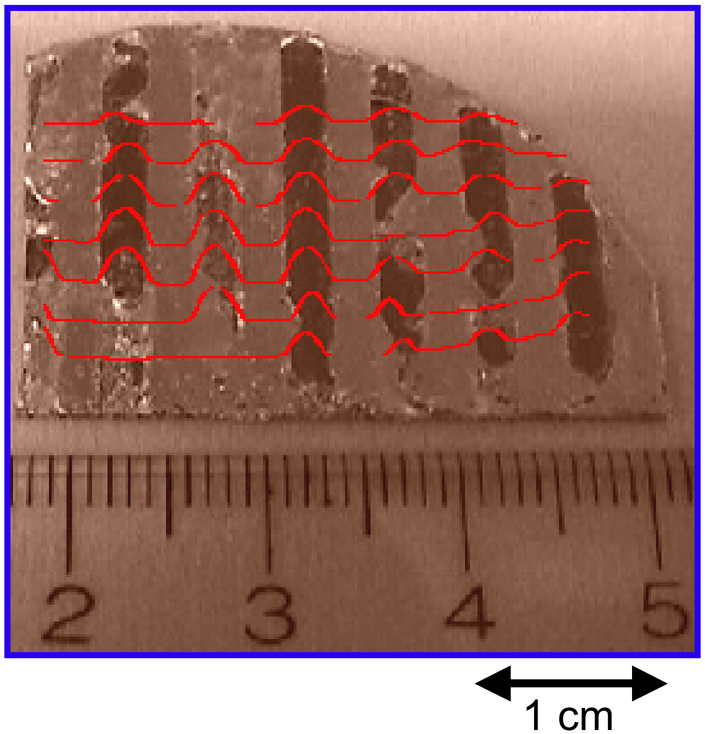
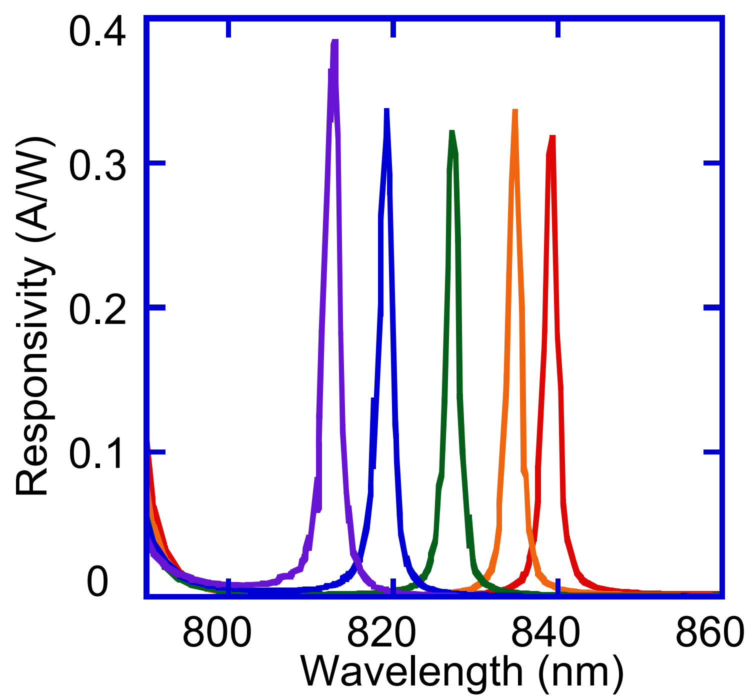
Spatially Graded Single-Wave Detectors

- Periodic detector arrays are achieved using periodically patterned substrate growth
- Max 132 nm/mm wavelength spread was obtained previously – a great leverage to obtain a wider spectra range





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