Optical MEMS in Compound Semiconductors

Advanced Engineering Materials, Cal Poly, SLO

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AOM

ADVANCED OPTICAL

MICROSYSTEMS

Outline

- Brief Motivation
- Optical Processes in Semiconductors
- Reflectors and Optical Cavities
- Diode Lasers and Amplifiers
- Tunable Microcavity Devices

Motivation

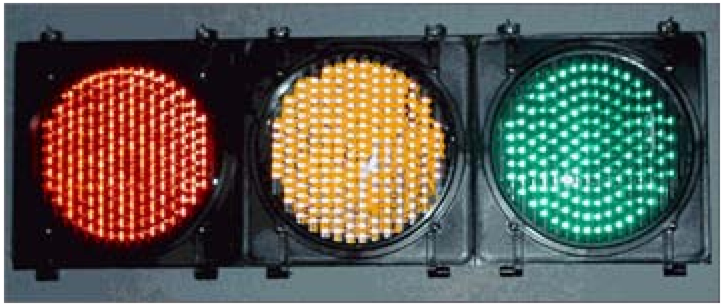
Extending the functionality of microsystems (sensors, actuators, etc.) to realize 'optically active' structures

- Microelectromechanical systems (MEMS) are typically fabricated in silicon using procedures borrowed from integrated circuit manufacturing
- Compound semiconductors have unique properties
  - capable of efficient light absorption and emission
  - high carrier mobility and novel electronic properties
  - potential to utilize piezoelectric effects
- Integrating micromechanical elements allows for:
  - "dynamic" sources (capable of wavelength tunability)
  - sensors and actuators with optical functionality

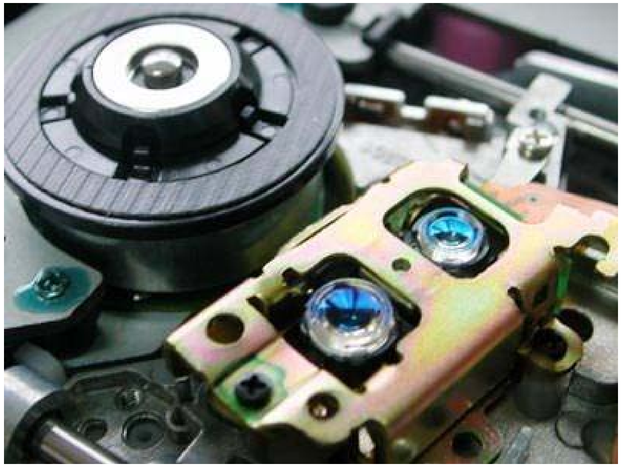
Motivation

Compound semiconductor photonic devices

- Light emitting diodes

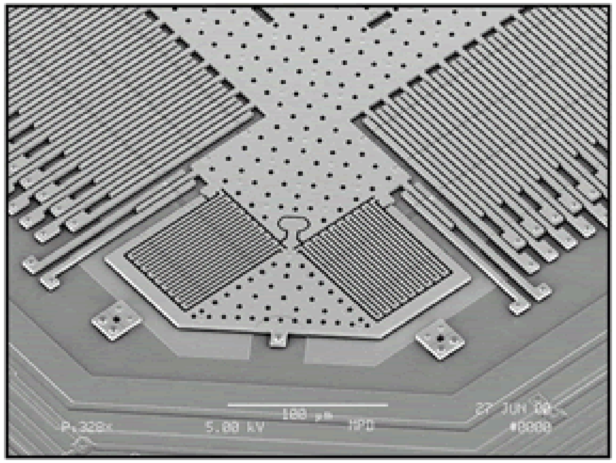


- Diode lasers (from DVDs to fiber optic networks)

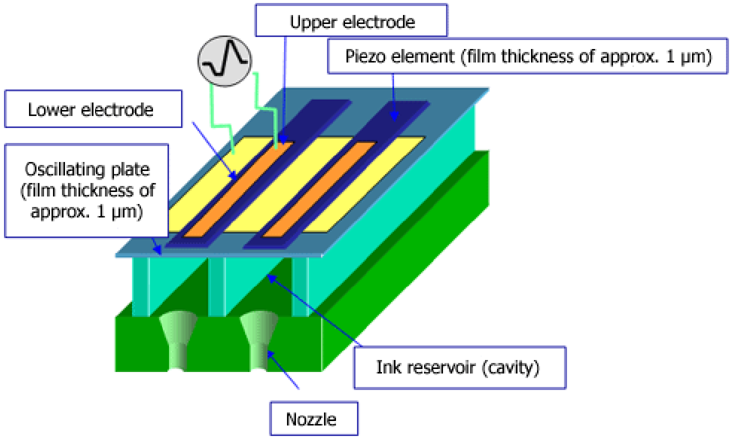


Motivation

Microelectromechanical systems (MEMS)



- Accelerometers
- Ink jet printer cartridges
- Digital mirror devices

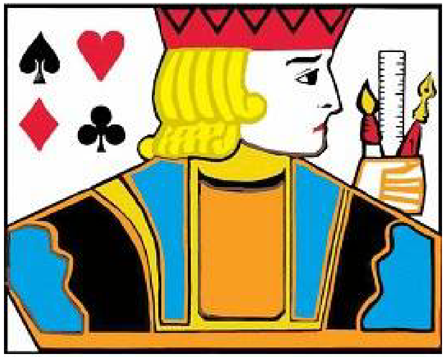


Motivation

The convergence of photonics and MEMS

- Potential for ‘dynamic’ optically active devices
  - not simply passive reflectors for shuffling photons
  - active manipulation of light: production, detection, amplification

- Incorporates a broad spectrum of scientific disciplines
  - solid state physics
  - quantum mechanics
  - classical mechanics
  - materials science
  - chemistry
  - electrical engineering
  - mechanical engineering



JACK of all Trades

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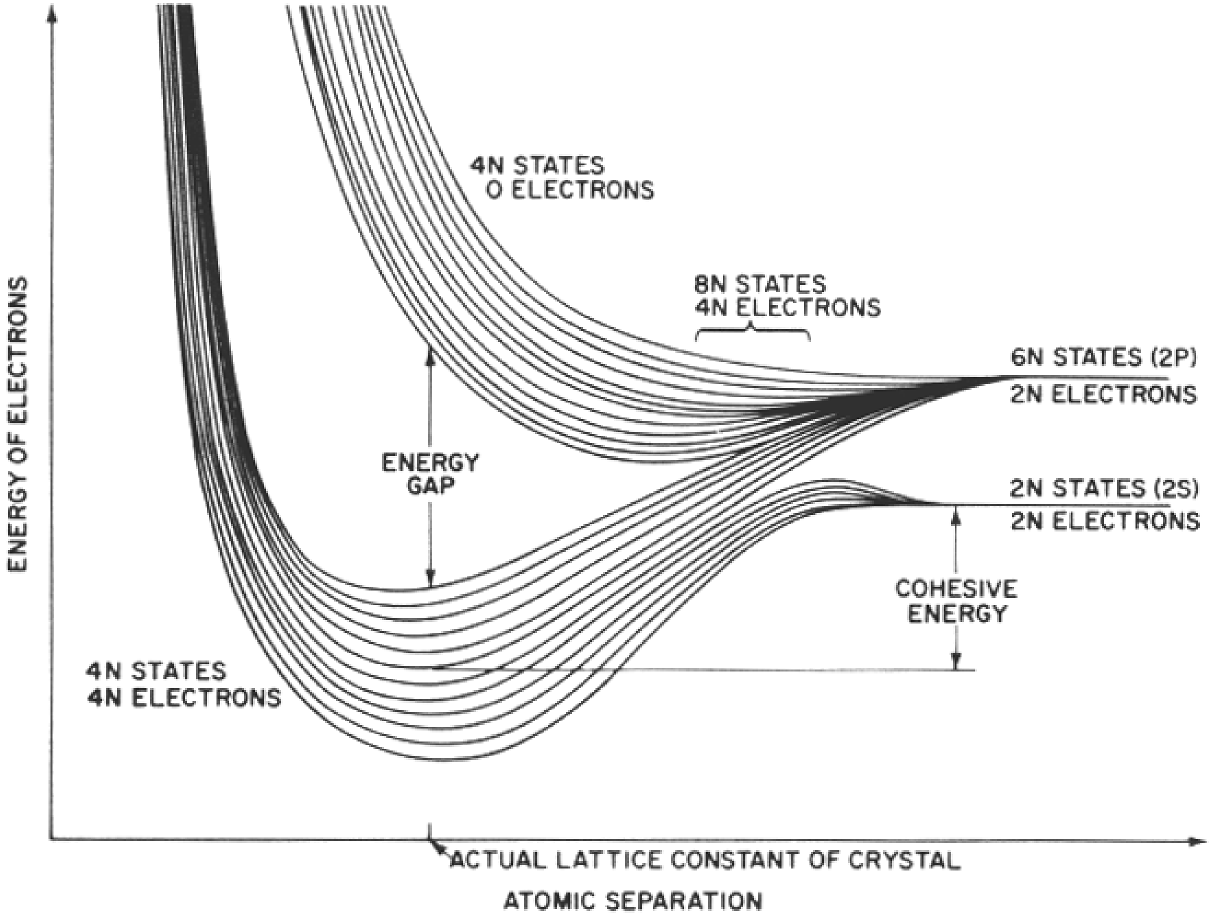
Band Theory of Solids

- Isolated atoms exhibit discrete emission/absorption lines
  - electrons are bound within well-defined states



- In solids these states broaden into "bands"
  - Pauli exclusion principle drives splitting of levels
  - electrons seek to occupy lowest available states

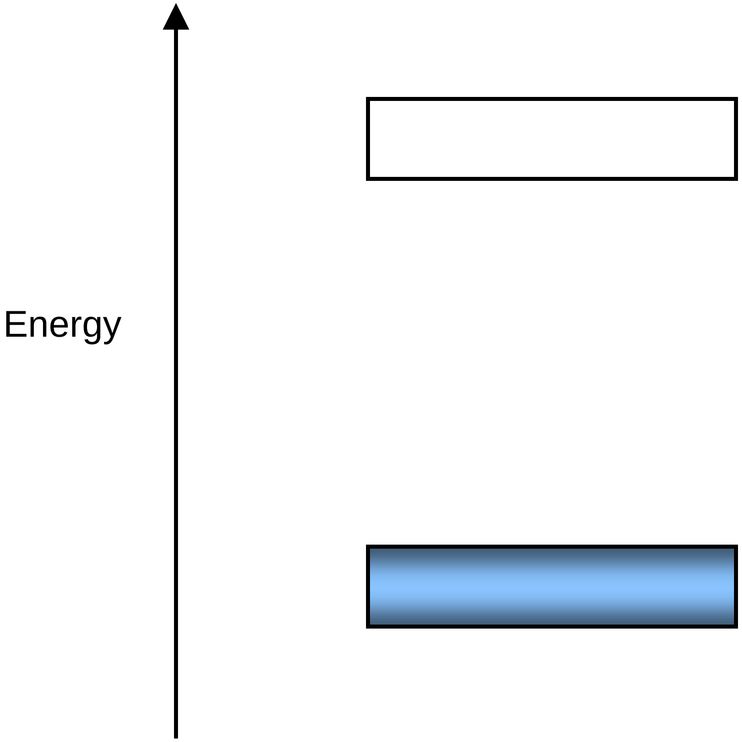
Band Theory of Solids

- Occupancy of the bands, as well as their energy separation determines the electronic properties of the material
  - atomic valence structure has large impact on properties

- Insulators
  - filled bands with **large** energy gap between

- Metals
  - partially filled or overlapping bands

- Semiconductors
  - basically insulators with a reduced gap



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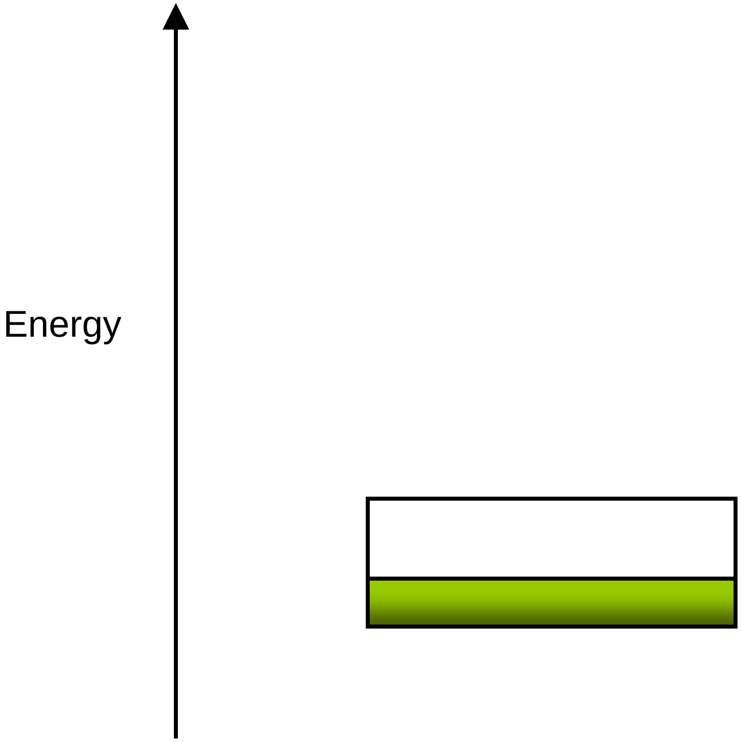

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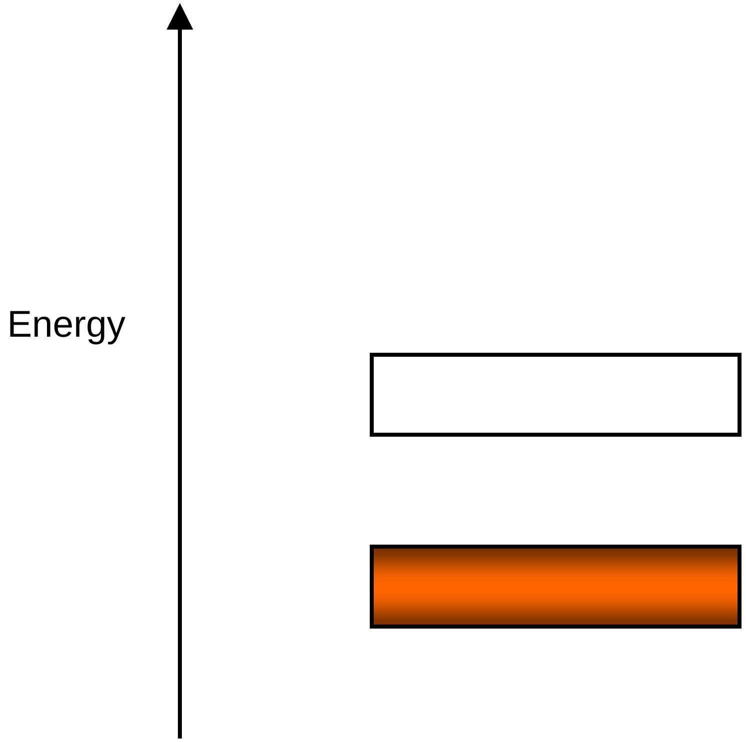
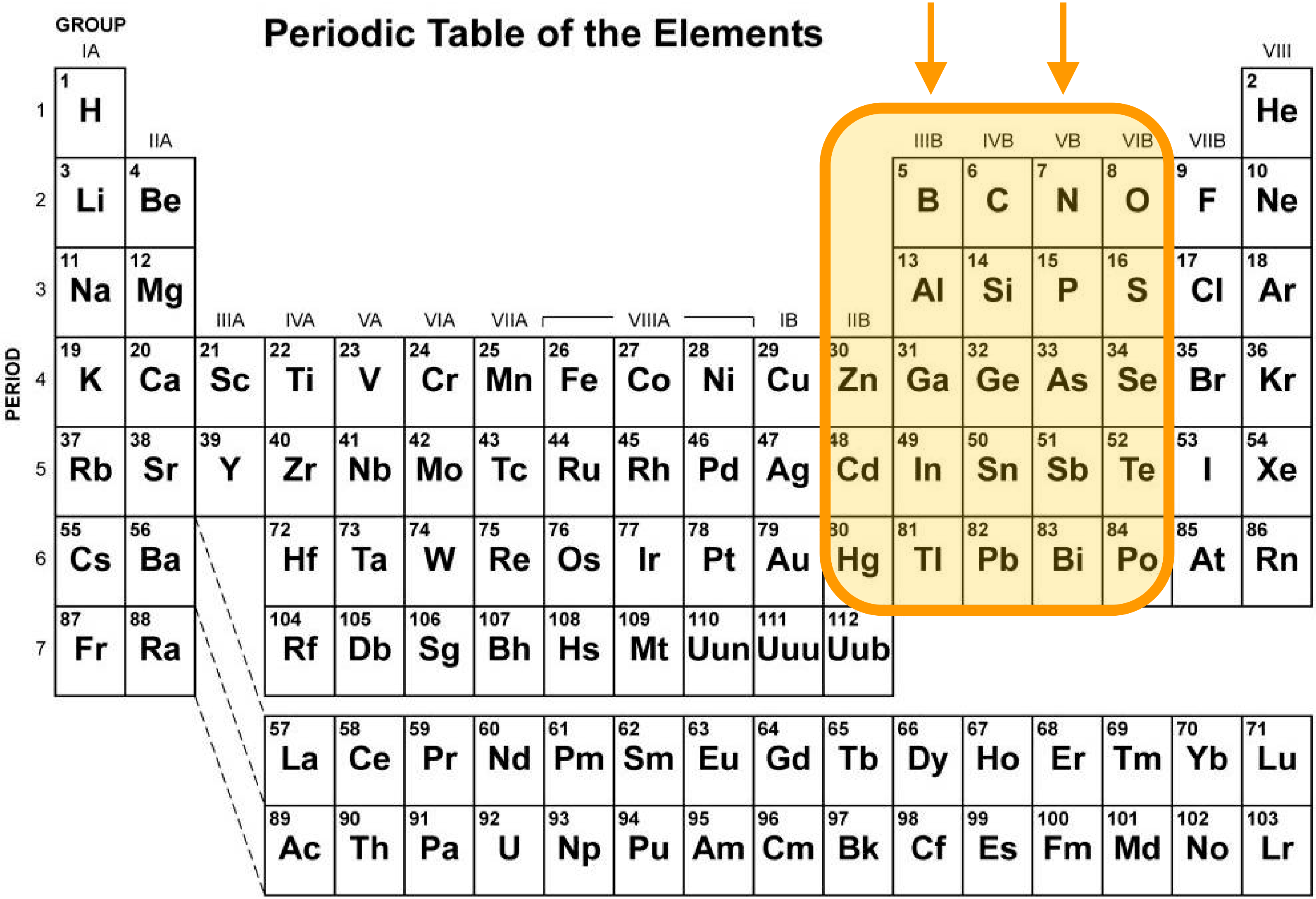


Relevant Materials

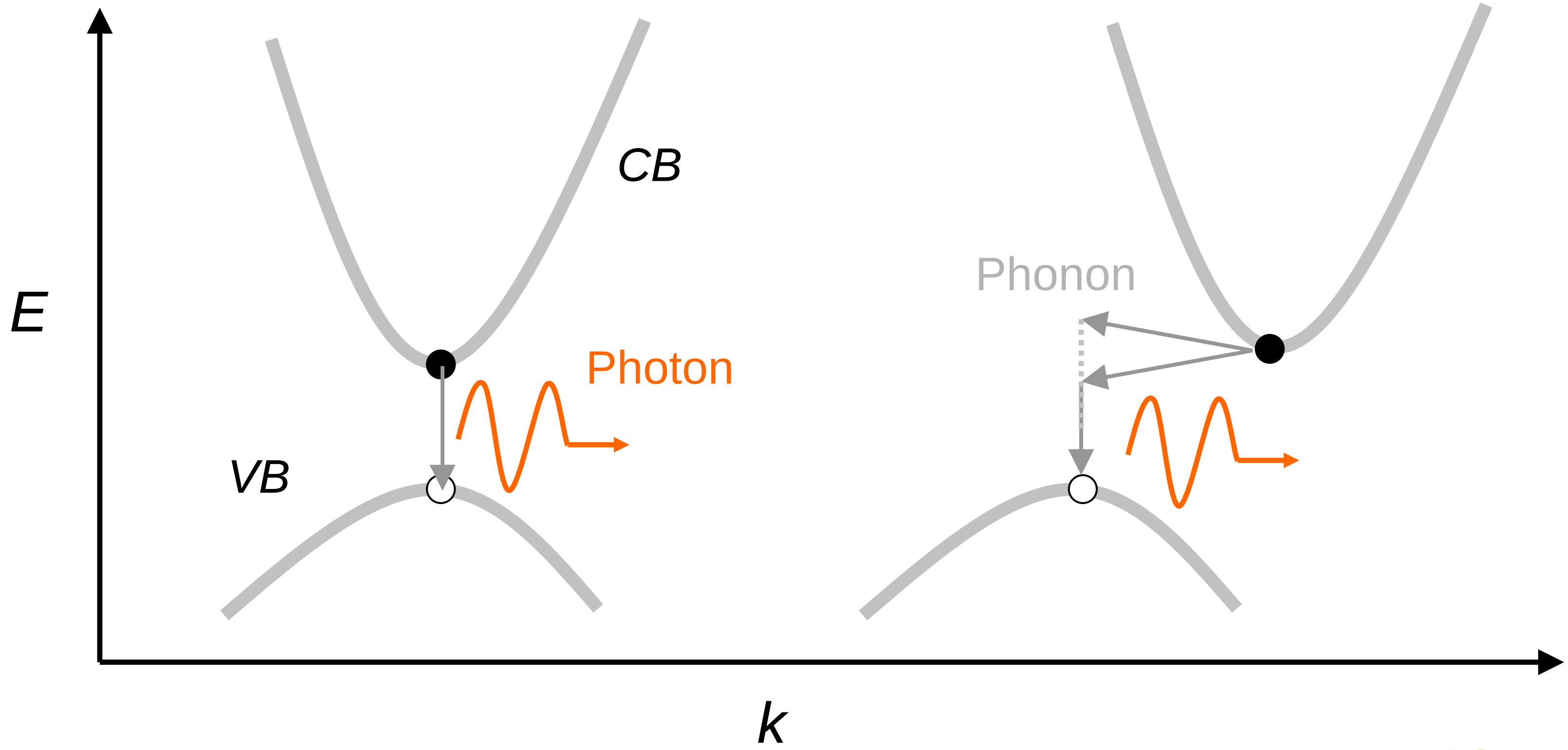


Periodic Table of the Elements

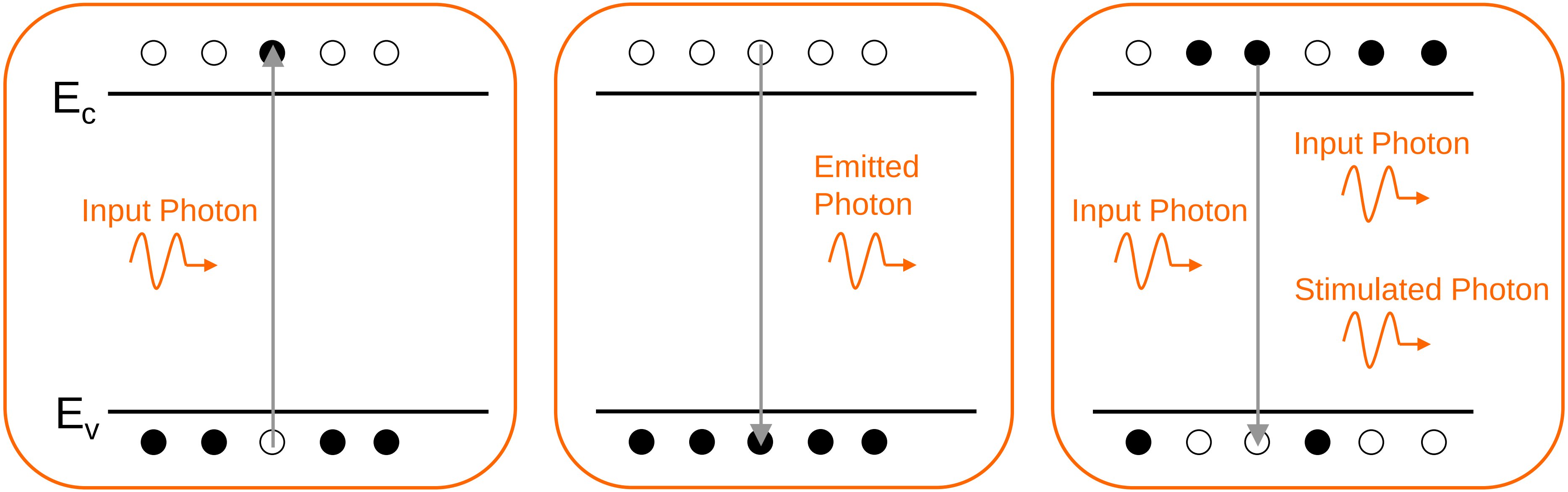
PERIOD	GROUP IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						
				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Optically 'Active' Materials

- Two distinct band structures: direct vs. indirect
  - photons have very low momentum
  - phonons required for momentum transfer
  - direct bandgap exhibits efficient emission/absorption

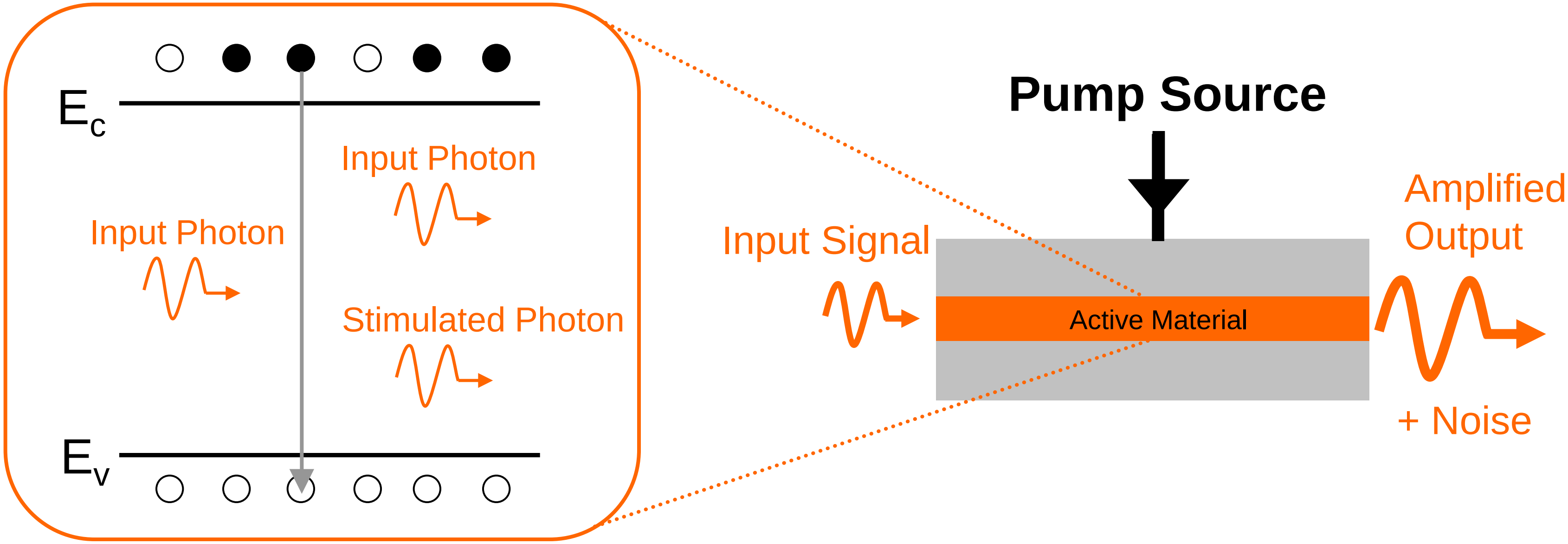


Absorption and Emission Processes



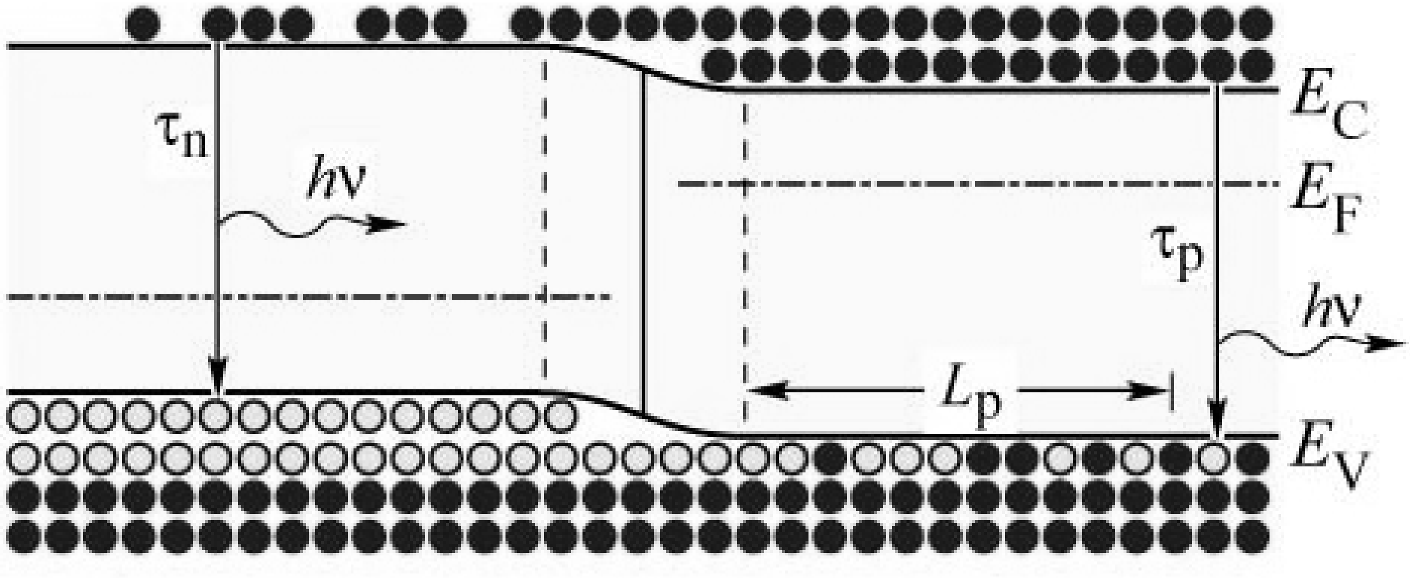
- ***stimulated absorption*** = photo-excitation of electron (e^-)
- ***spontaneous emission*** = relaxation of e^-, random photon out
- ***stimulated emission*** = photo-induced relaxation, identical photon

Optical Amplification



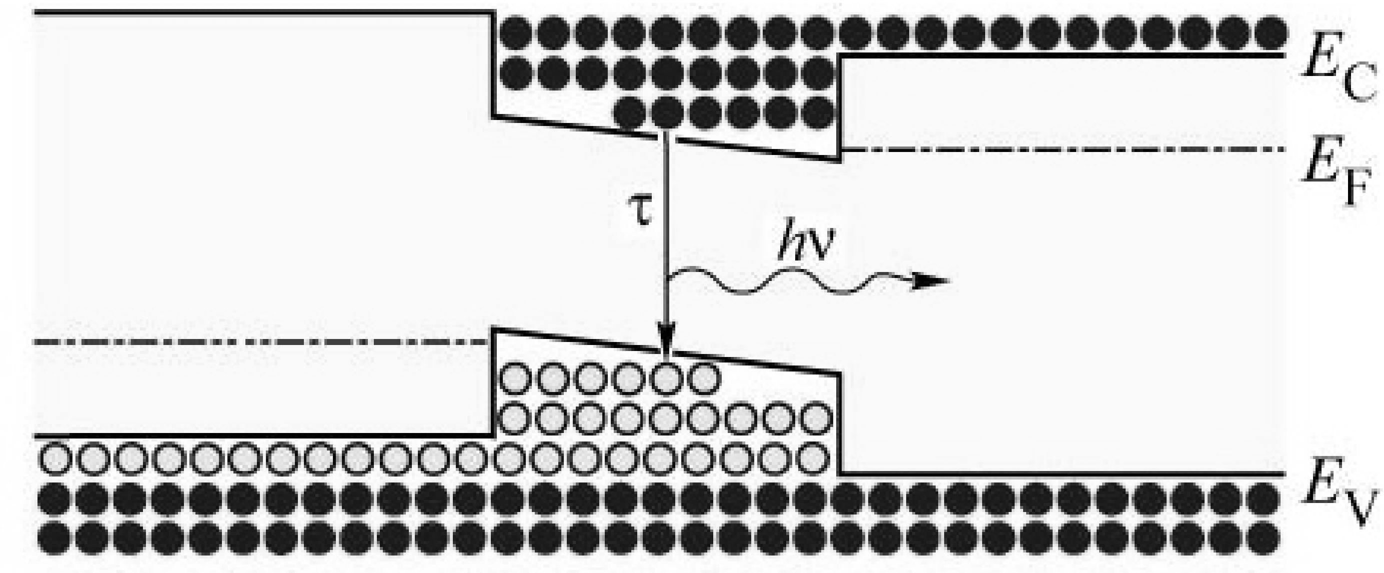
- Photon amplification through stimulated emission of radiation
  - input photon induces electrons to transition from CB to VB
  - stimulated photon is identical in all respects to the input photon
  - 1 photon in = *N* photons out

Direct Electrical Injection: p-n junction



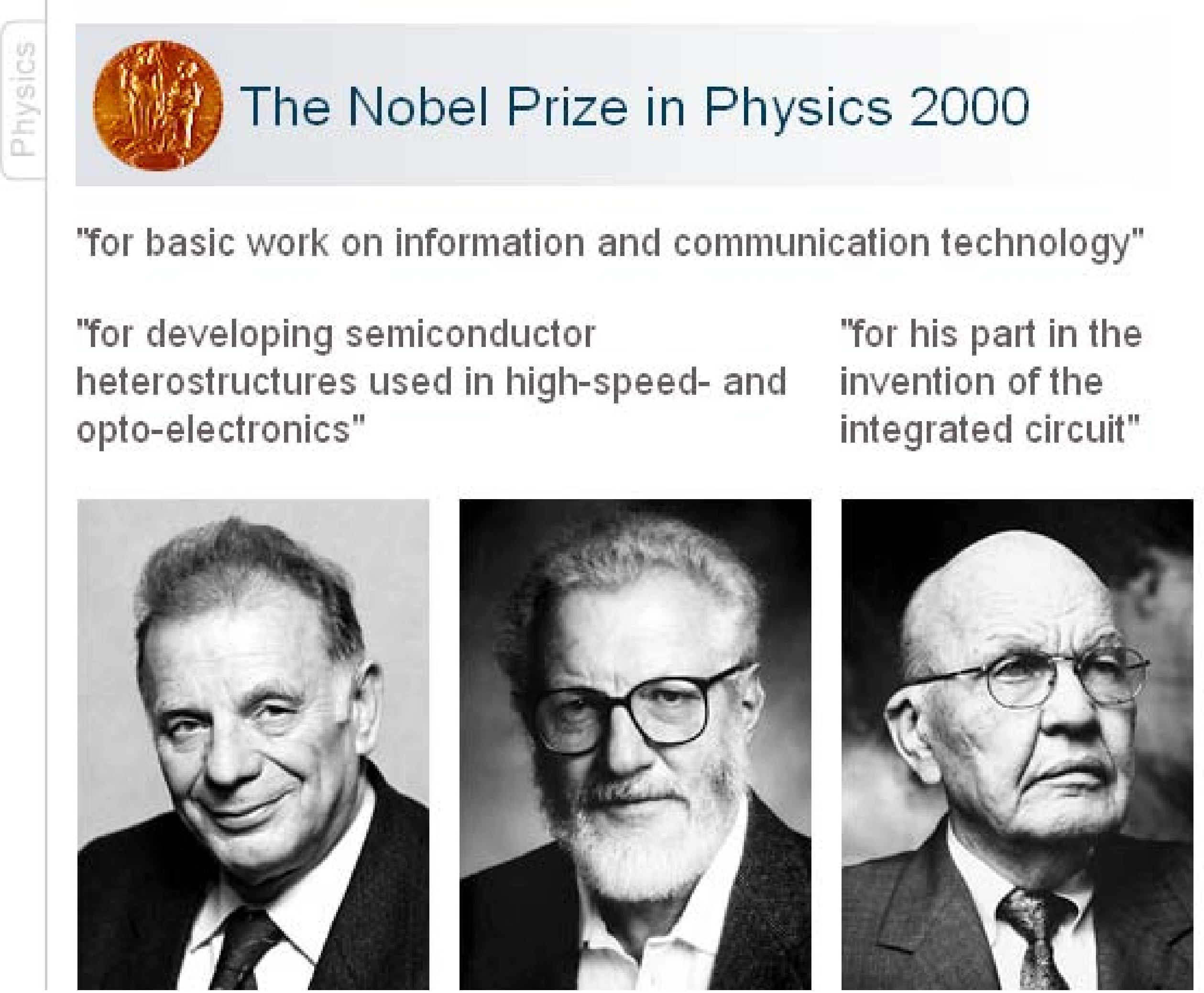
- Forward biased p-n **homo**junction
  - carriers combine (near) depletion region under forward bias
  - possibility for creating a population inversion at junction
- Unfortunately, efficiency of these structures is rather poor
  - carrier leakage past junction and optical re-absorption

Direct Electrical Injection: p-n junction



- Forward biased p-n **hetero**junction
  - carriers *confined* to depletion region
  - population inversion at junction
- Efficiency of these structures largely exceeds homojunctions
  - carrier leakage and optical re-absorption reduced

The Semiconductor Heterostructure



Physics

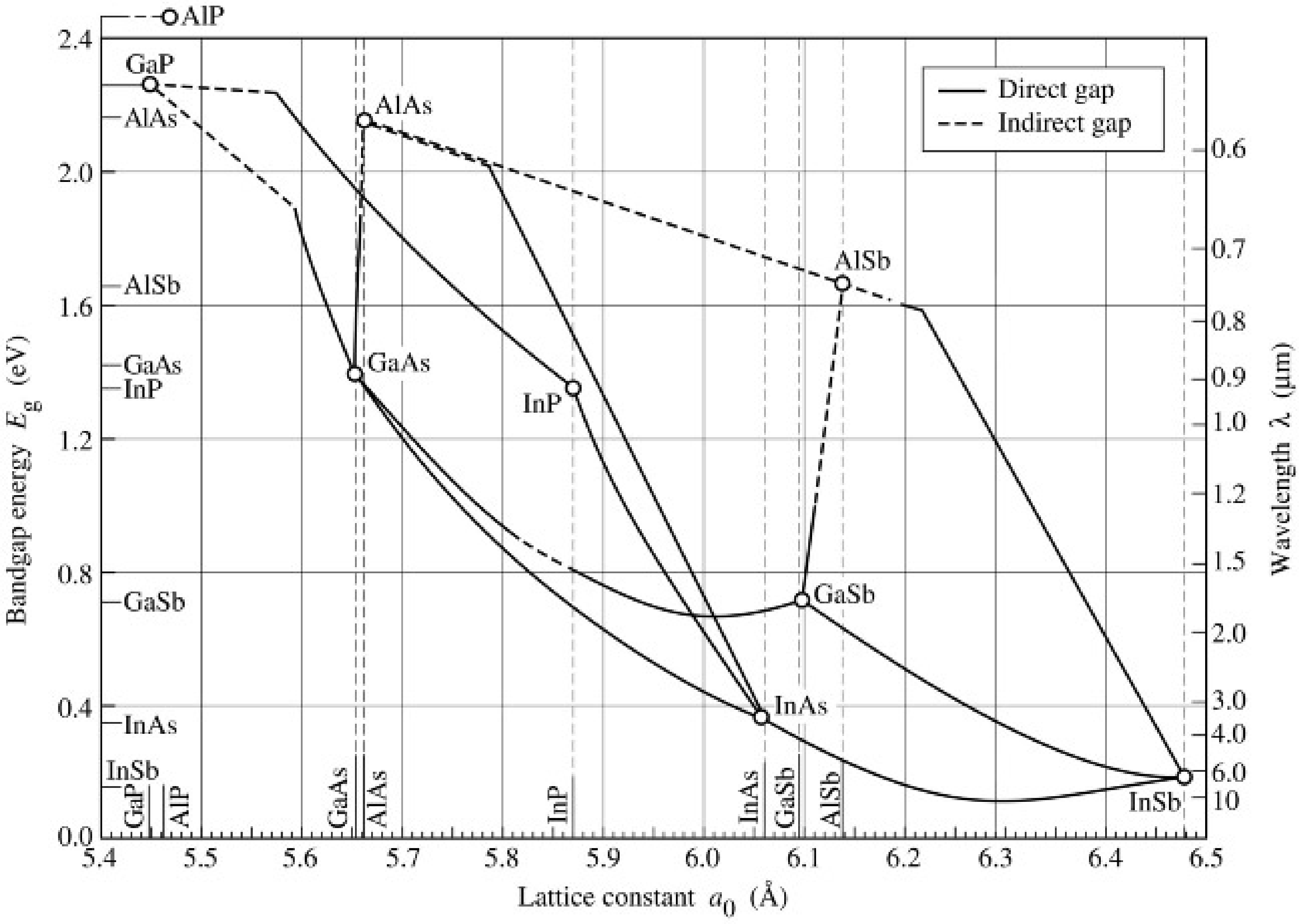
The Nobel Prize in Physics 2000

"for basic work on information and communication technology"

"for developing semiconductor heterostructures used in high-speed- and opto-electronics"

"for his part in the invention of the integrated circuit"

Map of the World



Heterostructure Examples

- Surround low bandgap layer with higher bandgap materials
  - with matched lattice constant structures remain single-crystal
- Quantum confined heterostructures: quantum wells and dots
  - low bandgap layer exhibits quantum confinement effects
  - extremely thin films generated by high quality epitaxial processes

Optical Processes Summary

- Semiconductors have unique electronic properties
- Not all semiconductors are created equal!
  - direct bandgap required for efficient optical functionality
  - III-V materials such as GaAs and InP
- Electron-hole recombination processes generate photons
  - spontaneous emission from random recombination
  - stimulated emission for optical amplification
- Optical and electrical carrier injection
  - photon emission processes require electron-hole pairs
  - efficient recombination enabled by heterostructures
  - thin layers can exhibit quantum effects

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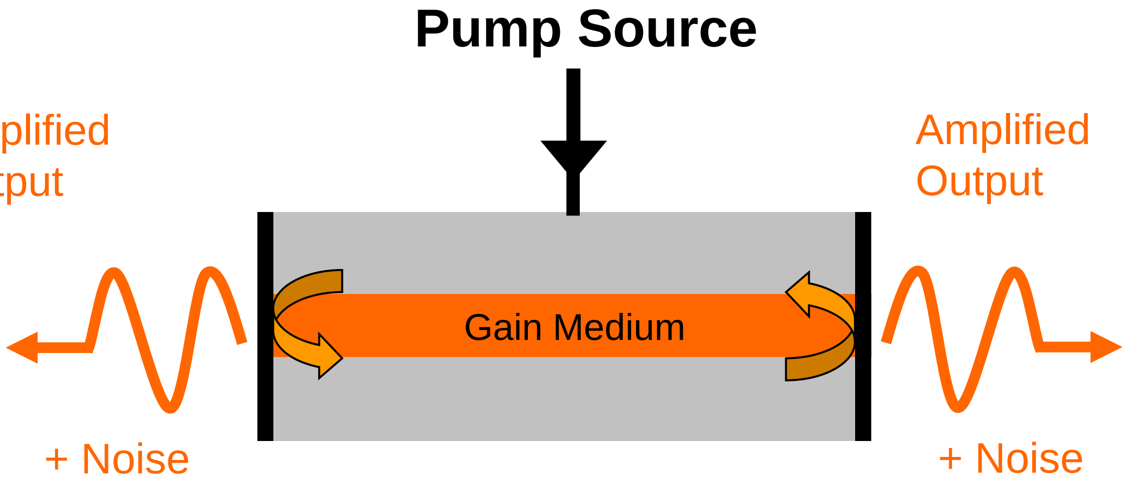
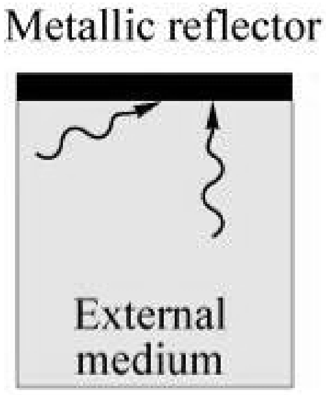
Requirements for a Laser



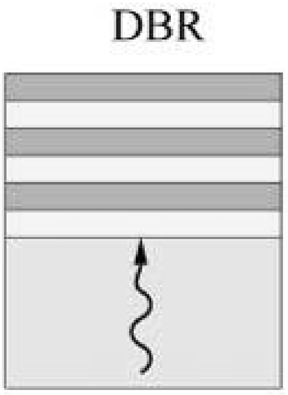
- LASER: Light amplification by stimulated emission of radiation
- Three key components:
  - **Pump** = produce population inversion
  - **Gain Medium** = realize photon amplification
  - **Feedback** = maintain large photon density

Types of Mirrors



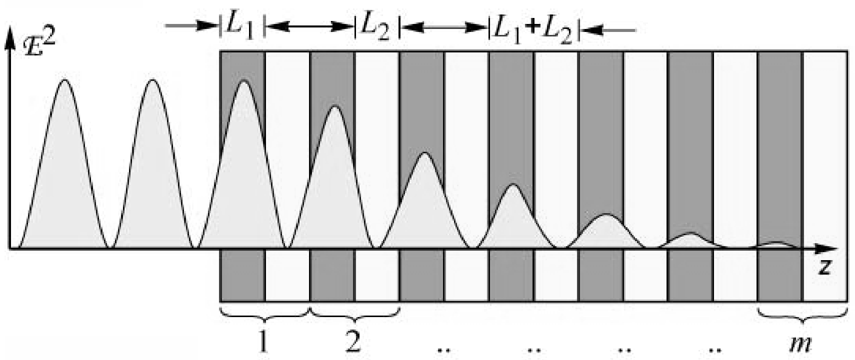
$R = 80 - 98\ \%$

$T = 0\ \%$



$R < 100\ \%$

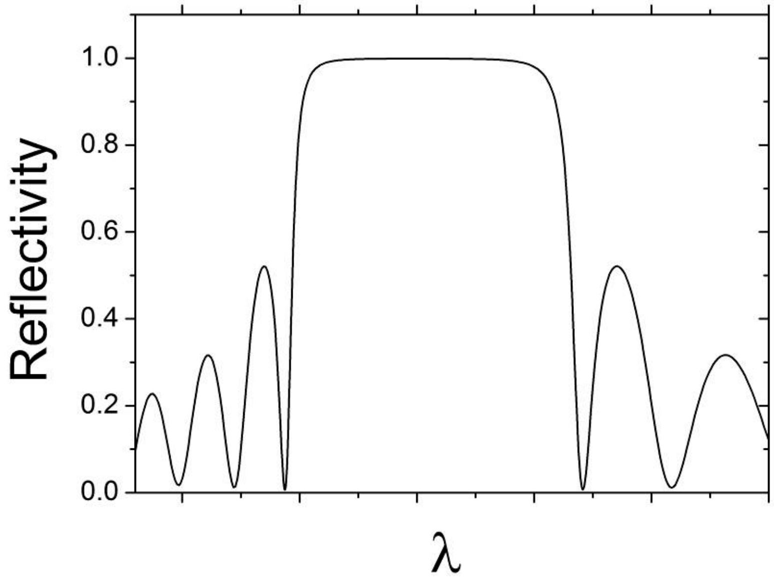
$T = 1 - R$

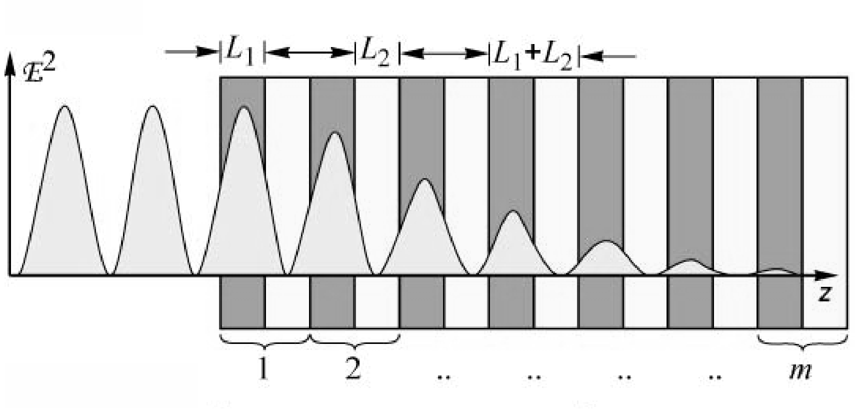


$$L_1 = \frac{\lambda}{4n_1} \qquad r_1 = \frac{n_1 - n_2}{n_1 + n_2}$$

- Metallic mirrors
  - simple, but lossy due to absorption, difficult to tune R
- Distributed Bragg Reflectors (DBRs)
  - repeating stacks of alternating "quarter-wave" layers
  - individual layers are transparent, reduced absorption

Distributed Bragg Reflectors

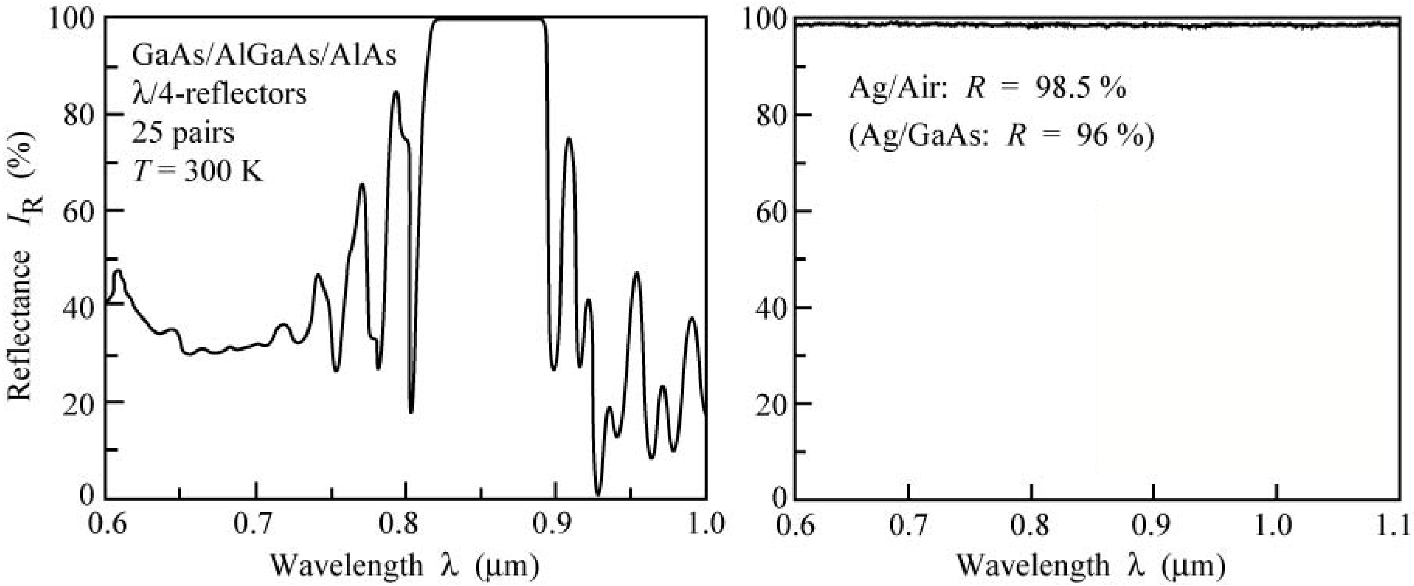




$$r_{DBR} = \left[\frac{n_o (n_2)^{2N} - n_s (n_1)^{2N}}{n_o (n_2)^{2N} + n_s (n_1)^{2N}} \right]^2$$

- At the Bragg wavelength all reflections add in phase
- Advantages:
  - tune reflectivity by changing number of layers (or materials)
  - very low absorption loss as layers are transparent
  - very high reflectivity possible (99.9999%)

Distributed Bragg Reflectors



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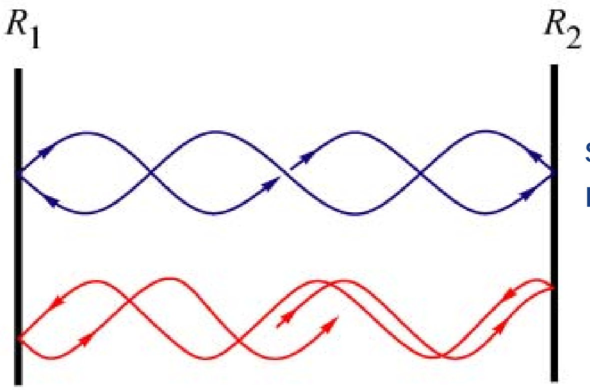
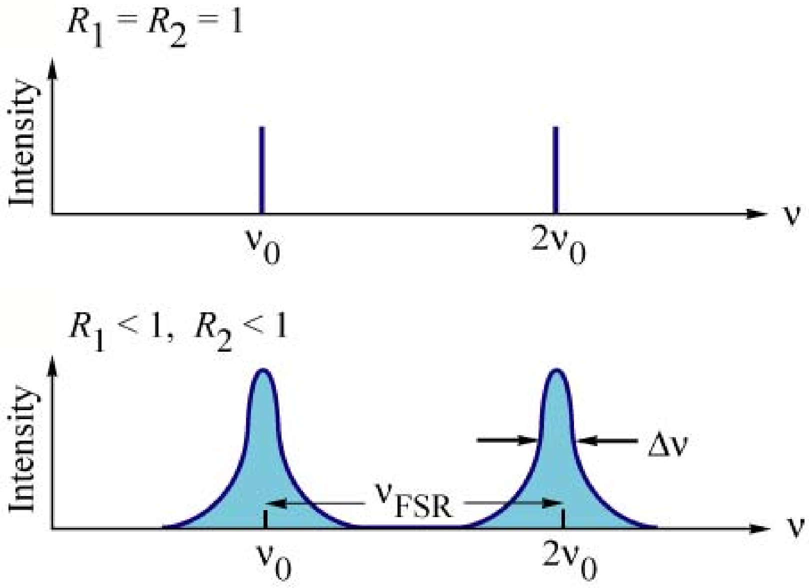
Optical Cavities

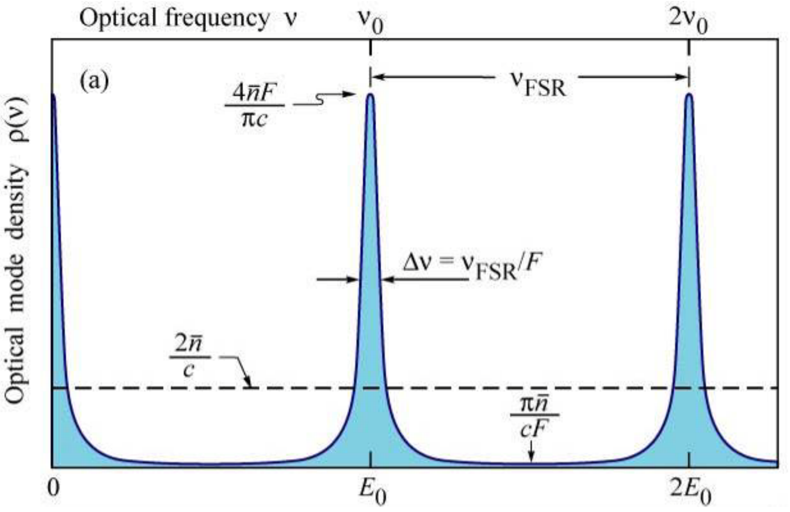


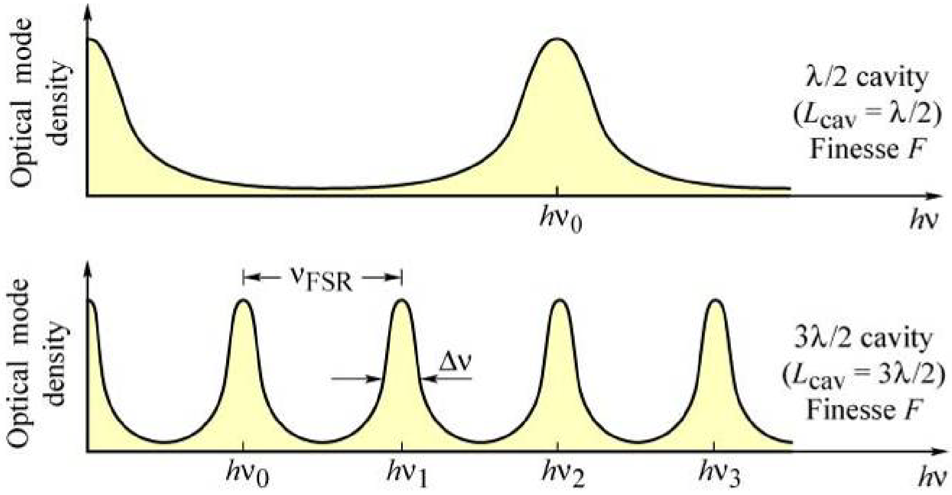
supported mode



- To achieve feedback we need to incorporate 2 mirrors
  - force photons to make multiple passes through the gain medium
- Fabry-Pérot Etalon
  - exhibits 'resonances' at certain wavelengths
  - supports a number of optical modes

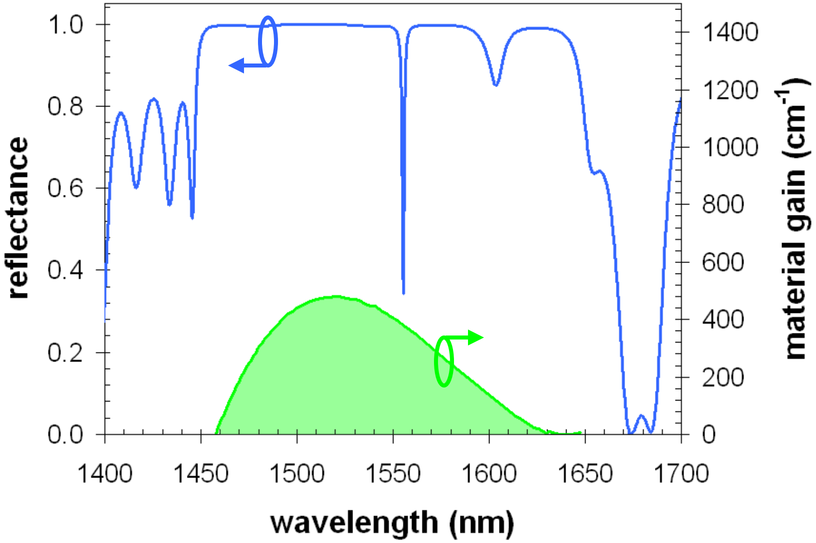
Fabry-Pérot Etalon





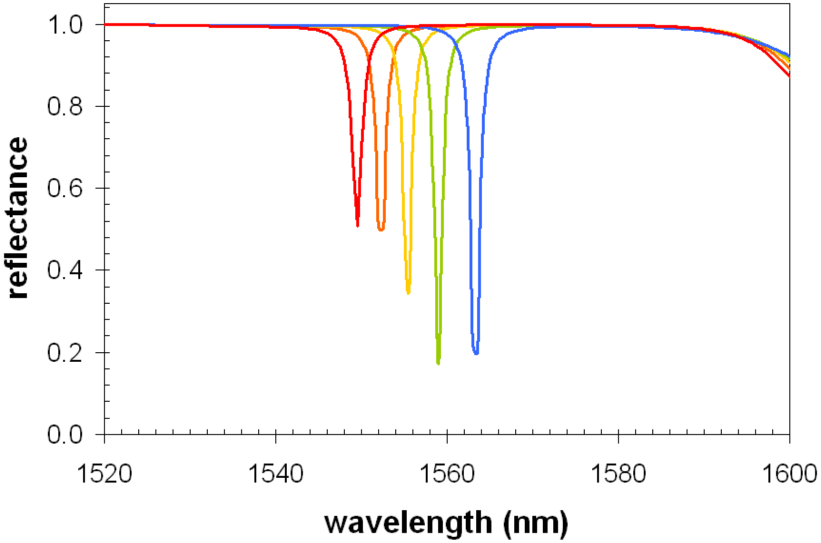
- Frequency spacing between resonances determined by:
  - physical separation of mirror elements
    - longer separation leads to more modes with reduced spacing
- Center frequency may be "tuned" by altering separation
  - useful for developing wavelength tunable devices

Advantages of Microcavity Structures



Single axial mode operation

- one optical mode overlaps with active material gain spectrum
- stable emission wavelength (controlled by cavity)
- gain peak must coincide with the supported mode!



Resonance Tuning:

- large free-spectral range and wide single-mode tunability
- vertical orientation allows for facile integration of MEMS
- continuous tuning through physical path length changes
- rapid λ scanning possible (MHz)

Reflectors and Cavities Summary

- Lasers (and some amplifiers) require photon feedback
  - realized by incorporating gain medium in a cavity
  - allows for the generation of a high photon density

- A variety of mirror options exist
  - air/semiconductor interface (30%)
  - metals (high reflectivity but lossy due to absorption)
  - low loss mirrors: Distributed Bragg Reflectors (DBRs)

- Fabry-Pérot cavities are the standard structure
  - two parallel mirrors at a given separation
  - optical interference in cavity results in resonances
  - mirror spacing determines center frequency of each mode

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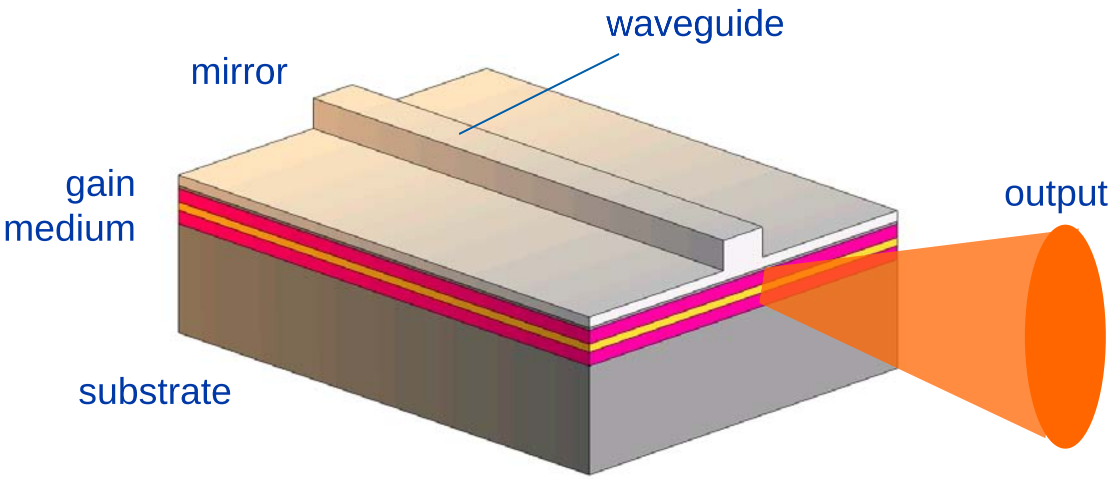
A Brief History of Semiconductor Lasers

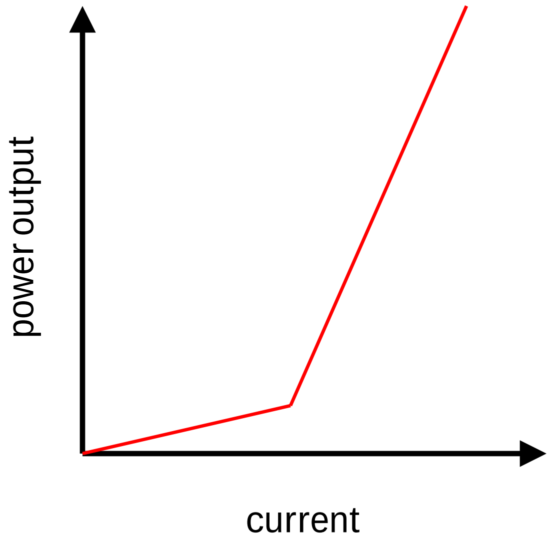
- First laser demonstrated by T. Maiman in 1960 at HRL
    - solid-state device with a ruby (Al_2O_3:Cr) active region
    - optically pumped with a flash lamp and silvered mirrors

- This started the race for the diode laser
    - MIT LL demonstrated efficient optical emission from GaAs
    - US competition includes: Linc. Labs, RCA, IBM, GE
    - GaAs p-n junctions and cleaved/polished mirrors

- First demonstration by R. Hall of GE in September 1962
    - threshold current of 10,000 A/cm^2
    - pulsed electrical injection
    - cryogenic operation

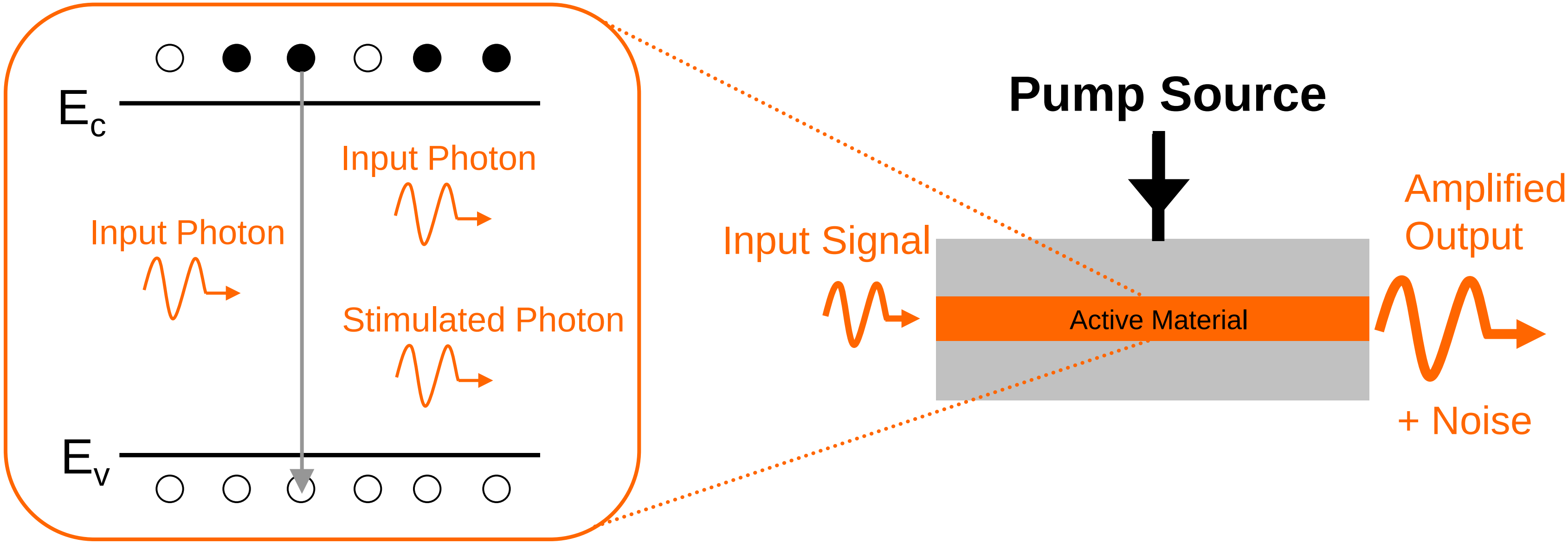
Typical Edge-Emitting Laser





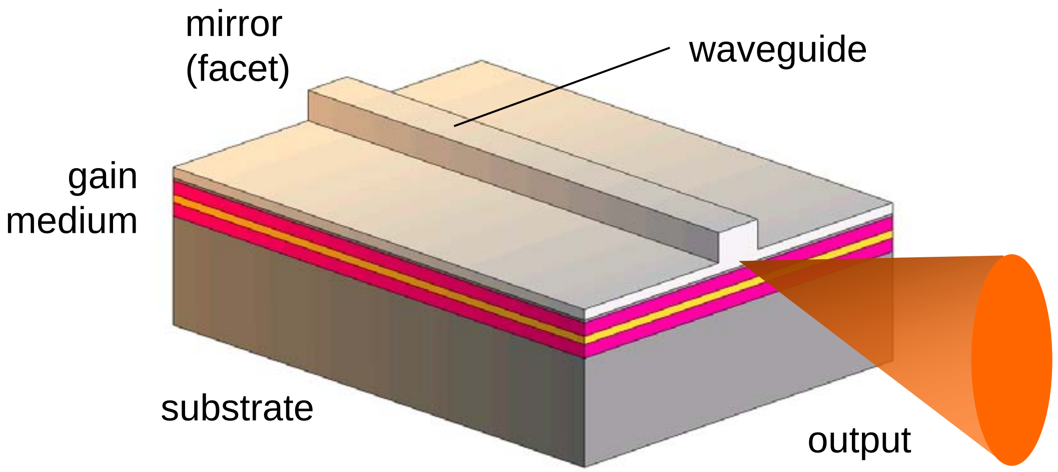
- Fabry-Pérot laser diode with ridge waveguide
  - direct electrical injection (milli-Amp); quantum well gain medium
  - double heterostructure for carrier and optical confinement
- Pervasive devices
  - CD/DVD players, communications, medical applications, etc.

Diode Lasers as Optical Amplifiers



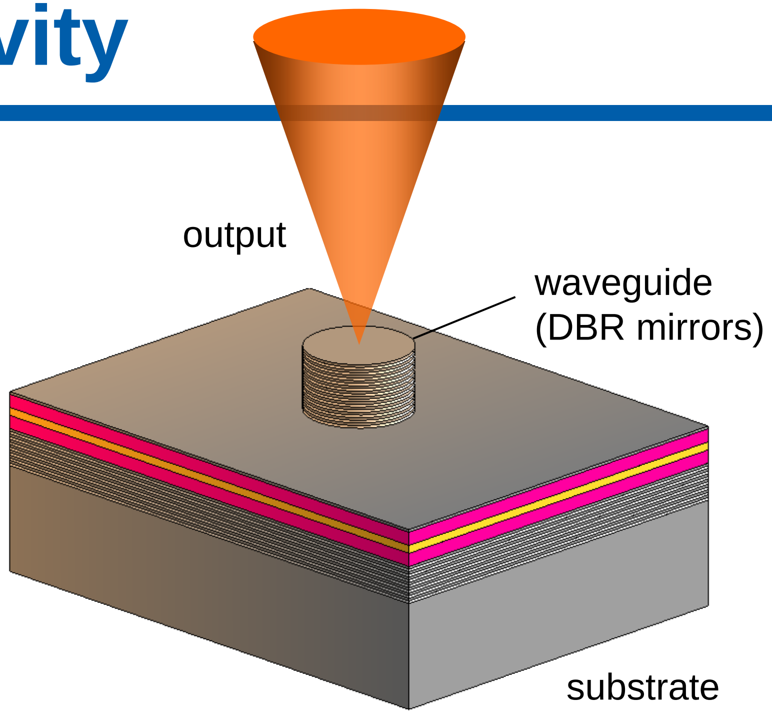
- Laser diodes may also operate as optical amplifiers
  - run laser below 'threshold' and inject external signal
  - stimulated emission process amplifies the injected signal
- Differences in design:
  - reduced feedback (or none at all); increased optical gain

In-Plane vs. Vertical-Cavity



In-plane

- High single pass gain
- Low reflectivity mirrors (facets)
- Highly astigmatic output
- Large footprint
- High power consumption
- In-plane integration



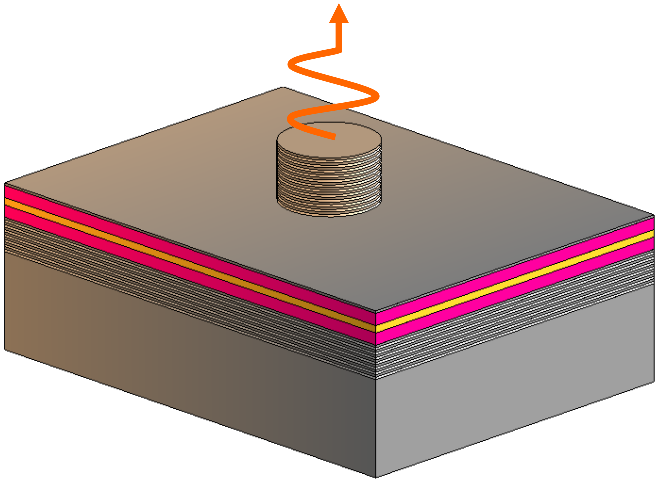
Vertical-cavity

- Low single pass gain
- High reflectivity mirrors (DBRs)
- Circular output (polar. indep.)
- Small active volume
- Low power operation
- 2-D arrays (vertical integration)

Microcavity Motivation

- Current interest in developing low cost optoelectronics
  - Short haul fiber-optic networks, fiber-to-the-home, etc.

- Vertical-cavity lasers and amplifiers offer a unique approach:
  - Cavity geometry allows for surface normal operation
  - Small size and low power consumption
  - Polarization independent gain
  - Construction of arrays



Summary: Diode Laser and Amplifiers

- First semiconductor laser demonstrated by GE in 1962
  - GaAs homojunction with very high threshold
  - improvements have made these devices ubiquitous

- Two distinct classes of diode lasers now available
  - FP edge-emitter is the most common
  - VCSELs (microcavity lasers) are becoming popular
    - require high reflectivity mirrors, have reduced output powers

- With proper design can be used as optical amplifiers
  - reduced feedback to avoid self-sustaining oscillation
  - increased gain for maximum amplification
  - mirror spacing determines center frequency of each mode

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Tunable Microcavities

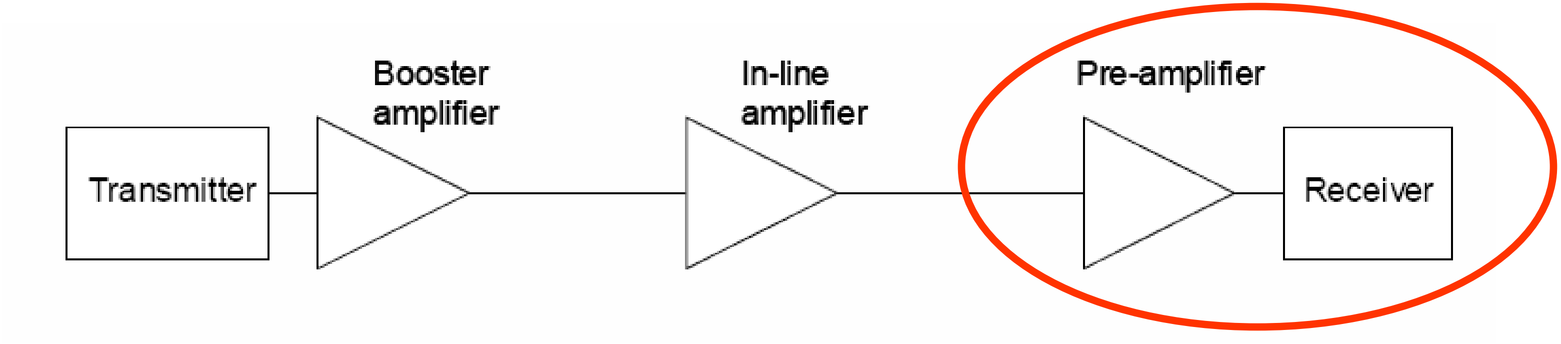
Advantages:

- Vertical orientation allows for straight forward integration of MEMS actuator structures
- Short cavity length:
  - inherently single-axial mode operation
  - continuous tuning through physical path length changes

Example Tunable Microcavity Device:

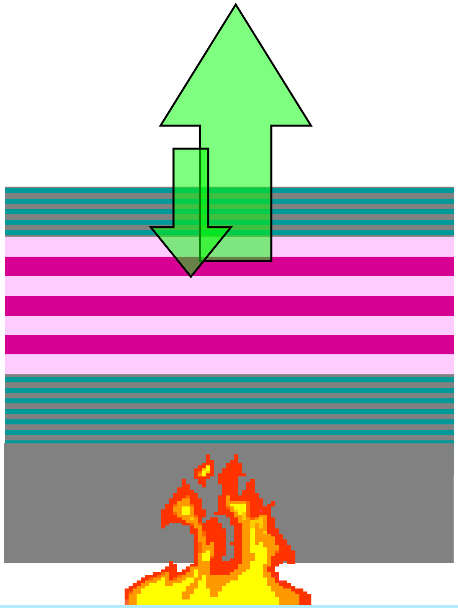
- Tunable vertical-cavity optical amplifiers (VCSOAs)

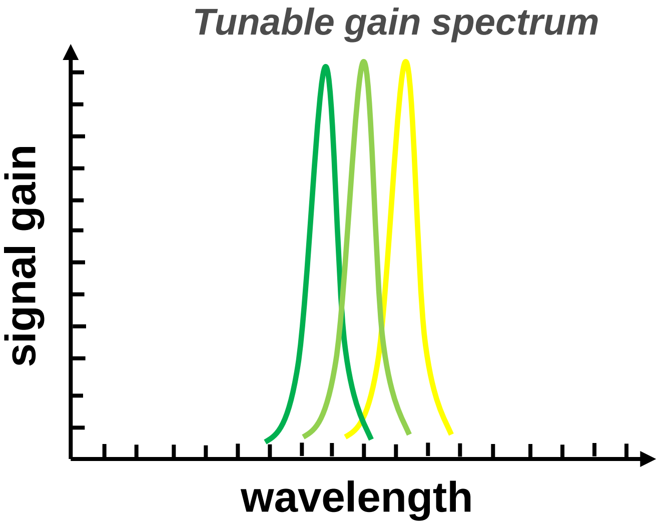
Optical Network Block Diagram



- Three basic types of optical amplifiers:
  - **Booster** - increase power at source (integrated w/laser)
  - **In-line** - make up for propagation losses (EDFA)
  - **Pre-amplifier** - enhance receiver sensitivity (APD)
- Improvements needed at the receiver end
  - PIN diodes: poor sensitivity; APDs: limited gain-bandwidth product
  - optical pre-amp to simultaneously enhance bit-rate and sensitivity
  - VCSOAs are capable of high-speed optical gain and filtering

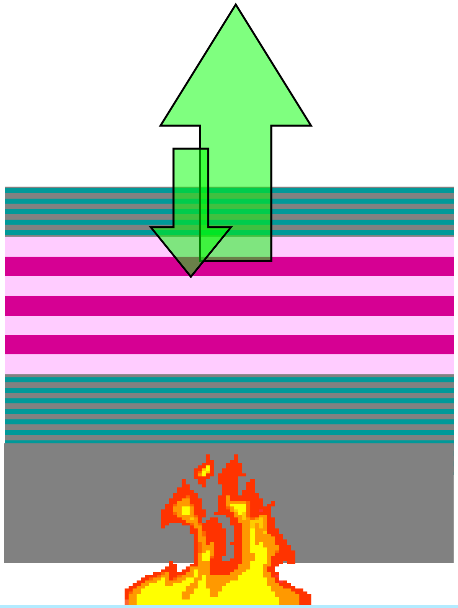
Fixed-Wavelength VCSOA

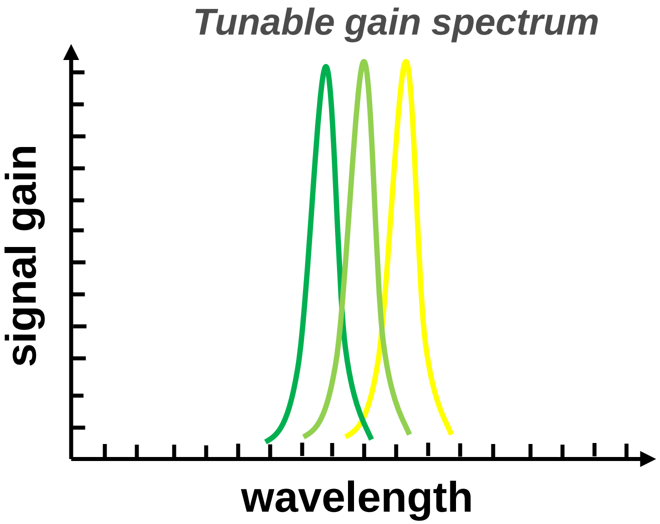




- Short active material length results in a small single-pass gain
- Fabry-Pérot operation leads to a narrow gain bandwidth
- Potential applications include:
  - Single-channel amplifiers, amplifying filters, premaplifiers in receiver modules
- In multi-wavelength (WDM) and reconfigurable optical networks wavelength tunable devices are desirable

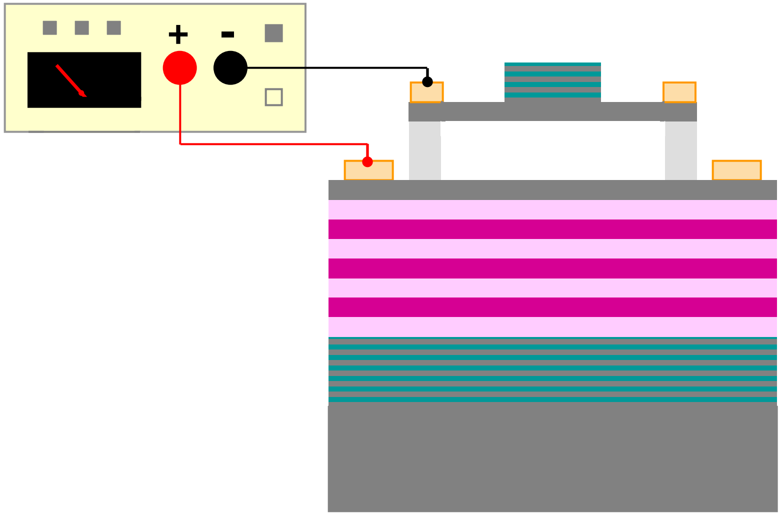
Fixed-Wavelength VCSOA

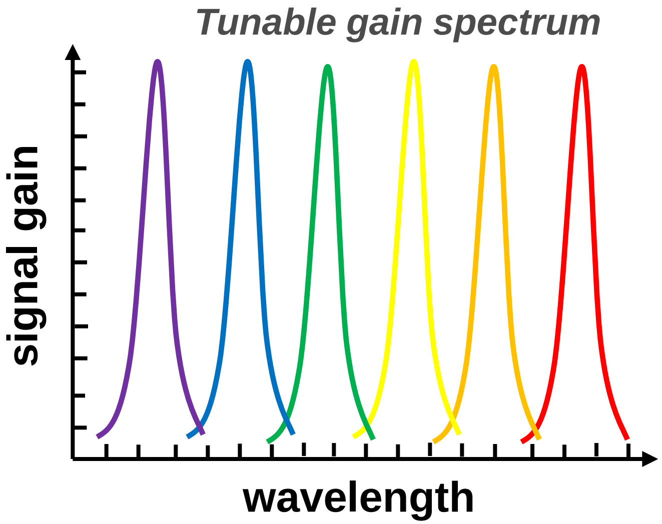




- Incorporating tunability allows the peak gain of the VCSOA to be adjusted to match the desired signal wavelength
  - Signal drift compensation
  - Selective multi-channel amplification in WDM systems
- Temperature tuning of 8 nm has previously been demonstrated
  - High power consumption and limited wavelength tuning range
  - Time response limited by thermal transients

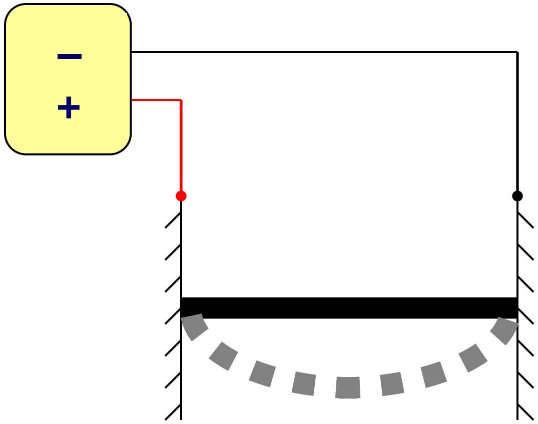
MEMS-Tunable VCSOA



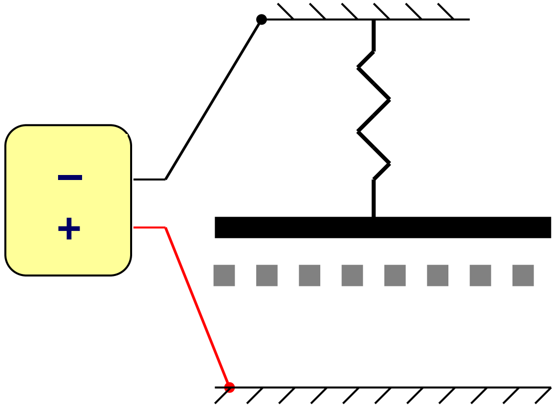


- Incorporating tunability allows the peak gain of the VCSOA to be adjusted to match the desired signal wavelength
  - Signal drift compensation
  - Selective multi-channel amplification in WDM systems
- MEMS-based tuning exhibits a number of advantages
  - Low power consumption and fast time response (<10 μs)
  - Continuous, wide wavelength tuning (>20 nm)

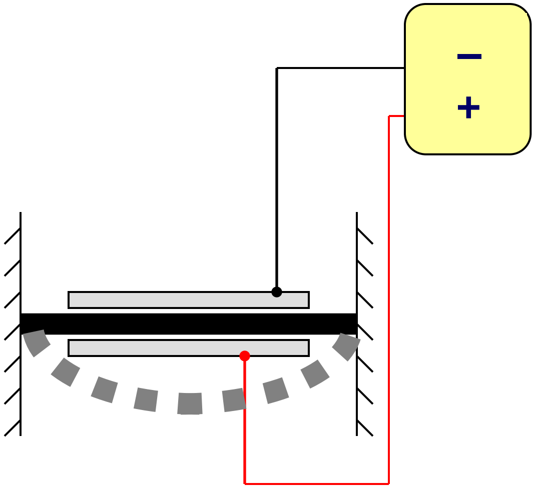
MEMS Actuator Background



Electrothermal



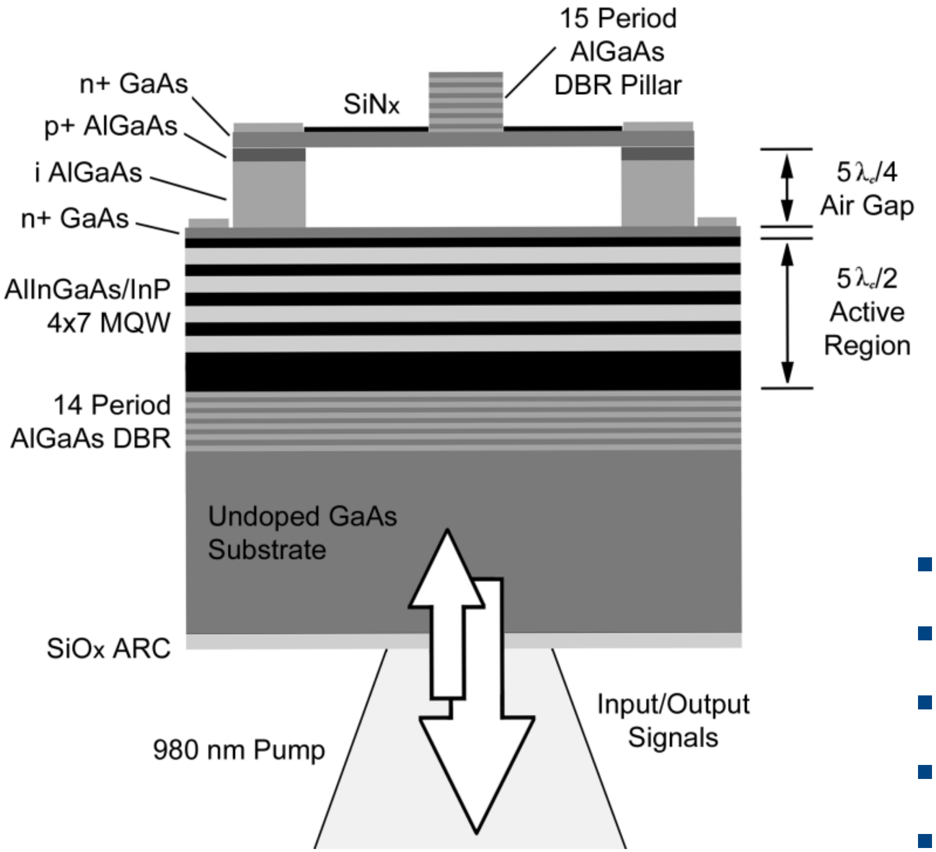
Electrostatic

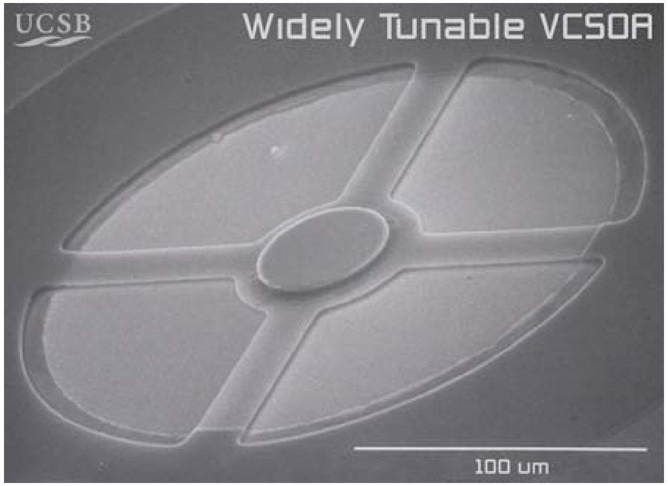


Piezoelectric

- **Electrothermal** – Joule heating leads to thermal expansion of actuator
- **Electrostatic** – Coulomb force generated in a capacitive system
- **Piezoelectric** – Noncentrosymmetric crystal structure, applied charge results in mechanical strain in material

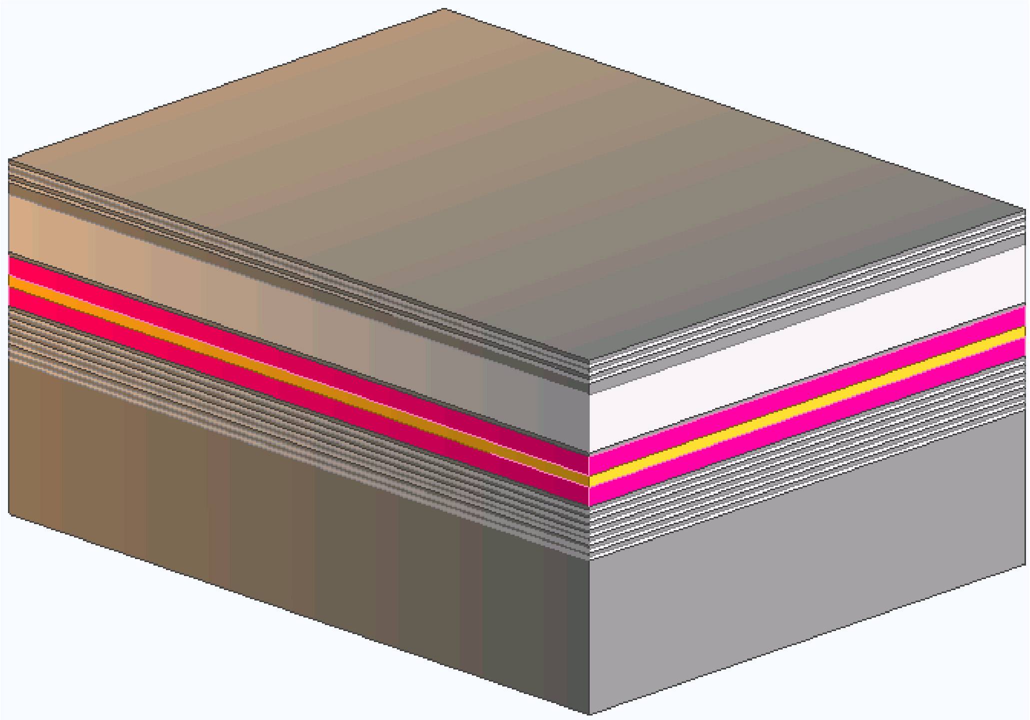
High-Performance Tunable VCSOA





- Reflection mode amplifier
- Transmissive bottom mirror
- High reflectivity suspended DBR
- Hybrid GaAs/InP/GaAs cavity
- 28 AlInGaAs quantum wells
- 980-nm EDFA pump for excitation

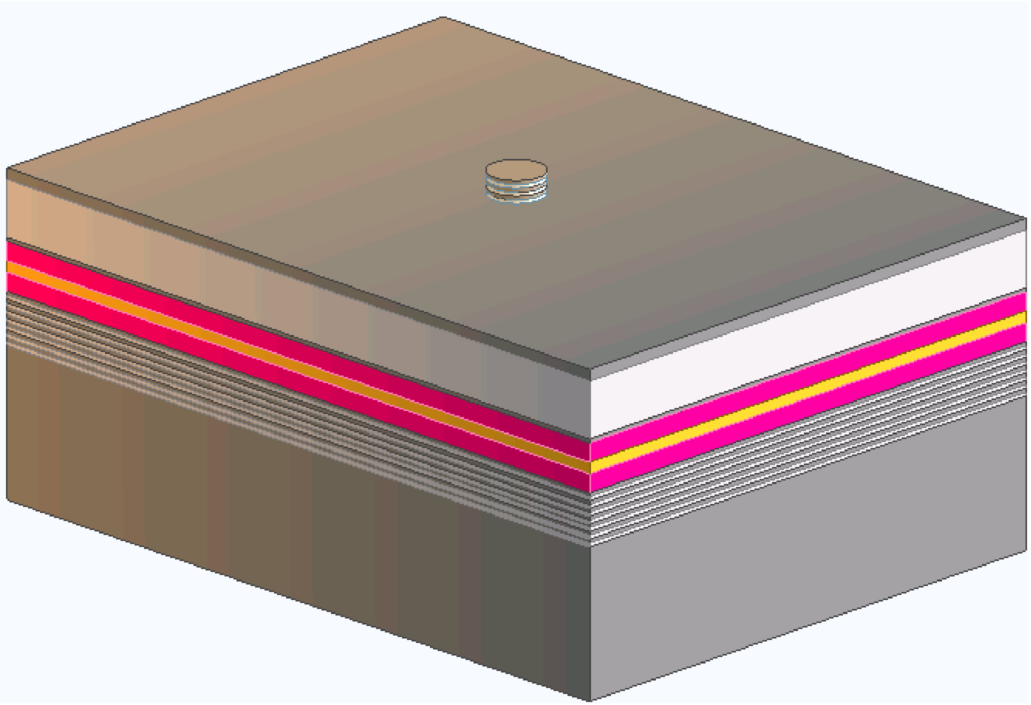
Fabrication Procedure



MEMS-Tunable VCSOA

- Direct wafer bonding of AlGaAs DBRs to InP-based active region
- DBR pillar etch ($SiCl_4$)
- Expose tuning contacts and evaporate Ge/Au/Ni/Au
- RIE etch of actuator geometry
- Isotropic wet etch in dilute HCl to release sample
- CO_2 critical point dry

Basic Fabrication Procedure



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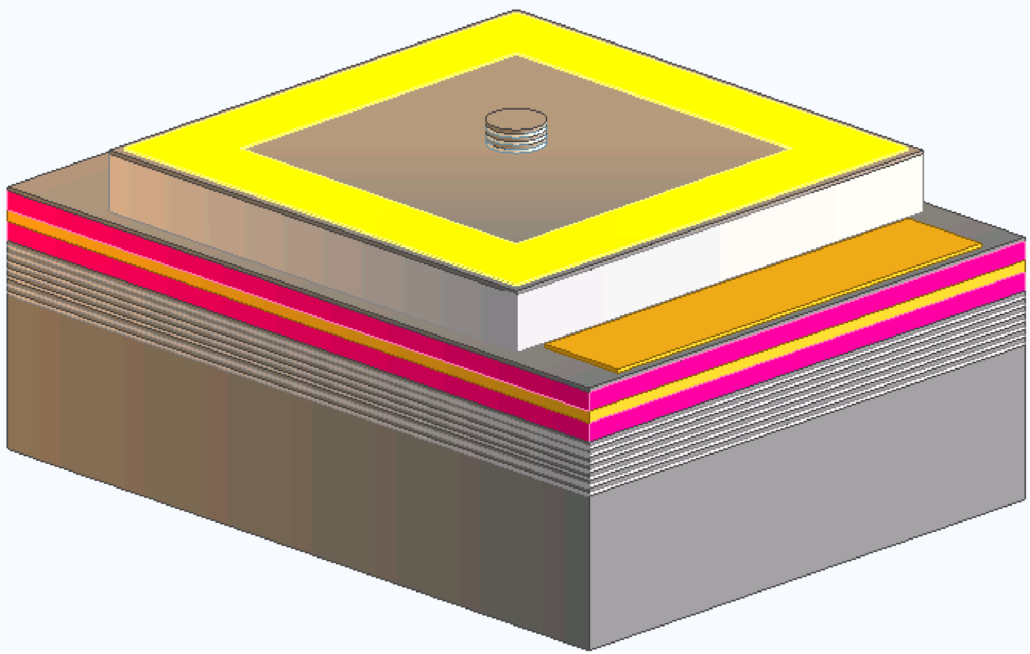

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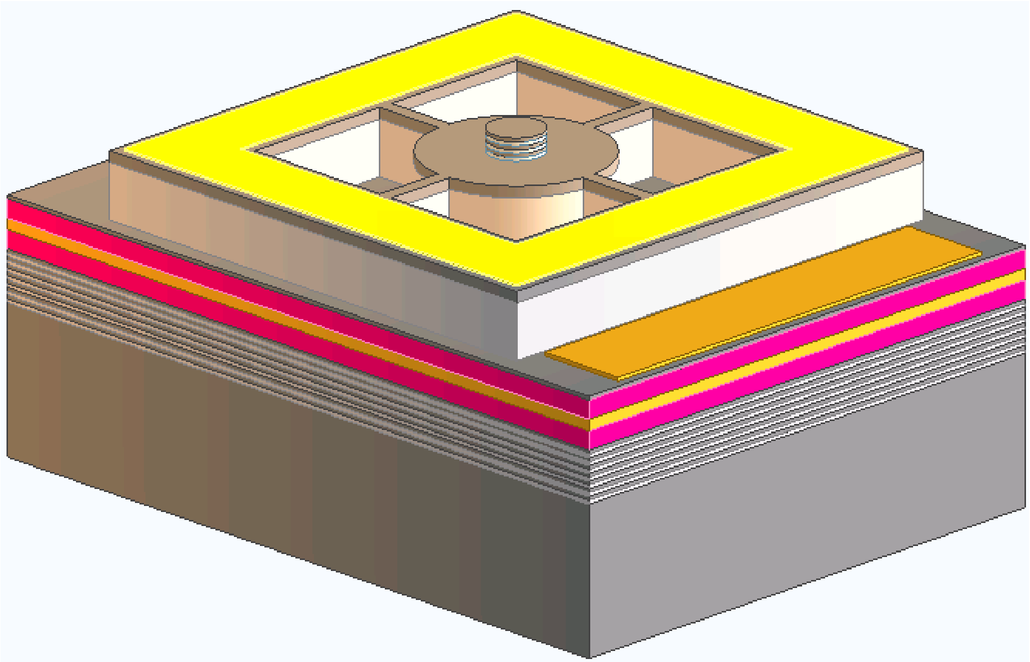

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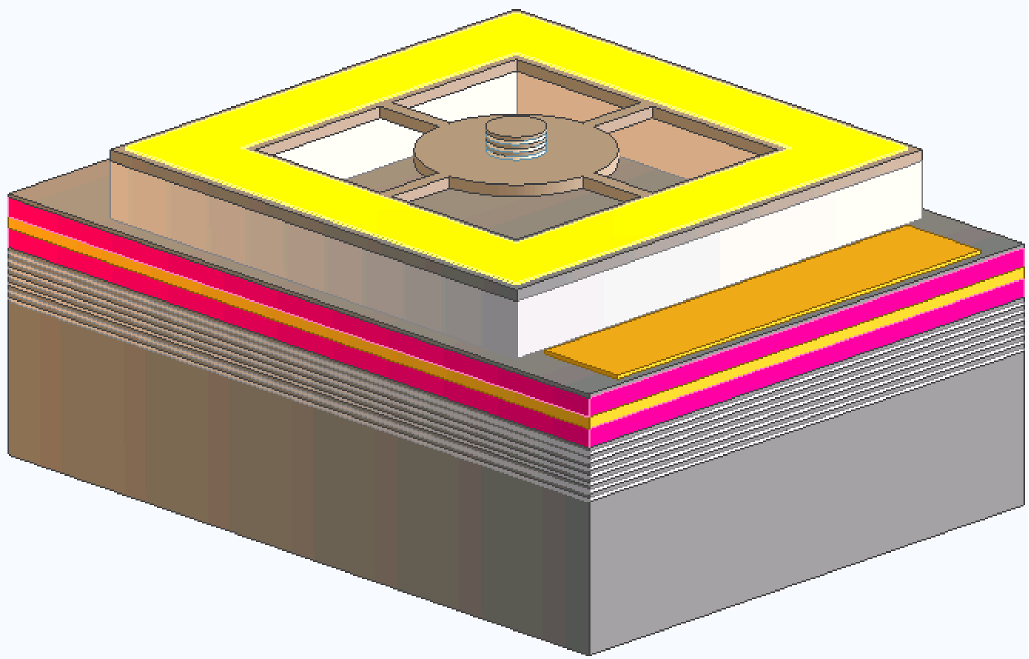

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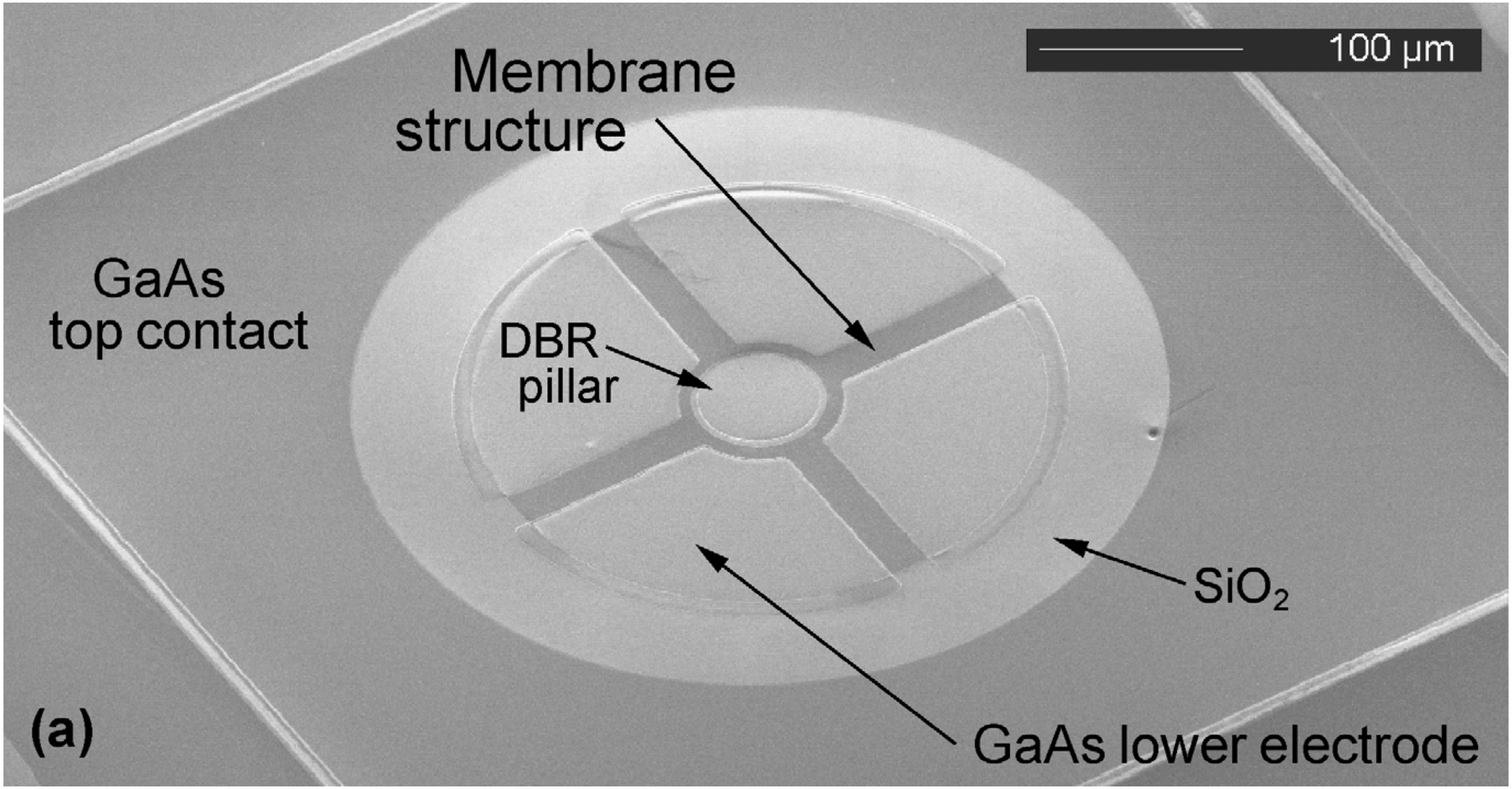
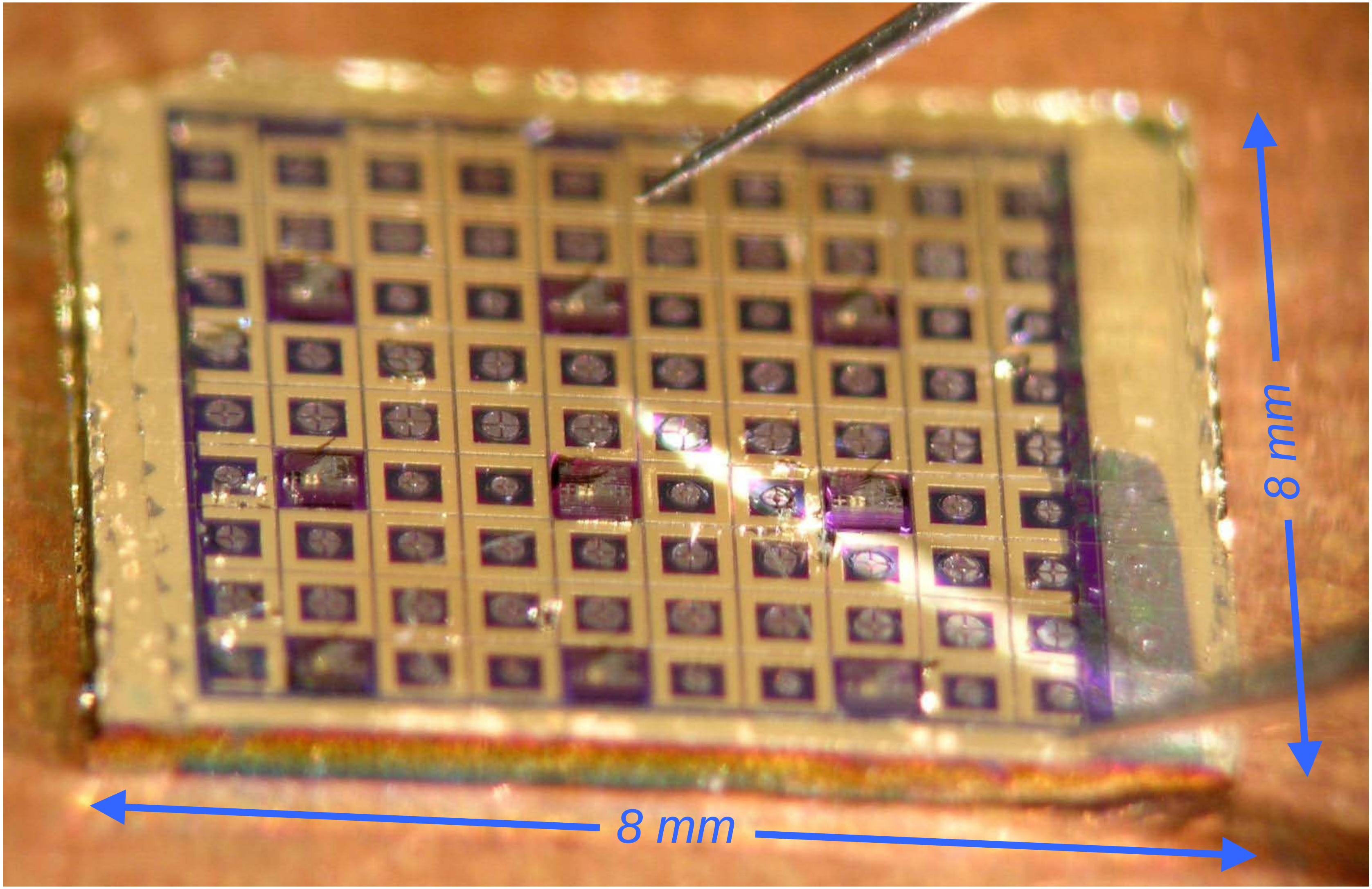
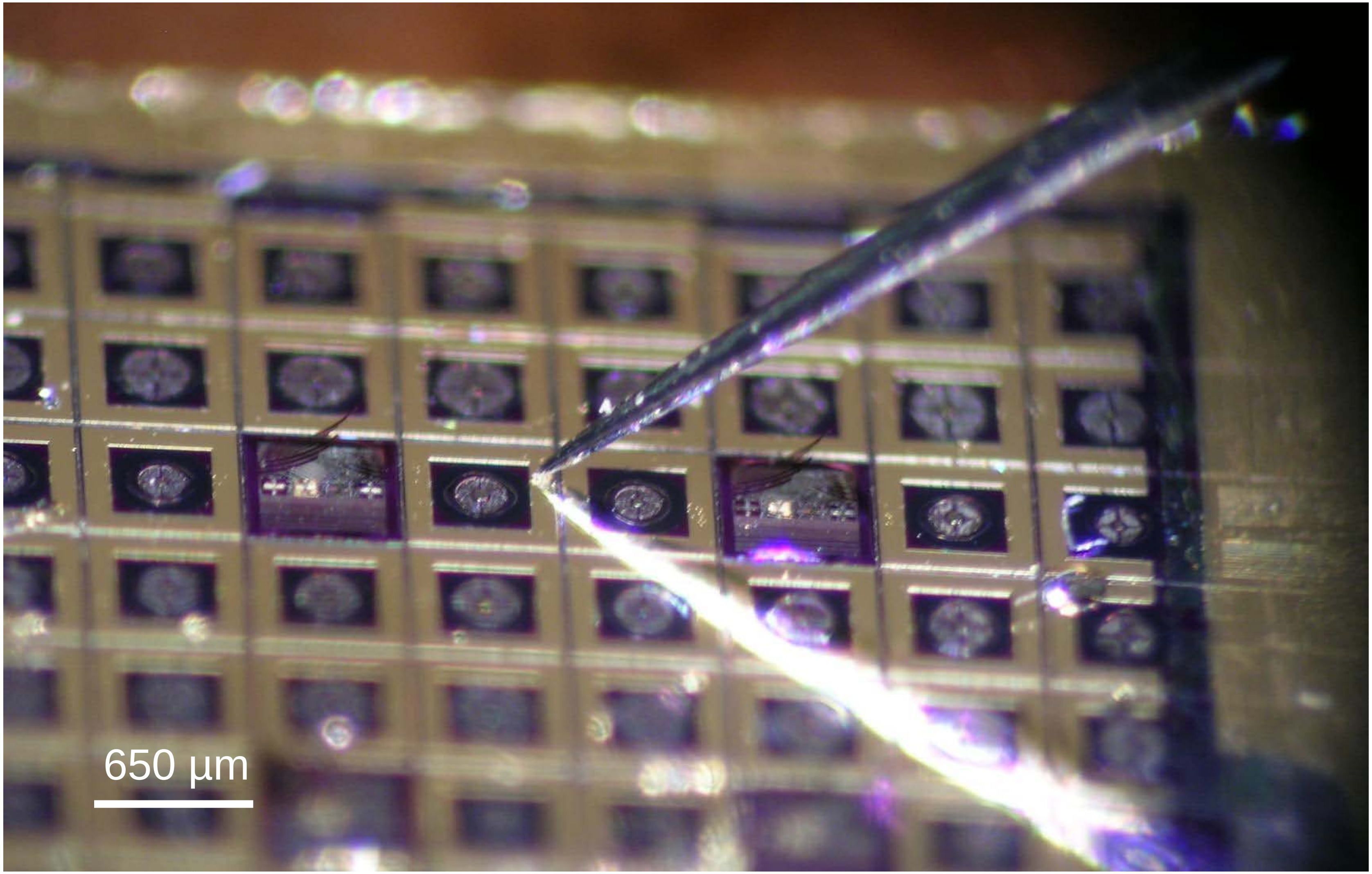
Micrograph of Mechanical Structure



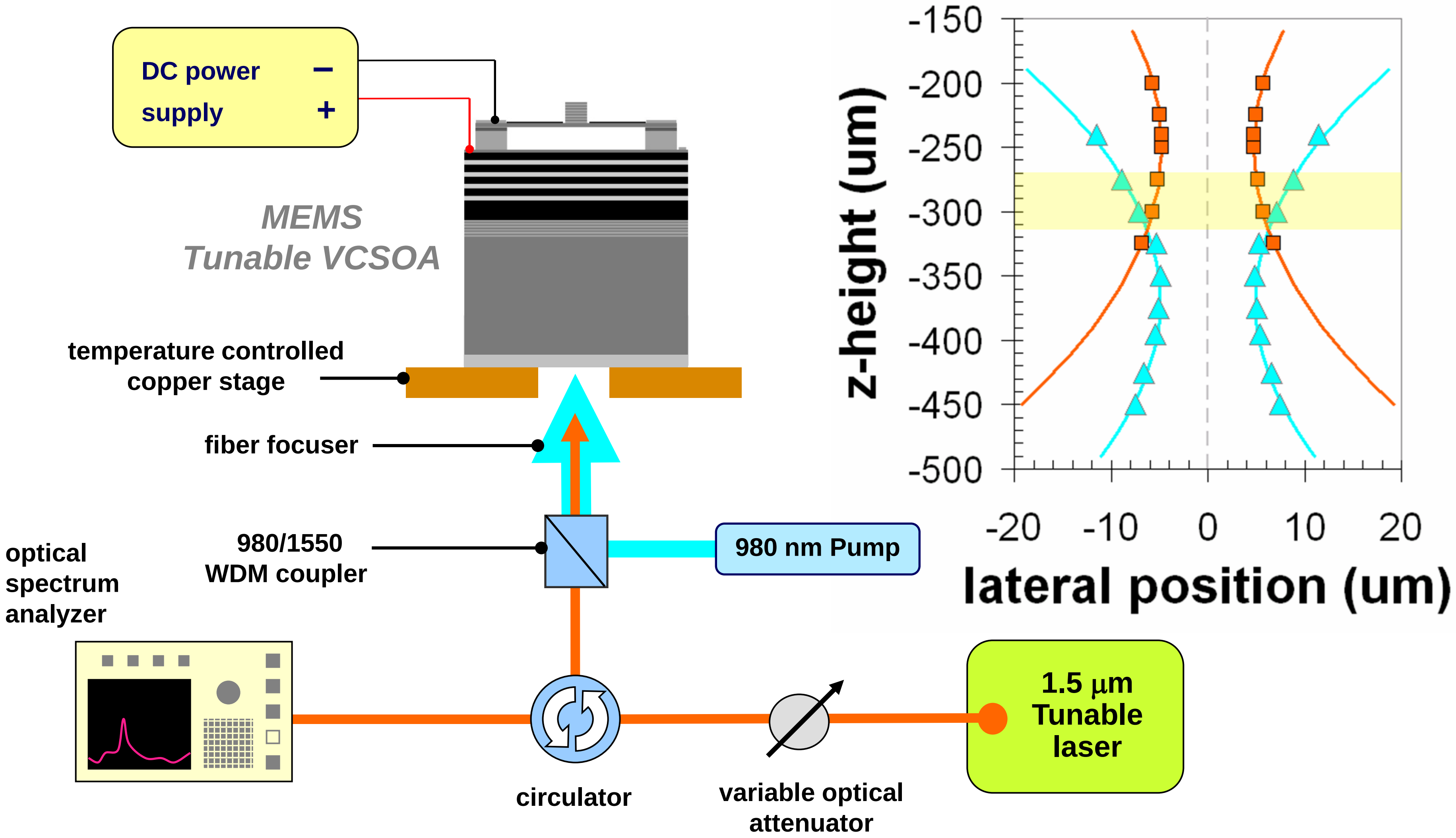
On-Chip 2-Dimensional Arrays



On-Chip 2-Dimensional Arrays



Experimental Setup



DC power supply – +

MEMS Tunable VCSOA

temperature controlled copper stage

fiber focuser

980/1550 WDM coupler

980 nm Pump

optical spectrum analyzer

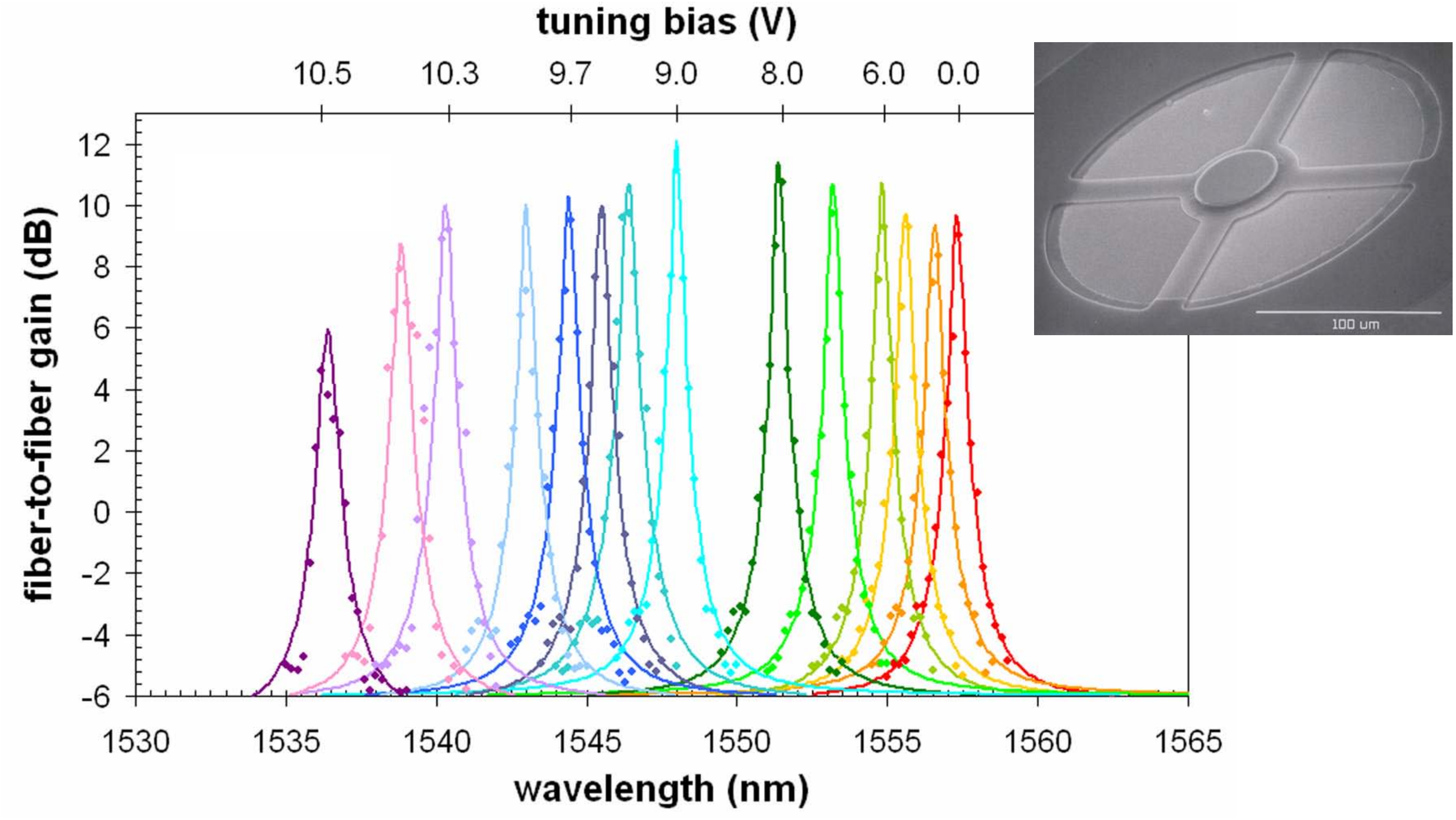
circulator

variable optical attenuator

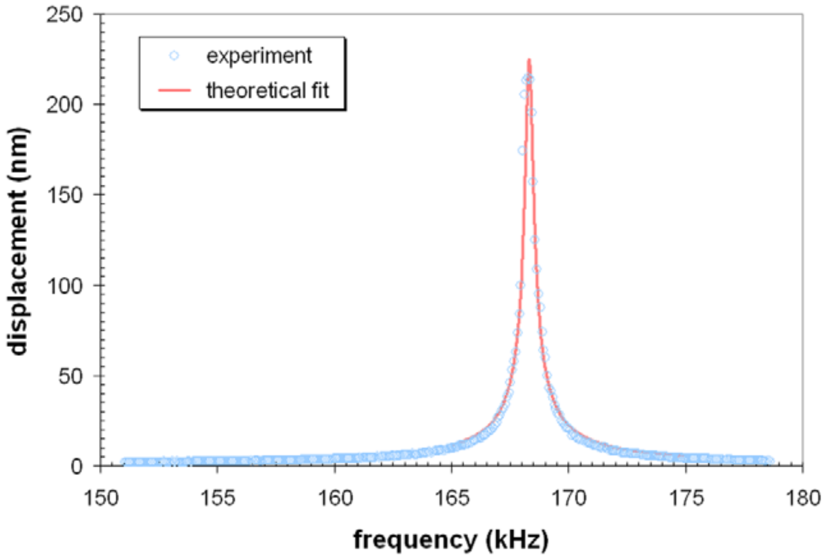
1.5 μm Tunable laser

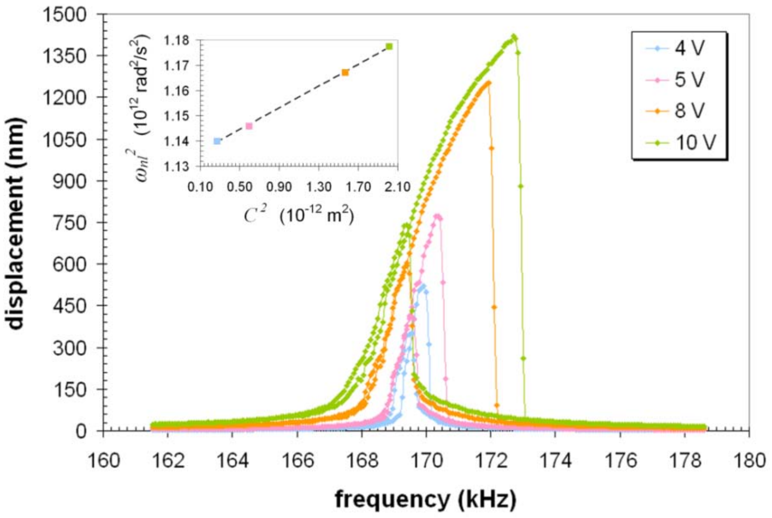
Wide Effective Tuning Range

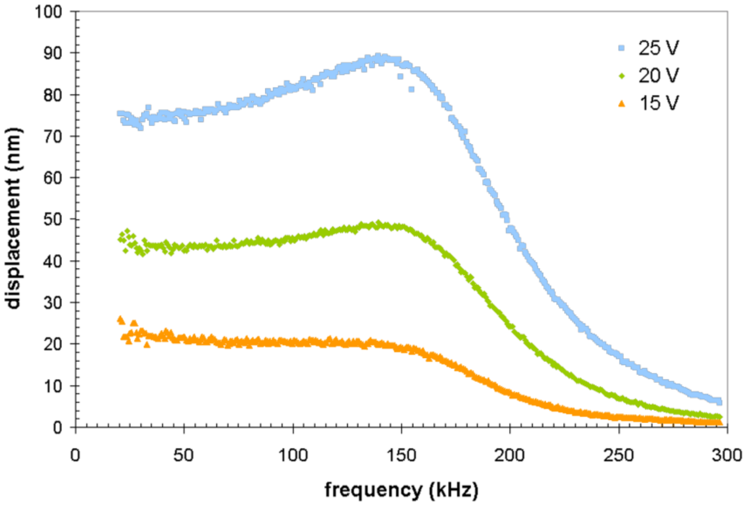
>5 dB fiber-to-fiber gain (>12 dB on chip) measured over 21 nm



Electrostatic Actuator Characterization







MEMS characterization via LDV:

- Simple harmonic response for small signal (2 V) excitation in vacuum
- Duffing response for large deflection
- Significant damping at ambient press.
  - Q of 1.2, response time of 6 μs

Summary and Conclusions

- The integartion of MEMS can enhance the performance of compound-semiconductor-based devices
- Microcavities are an active research topic both in the fundamental and applied sciences
- Example Device Highlighted:
  - Development of MEMS-tunable vertical-cavity SOA for use as a wavelength-agile optical preamplifier
  - 21 nm of tuning near 1550 nm, >12 dB fiber-to-fiber gain