Micro-sensors - what happens when you make "classical" devices "small":

MEMS devices and integrated bolometric IR detectors

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Where are the targets of opportunity for "small" machines?

- actuation?
  - what do you control?: fluid flow, object position
  - motors?
  - optical beam paths?
    - work required only that necessary to move MEMS device itself (doesn't have to do work on the "environment"!)
- sensing?
  - velocity, acceleration, temperature, pressure, distance are main "mechanical state variables"
  - chemical/pathogen sensing
  - mm-wave, sub-mm wave, FIR detection?
- other application domains?
  - optics (see above)? electronics (field emission devices, vacuum microelectronics)?

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What do you sense in a MEMS sensor?

- mechanical part of most MEM sensors produce displacement in response to the environmental stimulus
  - how do you sense the mechanical movement?
    - electrical: resistance, capacitance, inductance
    - optical:
      - interference, reflectance, transmittance
- exceptions:
  - "chemFETs," Hall effect and the like (but they are not really MEM devices)
  - thermal device: bolometers (a radiation sensor)
  - thermal device: hot wire anemometers, TC pressure gauges, flow gauges
  - chemically-induced optical changes

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Micro-Electromagnetic Device Group: Current Research in MEMS-related areas

- optical pressure sensors
  - design and fabrication
- inductive proximity sensors
  - design (sensor and sense/drive circuitry), fabrication, modeling
- microwave to infrared detectors
  - pit vipers and beetles
- chemical sensors
  - collaborative project with chemistry
- microwave/rf transmission line structures
  - impact of finite metal resistance, finite substrate conductivity (e.g., semiconducting substrates) on transmission line loss and dispersion

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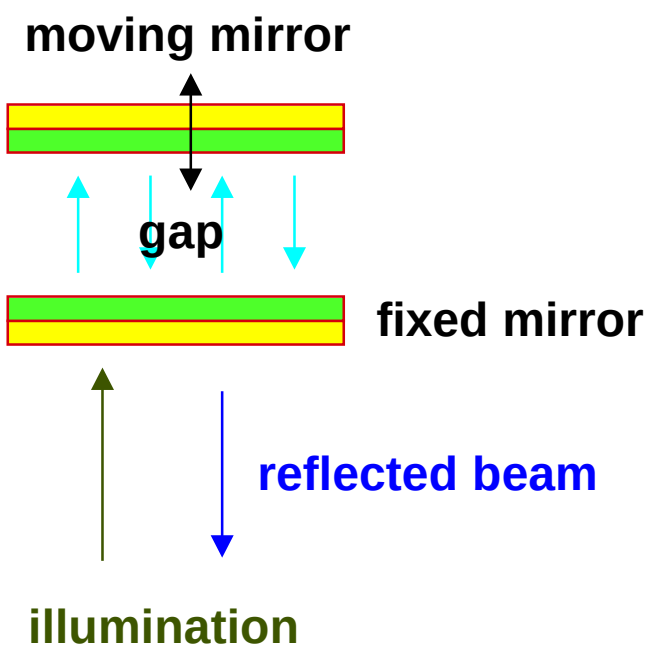
MEMS example: Optically-interrogated pressure sensors

- why use optical sensing?
  - use in hostile environments
  - immunity from EMI/noise
- Fabry-Perot displacement sensors
  - detect via changes in reflectance
    - need absolute displacement!
    - short cavity: *g* order λ
      - max travel less than periodicity
      - can use lower coherence source
  - how to fabricate micromachined version?
    - membrane supports moving mirror
    - design for linearity, sensitivity, yield?



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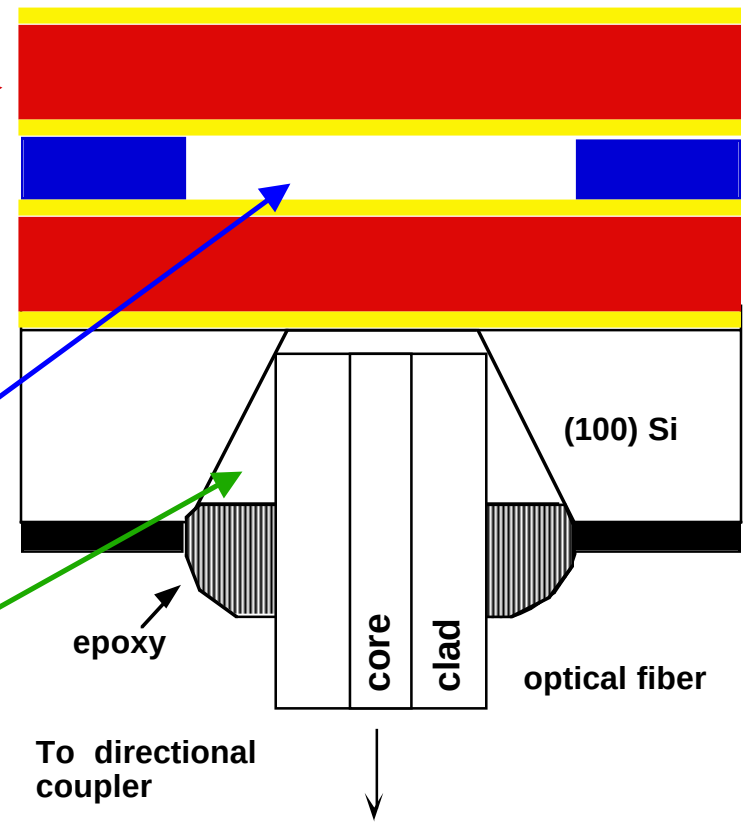
Surface micromachined Fabry-Perot cavity

- use LPCVD to deposit layers
  - SiO_2 / Si_3N_4 stacks used for mirrors/membranes
    - layer thicknesses tailor stress and reflectivity
    - 3:1 oxide/nitride thickness ratio for our process
  - poly used for sacrificial layer
    - thickness determines gap
- bulk anisotropic etch for optical access
  - no fusion bonding used



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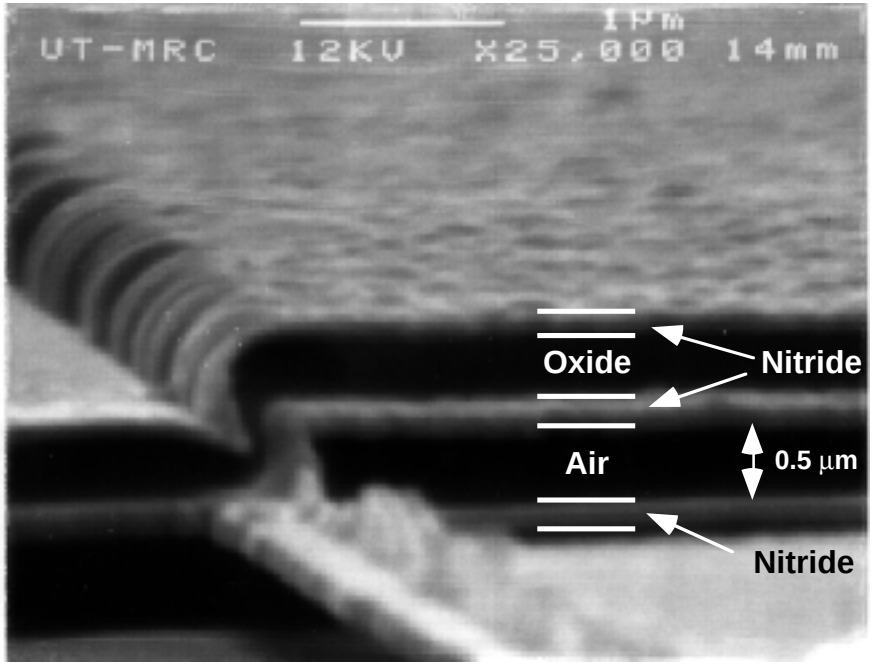
Fabry-Perot cross section

- Si_3N_4 / SiO_2 / Si_3N_4 three layer stacks for mirrors
- membranes must remain flat after release!
  - -net tensile stress
  - -geometry important
    - poly sacrificial layer
    - etch window for poly removal



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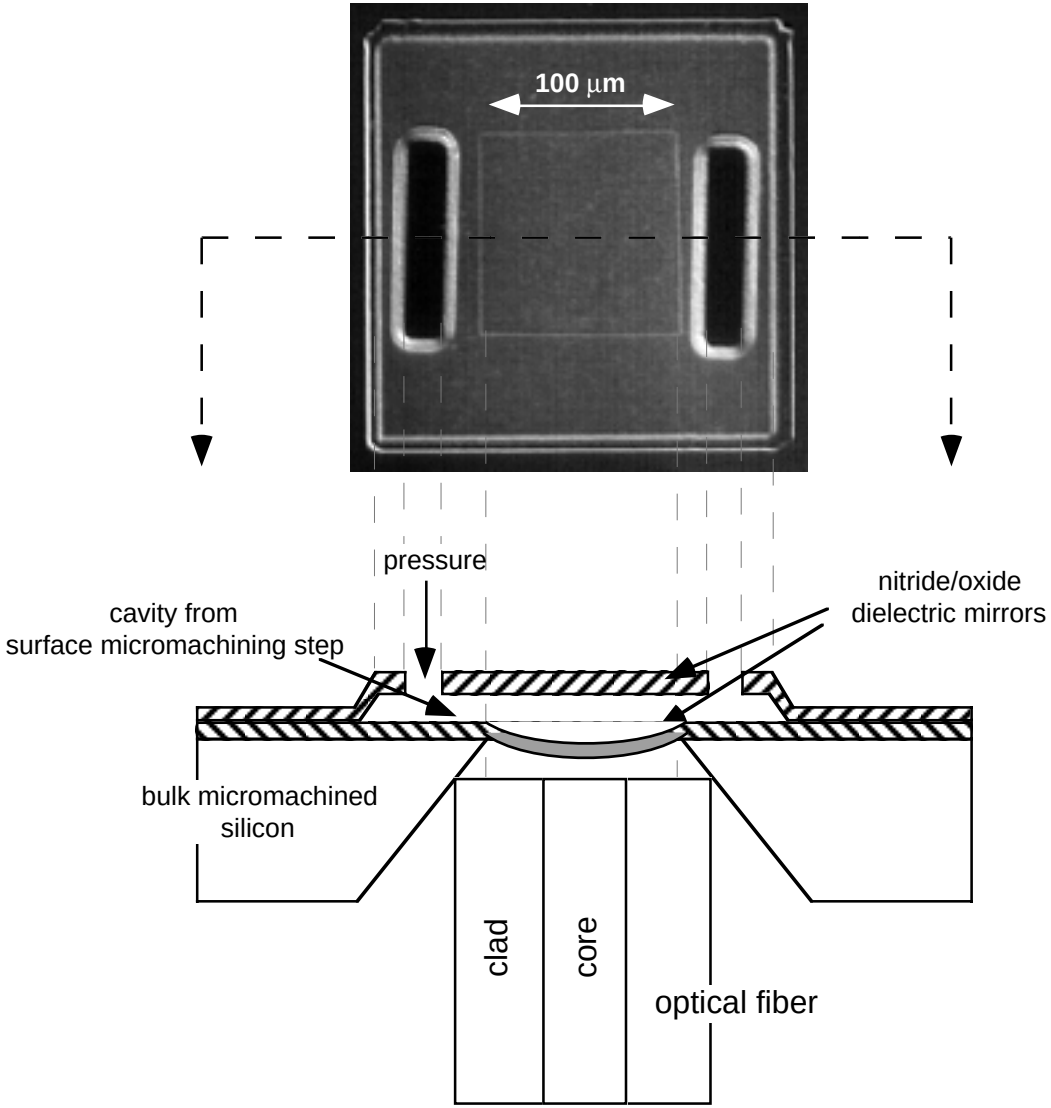
Complete micromachined F-P device



- prototype has "front" etch windows
- optical fiber "locks" into place
  - -after insertion apply force using optical positioner: fiber does not move

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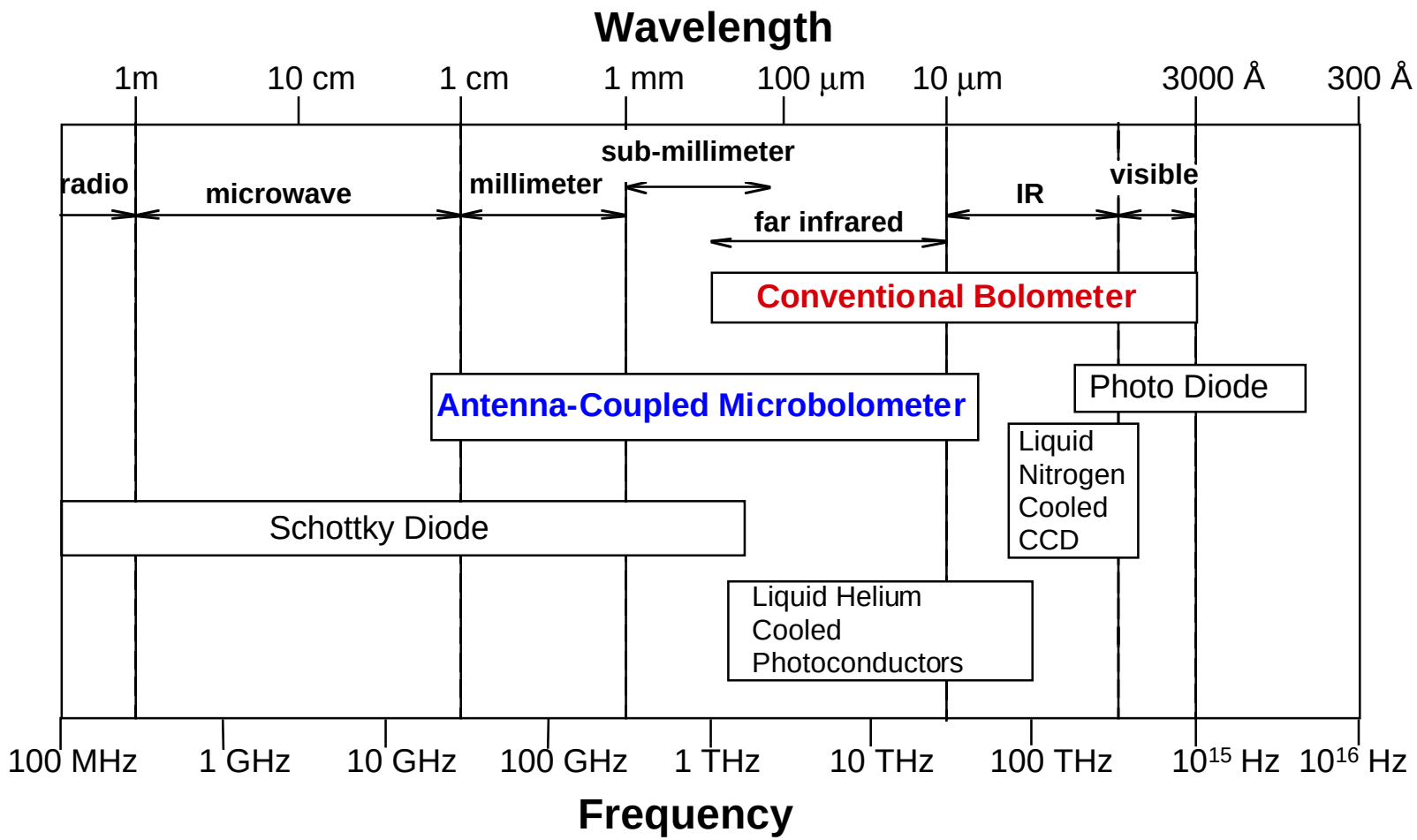
Spectral Range of Common Electromagnetic Detectors



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Detector Size Relative to Wavelength

- critical in determining "coupling efficiency"
- much larger than wavelength
  - "classical" absorber
  - detector is its own "antenna"
  - typical figure-of-merit: specific detectivity (D*)
- much smaller than wavelength: "micro-detectors"
  - very poor coupling
  - requires "antenna" structure
  - typical figure-of-merit: Noise Equivalent Power (NEP)
    - $D^* \approx (\text{effective area})^{0.5} / \text{NEP}$

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Single versus Multi- Mode Antennas

- **single mode: use for point sources**
  - one antenna, one detector
  - absorbed power: $P = kT$
  - effective area $\approx \lambda^2$
- **multimode: use for distributed sources**
  - n-element antenna "array," n detectors
  - $P = nkT$
  - effective area $\approx n\,\lambda^2$
  - $NEP_{array} = \sqrt{n}\, NEP_{single}$
- **regardless, $D^* \approx \lambda / NEP_{single}$**

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Optimum "Resistive" Loads: small detectors

- "detector" area << λ^2
  - behaves like classical "lumped" circuit element: resistor
- "absorption" requires an antenna
- efficiency depends on
  - antenna gain and beam pattern
  - detector/antenna impedance match

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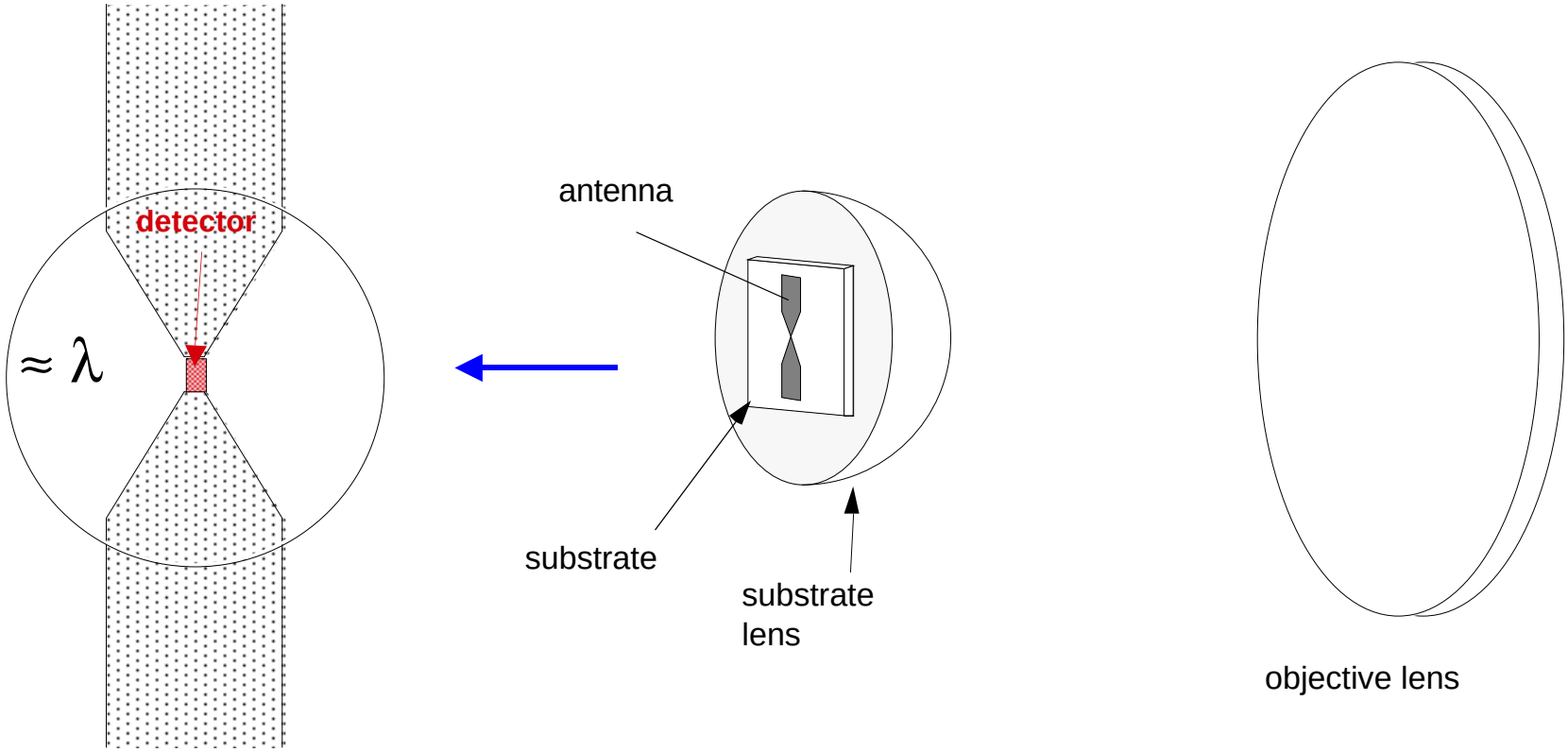
Quasi-Optical Detection System



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Behavior in IR (1-10 μm)

- antenna-coupled microbolometer
  - requires sub-micron size for lumped model to apply
- conductor losses in antenna
  - use "non-resonant" design: simple bow-tie
- substrate absorption impacts efficiency
  - couples most strongly to radiation incident from high dielectric substrate side of antenna

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Trade-offs: Small versus Large Thermal Detectors

- figure of merit improves as responsivity increases
  - NEP = Noise Voltage / Responsivity
- responsivity r (Volts/Watt)

$$r = I_{bias} \cdot \frac{dR}{dT} \cdot \frac{dT}{dP}$$

  depends on:
  - bias current
  - "thermometer" sensitivity: resistance change / temperature rise
  - thermal impedance: temperature rise / power in
- how do these quantities scale with size?

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Optimizing Responsivity: Thermal Impedance

- **limiting mechanisms: heat flow from small bodies**
  - **radiation: negligible**
  - **conduction: dominant for micron size objects**
  - **convection: can be significant for > tens of microns**
- **role of material properties**
  - **thermal conductivities: leads, bolometer, substrate**
    metal : semiconductor : insulator
    3 : 1 : 0.1 - 0.01
  - **heat capacities**
    2 : 1.6 : 2 - 1

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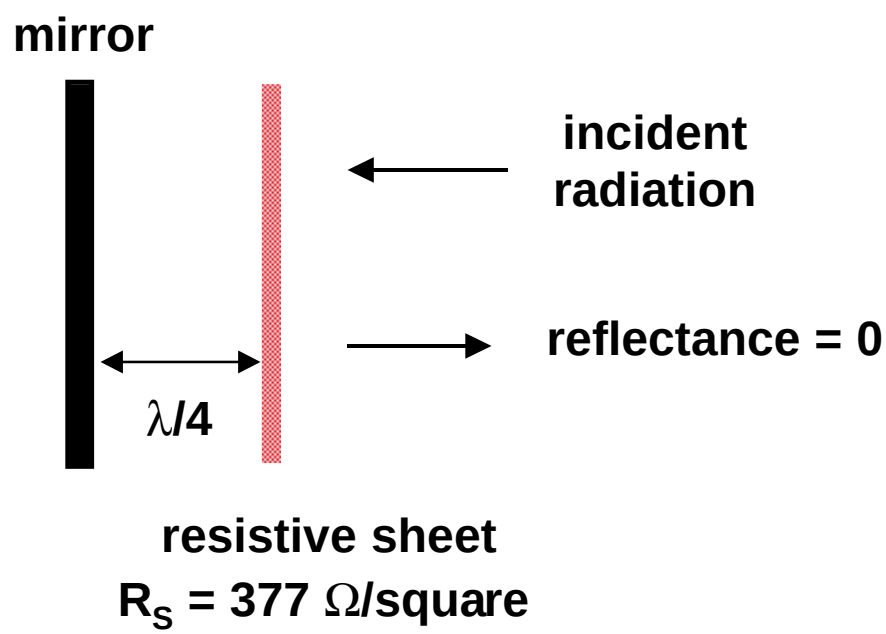
Optimum "Resistive" Absorbers: large detectors

- area >> λ^2
- "multimode" system
- impedance matched sheet
  - -absorption must be VERY strong
  - -requires both resistive sheet and perfect mirror
- 100 % absorption in resistive sheet at design wavelength



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"Large" Area Bolometer Designs

- can use micromachining to form "free standing" films
  - high thermal resistance still possible
    - if too large will be slow
  - bulk or sacrificial layer processes
- material selection
  - metals
    - skin depth ≈ 10nm @ λ_o = 5 μm
    - impedance matching requires very thin sheets
      - tens of Å ≈ few ohms/square
  - semiconductors
    - below-gap absorption weak
      - free carrier absorption

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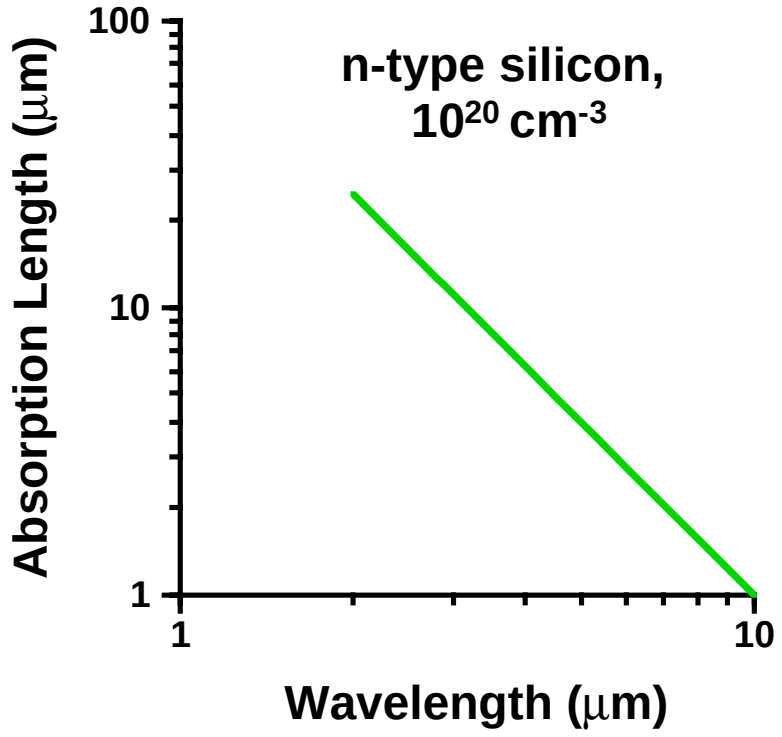
Free Carrier Absorption in Silicon

- absorption constant

  $\alpha \propto n \cdot \lambda^2$

- would appear very thick layers necessary for efficient absorption
- heavy doping also required



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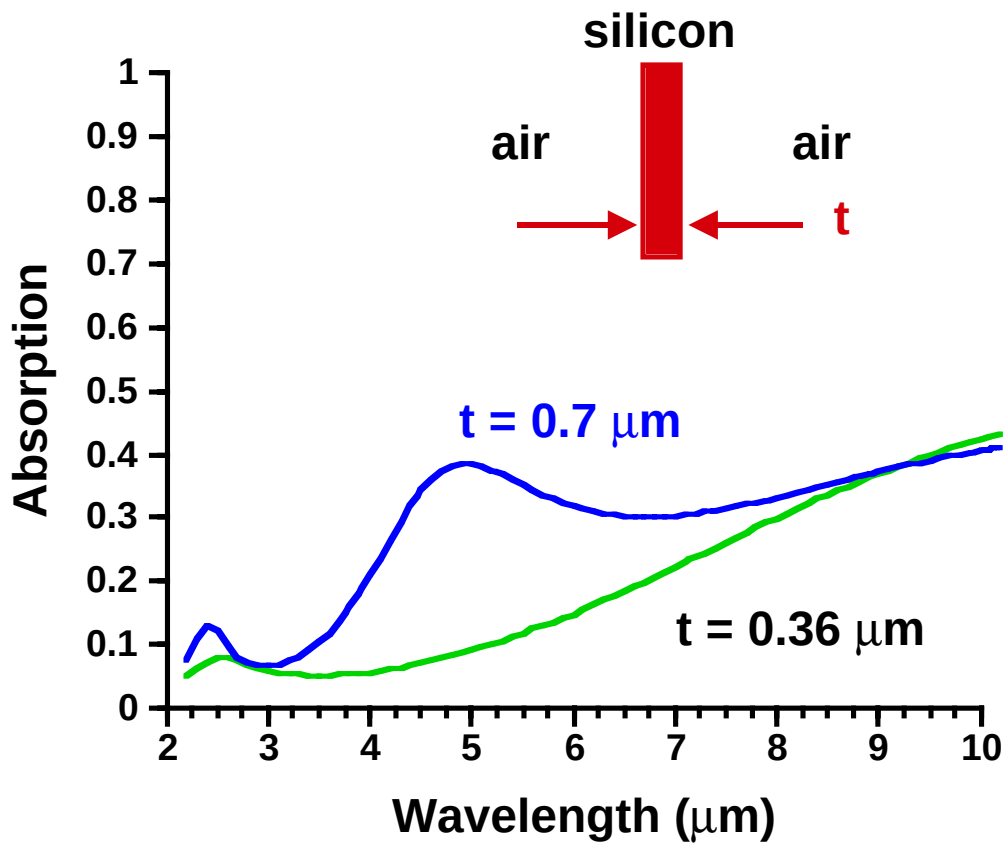
Free Carrier Absorption in Thin Silicon Films

- transfer matrix method used for calculations
  - -easily handles multiple layers, complex index of refraction
- equivalent to microwave network ABCD matrices



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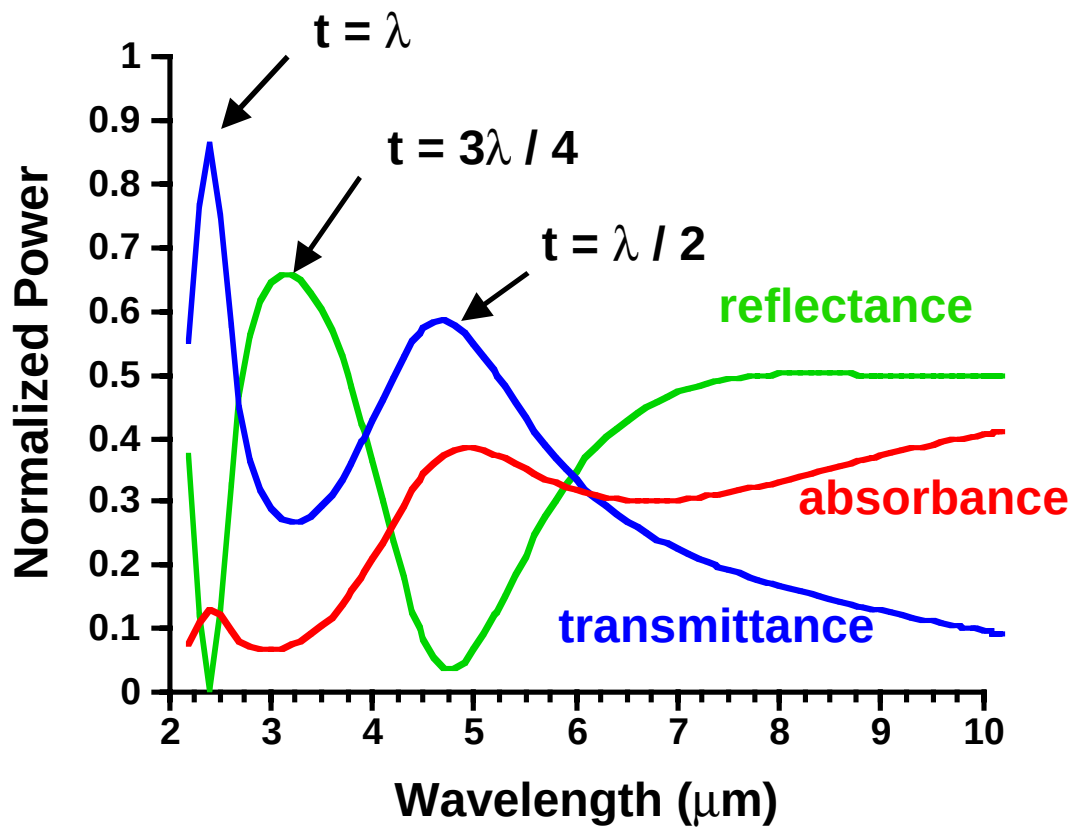
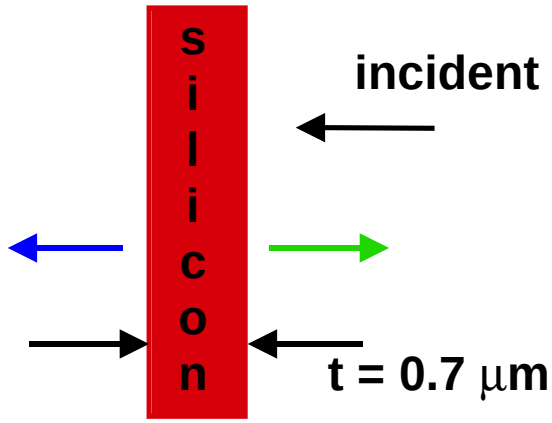
Interference Effects in Moderately Absorbing Films





- t = λ/2 ⇒ half wave window
- t = λ/4 ⇒ impedance inverter
- t = λ ⇒ full wave window

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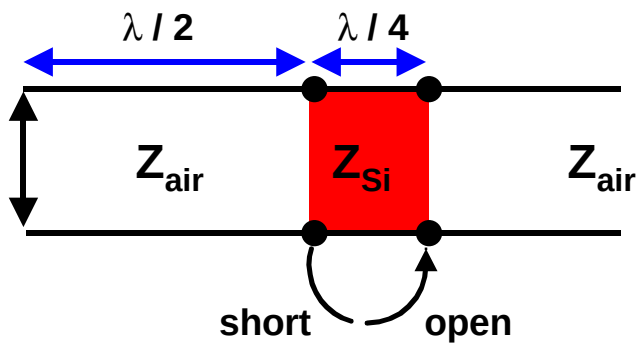
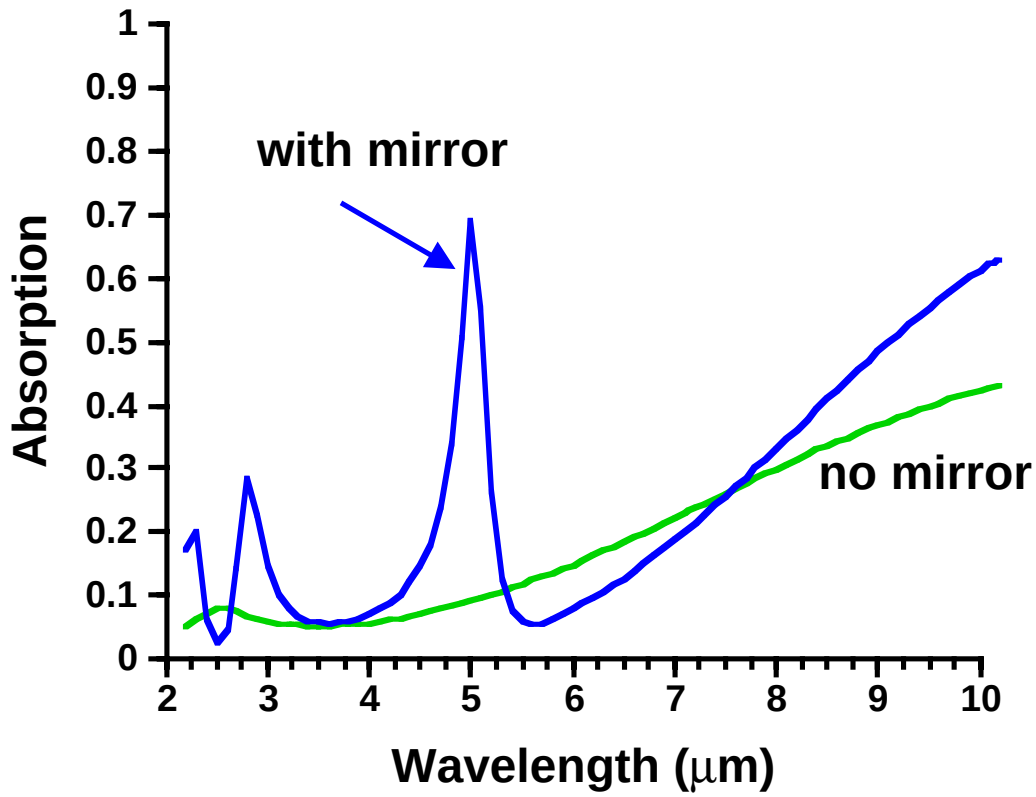
Impedance Matching using "Backshorts"

- 0.36 μm thick silicon sheet
  - $R_s^{dc} \approx 83\ \Omega$/square
- silver mirror place 2.5 μm behind sheet

- at $\lambda_o = 5\ \mu m$:





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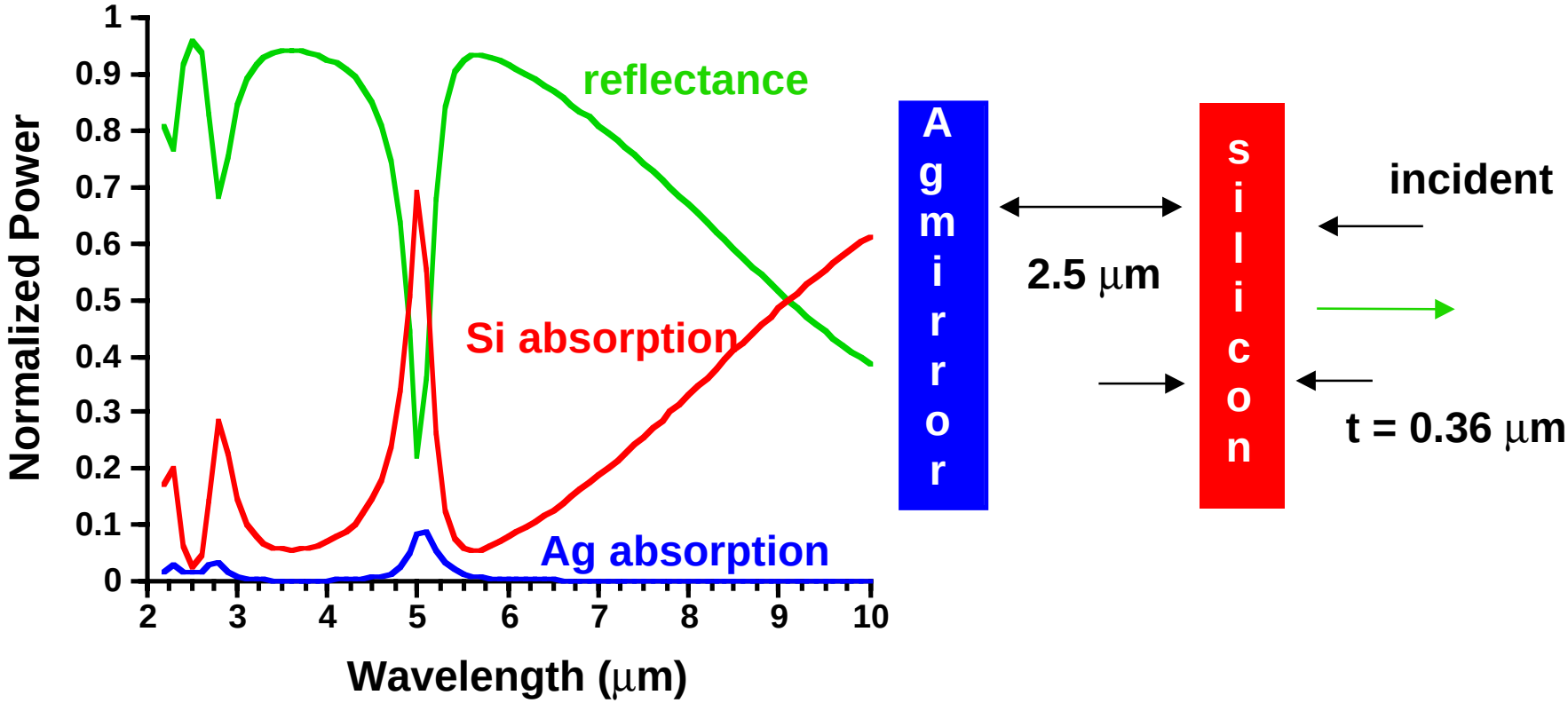
0.36 μm Silicon Film with Mirror



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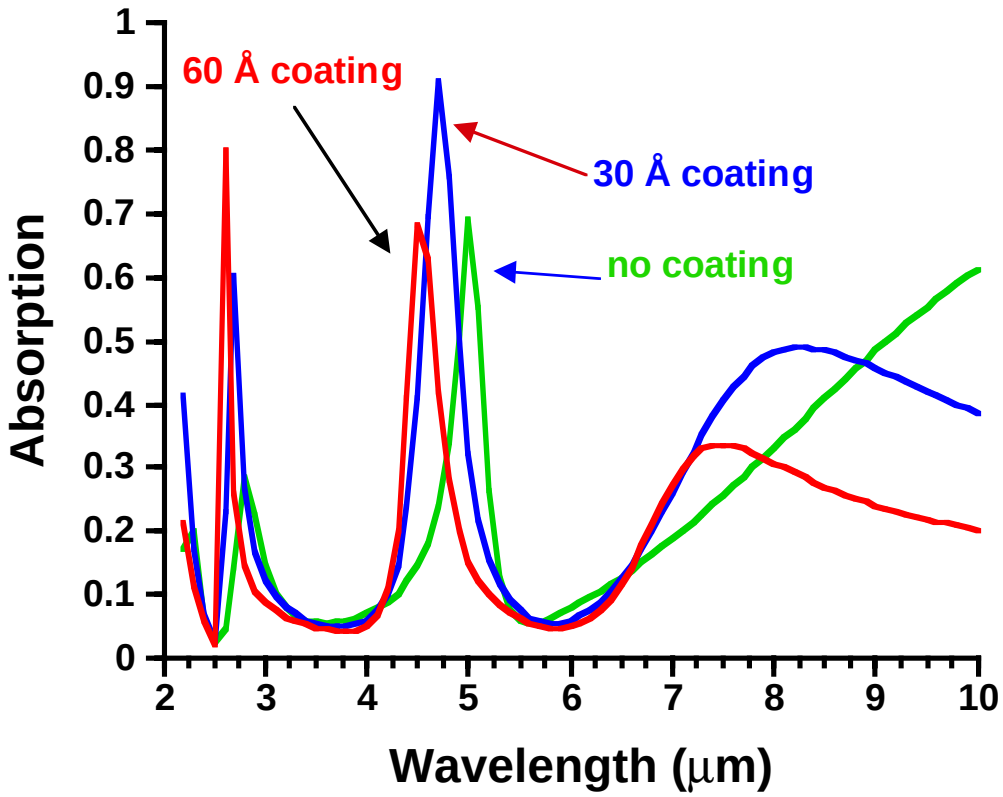
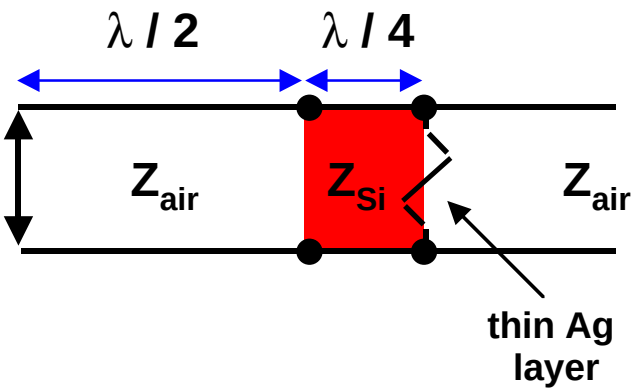
Enhanced Absorption using "Resistive" Coating





- 0.36 μm Si film, Ag mirror 2.5 μm behind
- front surface coated with thin Ag film
  - no coating
  - 30 Å ⇒ $R_s^{dc} \approx 6.7\ \Omega/\square$
  - 60 Å ⇒ $R_s^{dc} \approx 3.3\ \Omega/\square$

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Classical Devices Made Small

- radiation detection
  - bolometers can be made both fast and sensitive using dimensions at the micron scale
- multi-layer interference effects enhance IR absorption
  - interference effects in micromachined silicon membranes over mirrors can increase effective mid-IR absorption
  - 90 % absorption possible
- multi-layer dielectric stack mirrors / filters
  - can generate wavelength selectivity in “monolithic” form

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