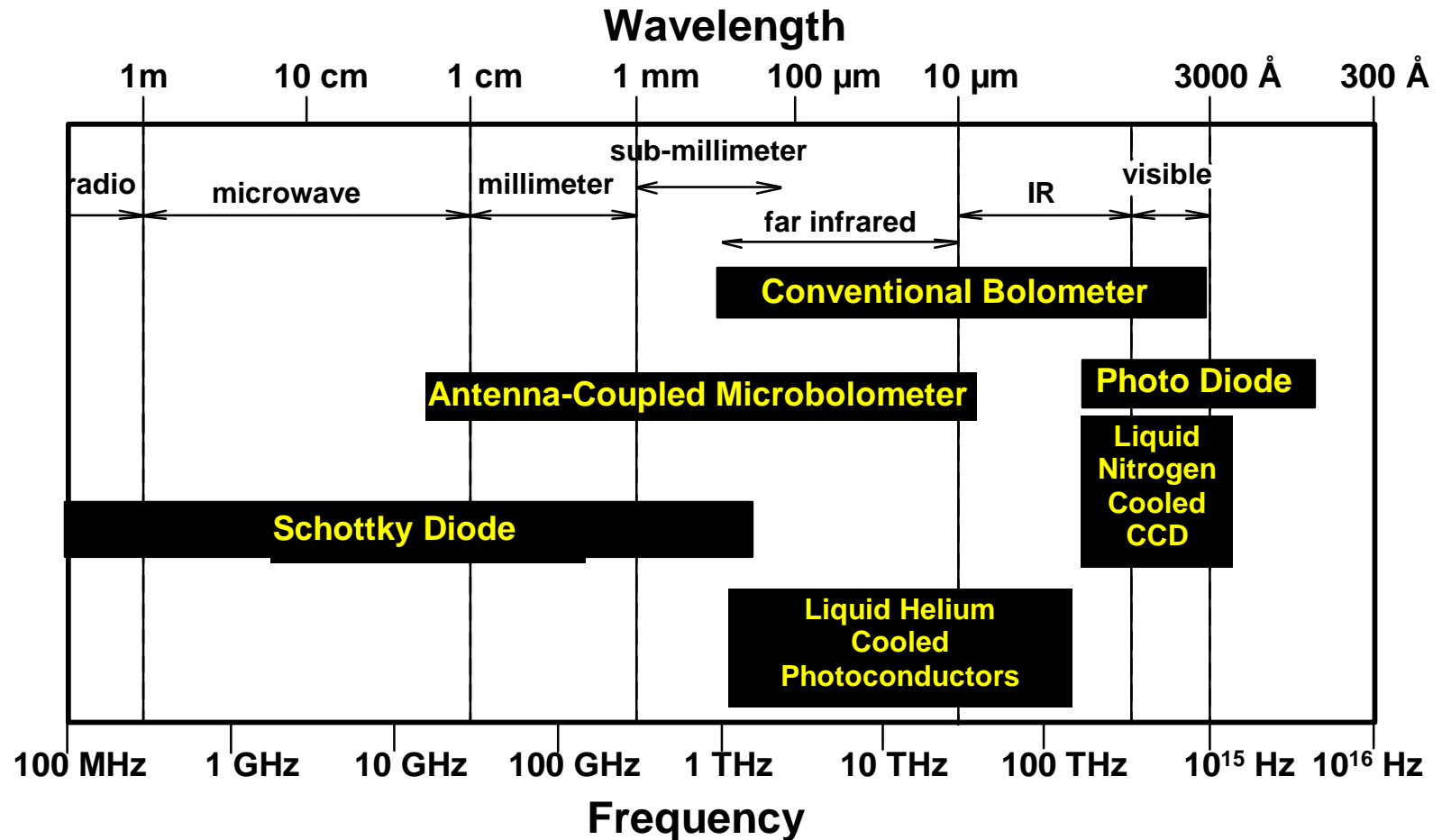


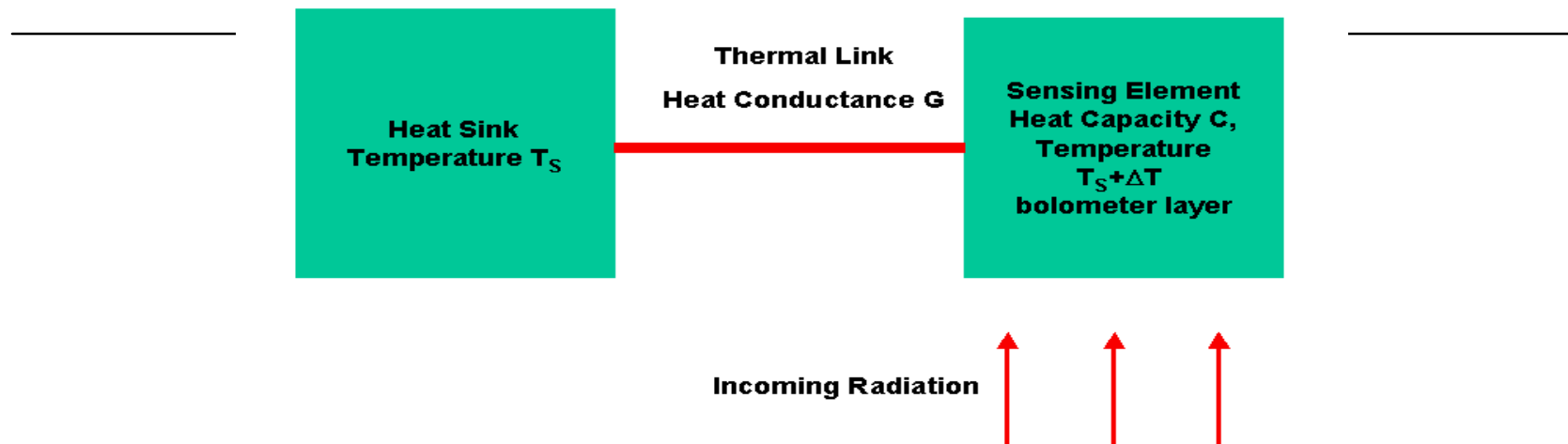
Case study: electromagnetic radiation detection

- **many modes of detection**
 - **rectification**
 - requires non-linear element (diode)
 - usually restricted to “low” frequencies
 - **photon detection**
 - generation of electron/hole pairs
 - usually restricted to “short” wavelengths
 - **thermal detection**
 - convert incoming E&M energy into heat
 - can be fairly independent of frequency/wavelength

Spectral range of common electromagnetic detectors



Basic thermal radiation detector: bolometer



- convert incident electromagnetic radiation to heat, heat capacity C , attached to a heat sink at temp. T_s via thermal resistance R .
- thermal time constant $t \gg C \cdot R$
- At “dc” $T_{\text{bolo}} = T_s + P_{\text{bolo}} \cdot R$
- temperature change ΔT resistance change ΔR voltage difference via constant applied bias current
- to maximize responsivity $\Delta R / \Delta T$ maximize thermal resistance R_{th} between bolometer and heat sink

Output voltage and responsivity

$$V = I_b \cdot \frac{dR}{dT} \cdot \Delta T = I_b \cdot \frac{dR}{dT} \cdot P_{\text{absorbed}} \cdot Z_{\text{thermal}}$$

$$\mathfrak{R} = \frac{V}{P_{\text{incident}}} = I_b \cdot \frac{dR}{dT} \frac{dT}{dP} \cdot \frac{P_{\text{absorbed}}}{P_{\text{incident}}} = I_b \cdot Z_{\text{thermal}} \cdot \frac{dR}{dT} \cdot \eta$$

$$\mathfrak{R} = I_b \cdot Z_{\text{thermal}} \cdot \alpha \cdot R_{\text{bolo}} \cdot \eta$$

$$\alpha = \frac{1}{R_{\text{bolo}}} \frac{dR_{\text{bolo}}}{dT}$$

$$\eta = \text{coupling efficiency}$$

- depends on bias current, temperature coefficient of resistance α , bolometer resistance R_{bolo} , device thermal impedance Z_{thermal} , and coupling efficiency η

Figure of merit: Noise Equivalent Power

- figure of merit is really the minimum detectable input power
 - depends on both responsivity and noise
- for simple resistive bolometer the lowest noise level is Johnson noise
 - noise voltage depends of bandwidth

$$V_{\text{johnson}} = \sqrt{4k_B \cdot T \cdot R \cdot BW}$$

- units for NEP are normally volts/root hertz

$$\text{NEP} = \frac{V_{\text{noise}}}{\mathfrak{R}}$$

- increased responsivity R tends to improve (decrease) NEP

Detector Size Relative to Wavelength

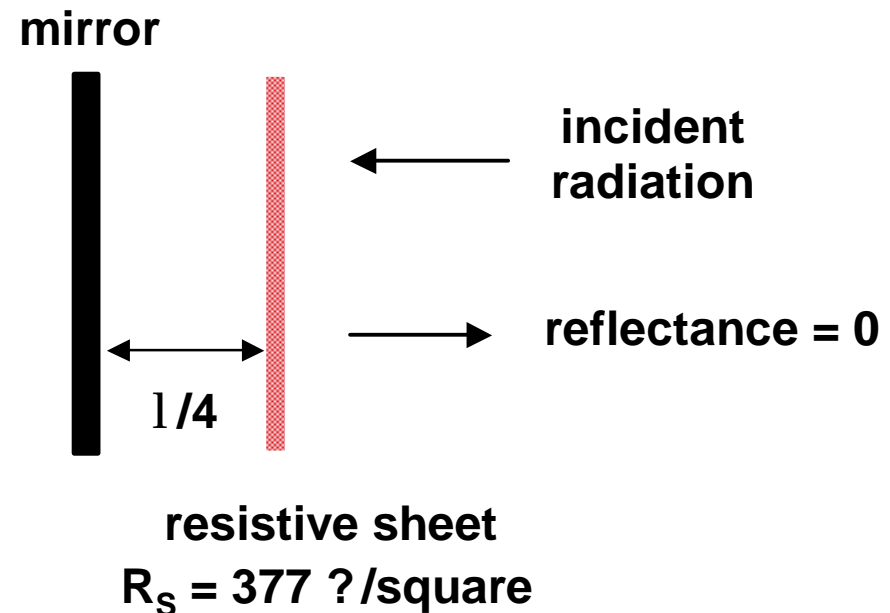
- critical in determining "coupling efficiency"
- much larger than wavelength
 - "classical" absorber
 - detector is its own "antenna"
 - typical figure-of-merit: specific detectivity (D^*)
 - typical units $\text{cm} \cdot (\text{root Hz}) / \text{watt}$
- much smaller than wavelength:
"micro-detectors"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

Single versus Multi- Mode Antennas

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

Optimum "Resistive" Absorbers: large detectors

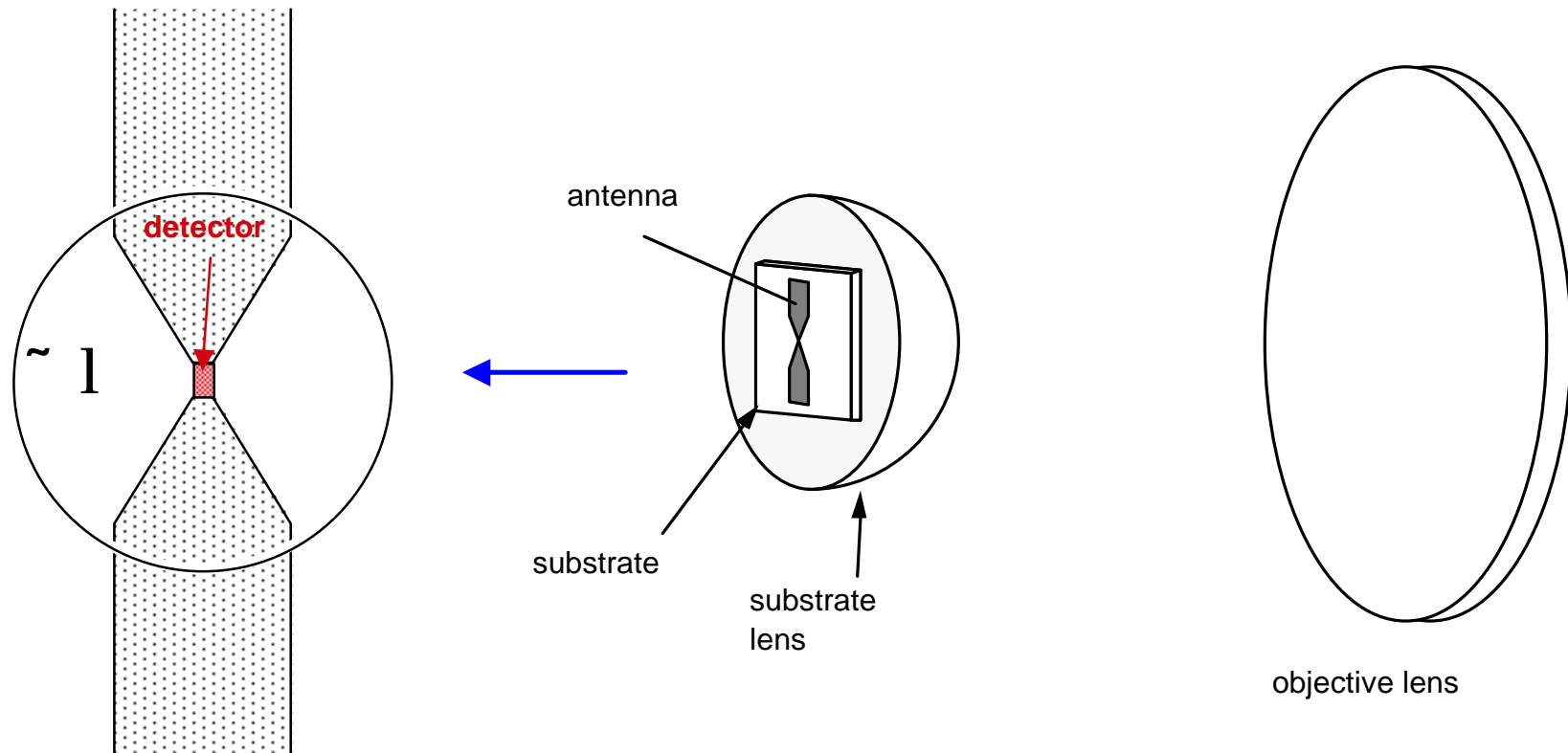
- $\text{area} \gg \lambda^2$
- "multimode" system
- impedance matched sheet
 - absorption must be VERY strong
 - requires both resistive sheet and perfect mirror
- 100 % absorption in resistive sheet at design wavelength



Optimum "Resistive" Loads: small detectors

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

Quasi-Optical Detection System



Trade-offs: Small versus Large Thermal Detectors

- figure of merit improves as responsivity increases
 - NEP = Noise Voltage / Responsivity

- responsivity r (Volts/Watt) $r = I_{\text{bias}} \cdot \frac{dR}{dT} \cdot \frac{dT}{dP}$

depends on:

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

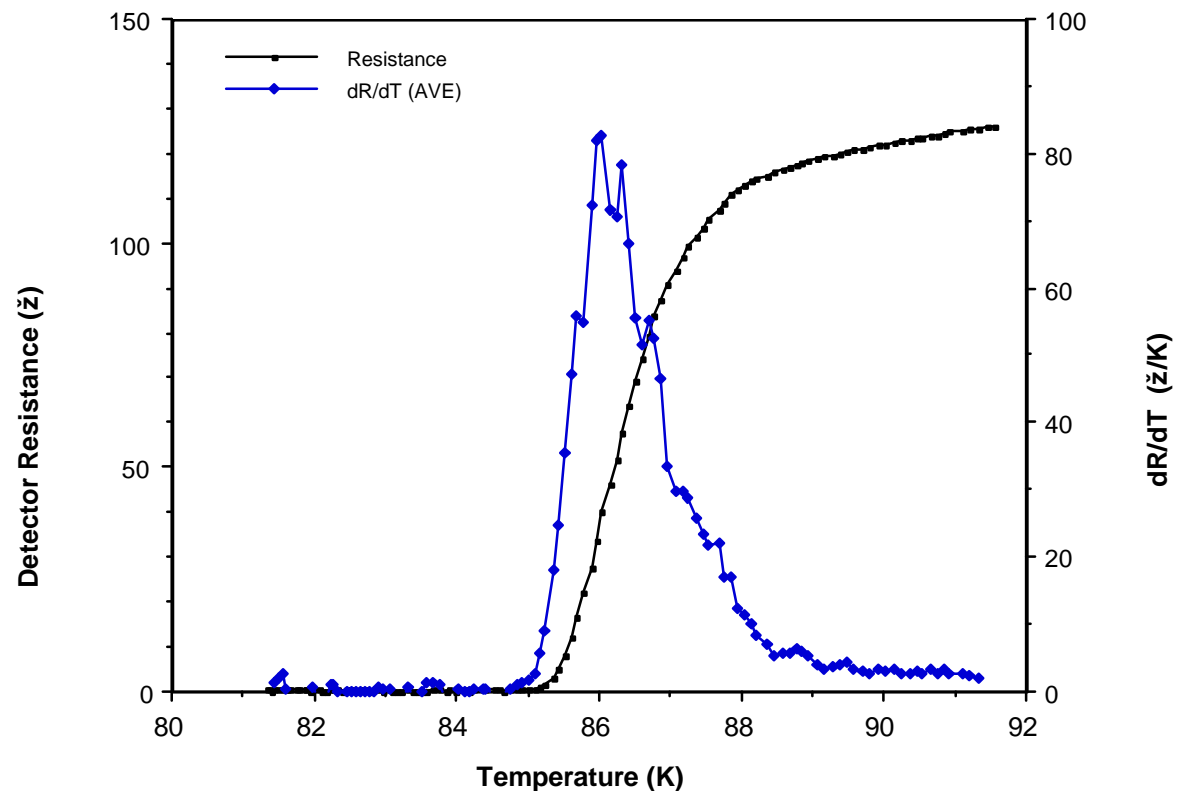
Optimizing responsivity: alpha (temp. coefficient of resistance: TCR)

- highest TCR from superconductors at their transition temperature
 - requires cooling system;
 - may present impedance matching (E&M absorption) problem due to low sheet R
- alpha of several bolometer materials
 - Y-Ba-Cu-O (YBCO) @ T_c : $\sim +0.5 - 1 \text{ K}^{-1}$
 - Vanadium Oxide (VO_x): $\sim -0.015 - 0.028 \text{ K}^{-1}$ (room temp.)
 - Semiconducting YBCO: $\sim -0.0299 - 0.0337 \text{ K}^{-1}$ (room temp.)
 - Ag: $\sim +0.0037 \text{ K}^{-1}$, Ni: $\sim +0.005 \text{ K}^{-1}$, Au: $\sim +0.0036 \text{ K}^{-1}$
 - Bismuth (Bi): $\sim -0.003 \text{ K}^{-1}$ (Room temp.)

Optimizing alpha: Superconducting Detector Strip

- temperature coefficient of resistance α :

- intrinsic semiconductors
- extrinsic semiconductors and metals: $\alpha \sim 1/T$
- transition edge materials
 - YBCO
 - VO₂



Optimizing responsivity: thermal impedance

- **Limiting mechanisms: heat flow from small bodies**
 - radiant: negligible ($W = \epsilon T^4$ W : total radiated power per unit area)
 - conduction: dominant for micron size objects
 - convection: can be significant for > tens of microns but negligible at low pressure
- **Thermal conductivity of various material**
 - Silicon (bulk): ~ 1.3 W/cm-K
 - Si_3N_4 : ~ 0.032 - 0.0385 W/cm-K
 - Bi (thin film): ~0.018 W/cm-K
 - SiO_2 : ~ 0.014 W/cm-K
 - Bi (bulk): ~ 0.0792 W/cm-K

Thermal properties

- **thermal diffusion equation**

$$\nabla^2 \phi = \frac{\rho \cdot C}{\kappa} \frac{\partial \phi}{\partial t}$$

- **f** is temperature change relative to ambient
 - **r** is material density
 - **C** is specific heat (units: energy · mass⁻¹ · kelvin⁻¹)
 - **k** is thermal conductivity (units: power · distance⁻¹ · kelvin⁻¹)
- **if f was a voltage this looks a lot like an electrical problem...**
- **or if f was a concentration this looks a lot like a diffusion problem for constant thermal diffusivity $D = \kappa / \rho C$**

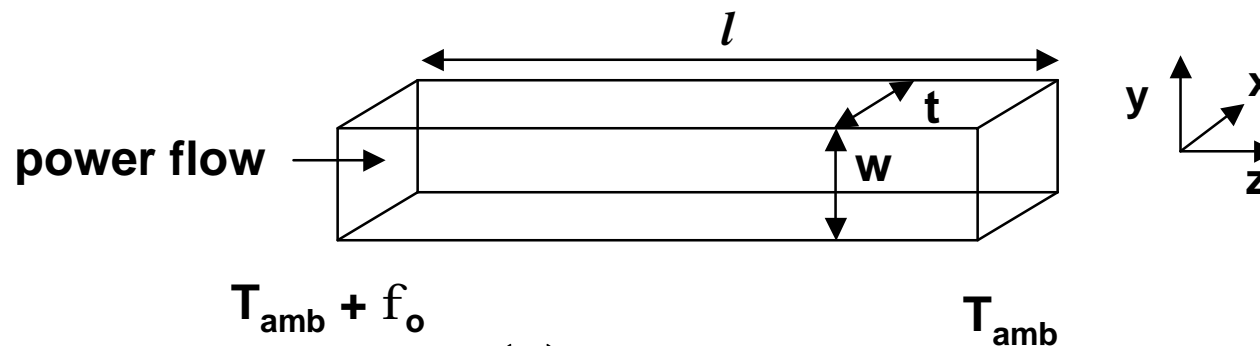
$$\frac{\partial \phi}{\partial t} = \frac{\kappa}{\rho \cdot C} \nabla^2 \phi$$

1-d “sinusoidal” heat flow

$$\underbrace{\nabla^2 \phi}_{1-d} = \frac{\rho \cdot C}{\kappa} \frac{\partial \phi}{\partial t}$$

$$= \frac{\partial^2 \phi}{\partial z^2}$$

- let's assume the power flowing from the “source” end of the bar is sinusoidally varying in time



$$\phi(z) = \phi_o e^{j\omega t - \gamma z}$$

$$\frac{\partial^2 \phi}{\partial z^2} = \frac{\rho \cdot C}{\kappa} \frac{\partial \phi}{\partial t} \Rightarrow \gamma^2 \cdot \phi_o e^{j\omega t - \gamma z} = \frac{\rho \cdot C}{\kappa} \cdot (j\omega) \cdot \phi_o e^{j\omega t - \gamma z} \Rightarrow \gamma = \sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}}$$

$$\phi_{\text{end}} = P \cdot Z_{\text{thermal}} = \frac{P}{t \cdot w} \cdot \sqrt{\frac{1}{j \cdot \omega \cdot \kappa \cdot \rho \cdot C}} \cdot \tanh\left(\sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}} \cdot l\right)$$

What does this really mean?

- consider “low frequency”: length of bar much less than thermal diffusion length

$$\gamma \cdot l = \frac{l}{L_{thermal}} = \sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}} \cdot l \ll 1$$

$$\phi_{end} = \frac{P}{t \cdot w} \cdot \sqrt{\frac{1}{j \cdot \omega \cdot \kappa \cdot \rho \cdot C}} \cdot \underbrace{\tanh \left(\underbrace{\sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}} \cdot l}_{\ll 1} \right)}_{\approx \text{argument}} \approx \frac{P}{t \cdot w} \cdot \sqrt{\frac{1}{j \cdot \omega \cdot \kappa \cdot \rho \cdot C}} \cdot \sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}} \cdot l$$

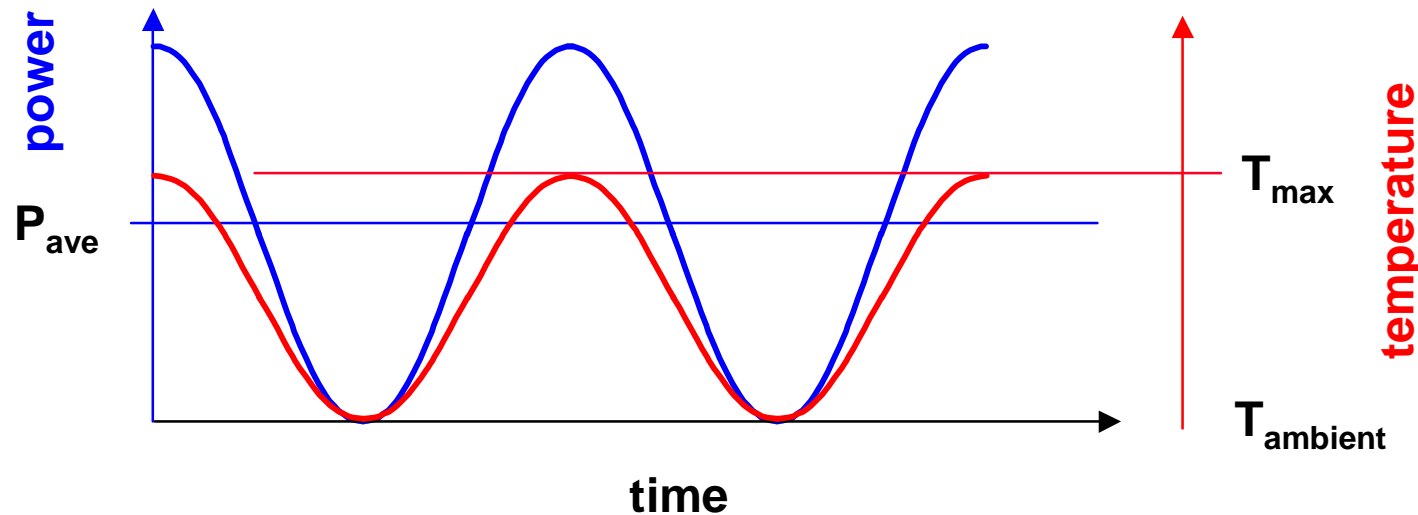
$$\phi_{end}^{“low freq”} \approx \underbrace{\frac{P}{t \cdot w}}_{\text{power density}} \cdot \frac{l}{\kappa}$$

- looks just like the resistance of a bar with “conductivity” κ

Low frequency thermal response

$$\Delta T = \frac{l}{t \cdot w \cdot \kappa} P$$

- the actual input power looks like
 - $P_{in} = P_{ave} \cdot [1 + \cos(\omega t)]$
- at “low frequency” the temperature “follows” (in phase) the input power
 - temperature rises as power increases
 - temperature falls as power decreases



High frequency thermal response

- consider “high frequency”: length of bar much longer than thermal diffusion length

$$\gamma \cdot l = \frac{l}{L_{thermal}} = \sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}} \cdot l \gg 1$$

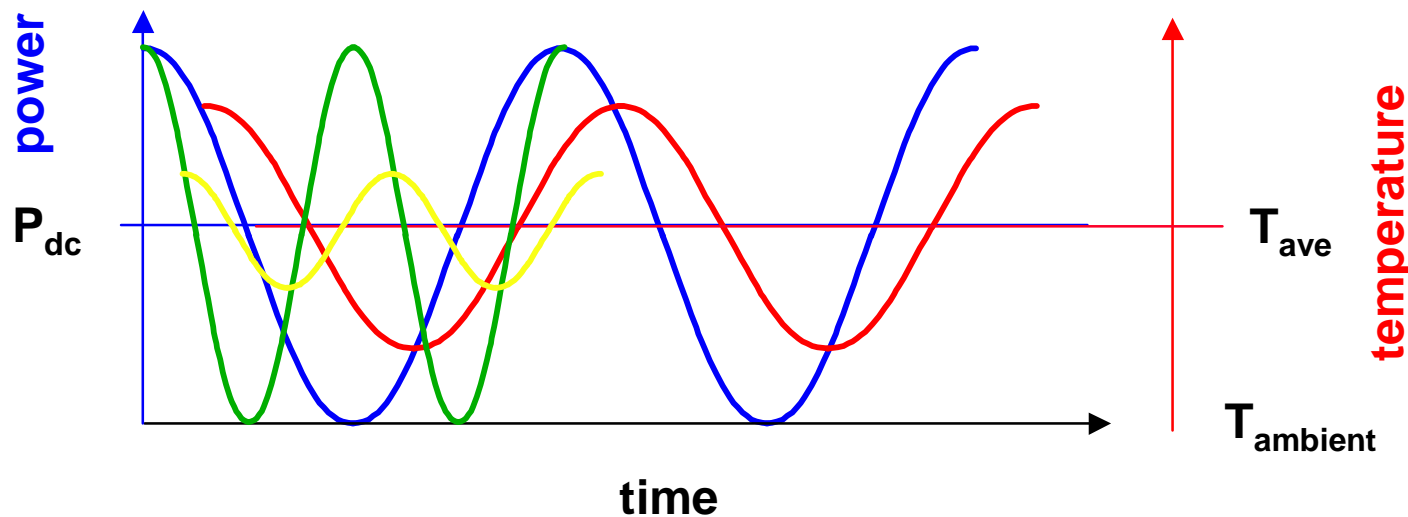
$$\phi_{end} = \frac{P}{t \cdot w} \cdot \sqrt{\frac{1}{j \cdot \omega \cdot \kappa \cdot \rho \cdot C}} \cdot \underbrace{\tanh \left(\underbrace{\sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}} \cdot l}_{\gg 1} \right)}_{\approx 1} \approx \frac{P}{t \cdot w} \cdot \sqrt{\frac{1}{j \cdot \omega \cdot \kappa \cdot \rho \cdot C}} \cdot \underbrace{L_{thermal}}_{L_{thermal}/\kappa}$$

$$\phi_{end}^{“high\ freq”} \approx \underbrace{\frac{P}{t \cdot w}}_{\text{power density}} \cdot \frac{L_{thermal}}{\kappa} = \frac{P}{t \cdot w} \cdot \sqrt{\frac{1}{2\omega\kappa\rho C}} \cdot (1 - j)$$

High frequency thermal response

$$\phi_{\text{end}}^{\text{"high freq"}} \approx \underbrace{\frac{P}{t \cdot w}}_{\text{power density}} \cdot \frac{L_{\text{thermal}}}{\kappa} = \frac{P}{t \cdot w} \cdot \sqrt{\frac{1}{2\omega\kappa\rho C}} \cdot (1 - j)$$

- the temperature “lags” the power by 45°
- as the frequency increases the magnitude of the temperature change decreases as $\frac{1}{\sqrt{\omega}}$



Superconducting transition edge bolometer

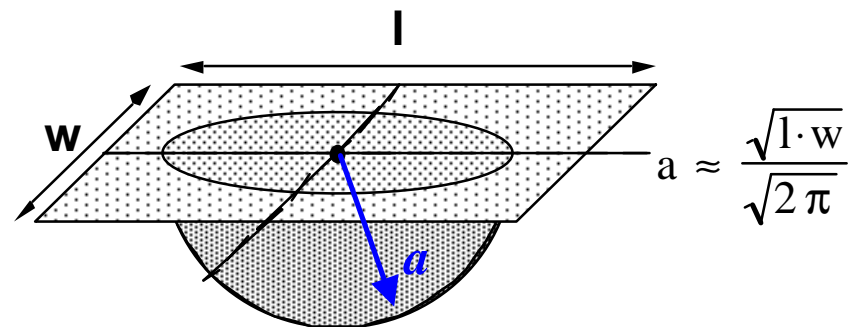
- **Richards, early 60's**
 - few square millimeter “black” coated glass slide
 - “bismuth black” used as broad-band absorber
 - suspended by silk threads in a cooled vacuum chamber
 - small superconducting “resistor” attached
 - threads coated with thin metal to allow electrical access
- **produced very high thermal resistance, moderate thermal capacitance**
- **how does this scale with size?**
 - need to look at thermal model and various heat transport mechanisms for small objects

Heat Conduction into Substrate

- approximate the detector-substrate contact area as a hemisphere
- use thermal spreading resistance
 - R_{thermal} scales as (area)^{-1/2}
 - cut-off frequency scales as 1/area
- for device on SiO₂
 - 10 μm x 10 μm
 - $R_{\text{thermal}} = 2.5 \times 10^4$ K/W
 - cut-off $f = 8.5$ kHz
 - 1 μm x 1 μm
 - $R_{\text{thermal}} = 2.5 \times 10^5$ K/W
 - cut-off $f = 850$ kHz
- for “large” devices clearly need to remove the substrate to increase R!

$$\phi = \phi_o \frac{r_o}{r} e^{j \cdot \omega \cdot t - \frac{(r-r_o)}{L_{\text{thermal}}}} \quad L_{\text{thermal}} = \sqrt{\frac{\kappa}{j \cdot \omega \cdot \rho \cdot C}}$$

$$\Delta T = \frac{1}{\underbrace{2\pi \cdot \kappa \cdot r_o}_{\text{thermal spreading resistance}}} P$$



$$R_{\text{thermal substrate}} \approx \frac{1}{\sqrt{2\pi} \cdot \kappa_{\text{substrate}} \cdot \sqrt{\text{area}}}$$

$$f_{\text{substrate}}^{\text{cut-off}} \approx \frac{\kappa_{\text{substrate}}}{\rho \cdot C_{\text{substrate}} \cdot \text{area}}$$

Thermal losses: convection to air

- simple spherical model for convective cooling
- h_c : surface coefficient of heat transfer
 - units: W / area•Kelvin

$$h_c = Nu \cdot \frac{k}{d}$$

- k : thermal conductivity
- d : diameter
- Nu : Nusselt number
- for free convection from spheres Nu is approximately

$$Nu = 2 + 0.45 \cdot (Gr \cdot Pr)^{1/4}$$

- Gr : Grashof number
- Pr : Prandtl number

Thermal losses: Convection

- **Gr: Grashof number** $Gr = \frac{\rho^2 \cdot g \cdot \beta \cdot \Delta T \cdot L^3}{\mu^2}$
 - g is acceleration due to gravity, ρ is density, μ is viscosity, β is the coef. of volume expansion, L is length of object
 - for air near room temperature

$$Gr \approx 3.4 \times 10^{-17} \cdot L^3 (L \text{ in microns}) \cdot \Delta T (\text{in Kelvin})$$

- **Pr: Prandtl number** $Pr = \frac{C \cdot \mu}{K} \approx 0.72 (\text{air near room temp})$
- so as long as $L < \text{cm}$ the Nusselt # is

$$Nu = 2 + 0.45 \cdot (Gr \cdot Pr)^{1/4} \approx 2$$

Thermal losses: Convection

- then h_c , surface coefficient of heat transfer
 - units: W / area•Kelvin

$$h_c \approx 2 \cdot \frac{\kappa}{d}$$

- thermal conduction from sphere is just (area • h_c)

$$G_c \approx 4\pi \cdot d^2 \cdot h_c = 8\pi \cdot \kappa_{\text{air}} \cdot d$$

- or

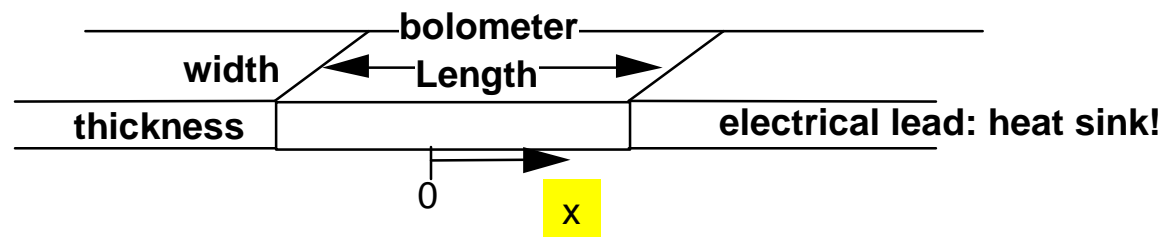
$$R_{\text{convect to air}} \approx \frac{1}{8\pi \cdot \kappa_{\text{air}} \cdot \sqrt{\text{area}}}$$

- looks just like thermal spreading resistance term!

$$R_{\text{substrate}}^{\text{thermal}} \approx \frac{1}{\sqrt{2\pi} \cdot \kappa_{\text{substrate}} \cdot \sqrt{\text{area}}}$$

What about heat sinking through the ends?

- use a simple bar model



- assume

- absorbed power is uniformly dissipated throughout bolometer, sinusoidally varying in time

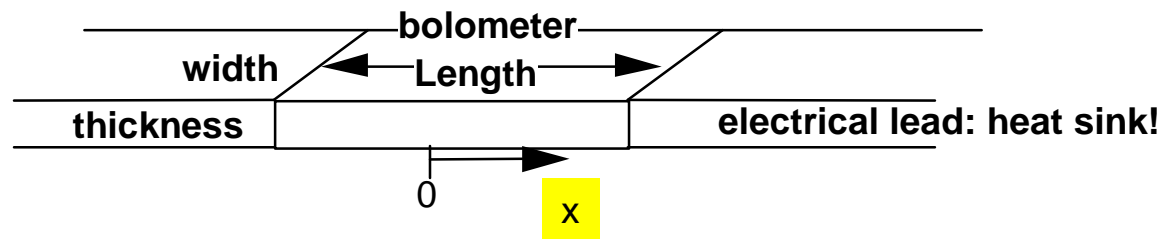
$$P_{\text{input}} = \frac{P_o}{2} (1 + e^{j\omega t})$$

- ends of detector are connected to perfect heat sinks

- thermal diffusion equation is then

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} = \frac{\rho_{\text{bol}} \cdot C_{\text{bol}}}{\kappa_{\text{bol}}} \frac{\partial \phi}{\partial t} - \frac{P_o}{2 \cdot L \cdot t \cdot w \cdot \kappa_{\text{bol}}} (1 + e^{j\omega t})$$

What about heat sinking through the ends?



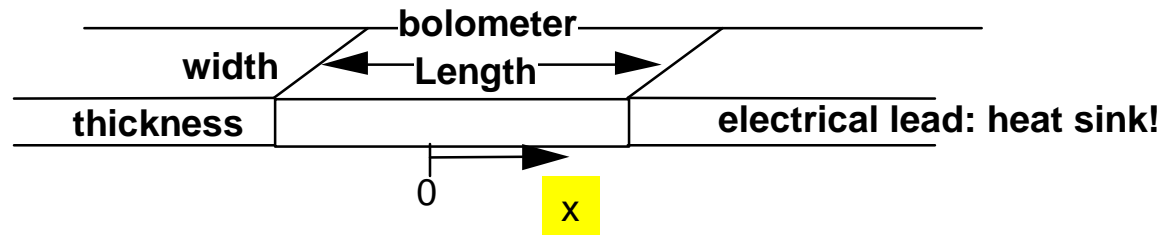
- since is symmetric, solve with $x = 0$ at center
 - assume
 - absorbed power is uniformly dissipated throughout bolometer, sinusoidally varying in time
 - ends of detector are connected to perfect heat sinks

$$\phi(x) = \frac{P_o}{2 \cdot L \cdot t \cdot w \cdot \kappa_{bol}} \cdot \left\{ \frac{L^2}{8} - \frac{x^2}{2} + j \cdot \frac{\kappa_{bol}}{\rho_{bol} \cdot C_{bol} \cdot \omega} \cdot e^{j\omega t} \cdot \left(\frac{\cosh[\gamma \cdot x]}{\cosh[\gamma \cdot L/2]} - 1 \right) \right\}$$

$$\gamma \equiv \sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}}$$

- if TCR is constant, then really want integral averaged temperature over the whole length of the bolometer

Heat sinking through the ends



- integral averaged temperature over the length

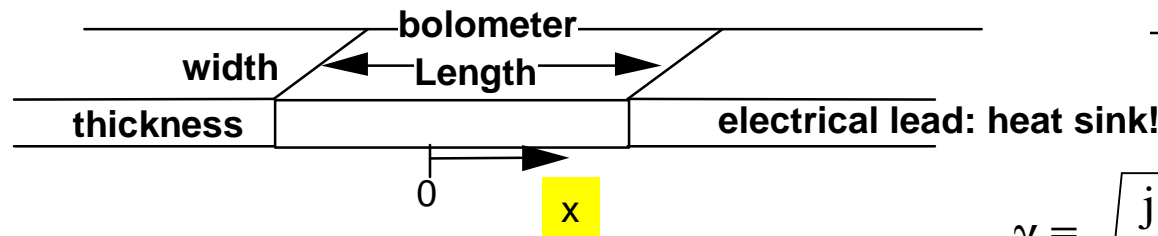
$$\langle \phi \rangle = \frac{1}{L} \int_{-L/2}^{+L/2} \phi(x) dx = \frac{P_o}{24 \cdot t \cdot w \cdot \kappa_{bol}} \cdot \left\{ 1 + 24 \cdot \frac{1}{(\gamma \cdot L)^3} \cdot e^{j\omega t} \cdot \left(\frac{\gamma \cdot L}{2} - \tanh \left[\frac{\gamma \cdot L}{2} \right] \right) \right\}$$

$$\gamma \equiv \sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}}$$

- ratio of time varying temp to time varying input power is the thermal impedance

$$Z_{thermal}(\omega) = 2 \frac{L}{t \cdot w \cdot \kappa_{bol}} \cdot \frac{1}{(\gamma \cdot L)^3} \left\{ \frac{\gamma \cdot L}{2} - \tanh \left[\frac{\gamma \cdot L}{2} \right] \right\}$$

Heat sinking through the ends



$$\gamma \equiv \sqrt{\frac{j \cdot \omega \cdot \rho \cdot C}{\kappa}}$$

- low frequency: $|g| \cdot L \ll 1$

$$\bar{\phi} \underbrace{\approx}_{|\gamma| \cdot L \ll 1} \frac{P_o \cdot L^2}{24 \cdot L \cdot t \cdot w \cdot \kappa_{bol}} \cdot \{1 + e^{j\omega t}\}$$

$$Z_{thermal} = \frac{\bar{\phi}}{P} \underbrace{\approx}_{|\gamma| \cdot L \ll 1} \frac{L}{12 \cdot t \cdot w \cdot \kappa_{bol}}$$

- high frequency: $|g| \cdot L \gg 1$

$$\bar{\phi} \underbrace{\approx}_{|\gamma| \cdot L \gg 1} \frac{P_o \cdot L^2}{2 \cdot L \cdot t \cdot w \cdot \kappa_{bol}} \cdot \left\{ \frac{1}{12} - j \cdot \frac{\kappa_{bol}}{\rho_{bol} \cdot C_{bol} \cdot \omega} \cdot e^{j\omega t} \right\}$$

$$Z_{thermal} \underbrace{\approx}_{|\gamma| \cdot L \gg 1} \frac{1}{\rho \cdot t \cdot w \cdot L \cdot C_{bol}} \cdot \frac{1}{j \cdot \omega}$$

- same as parallel R-C circuit with

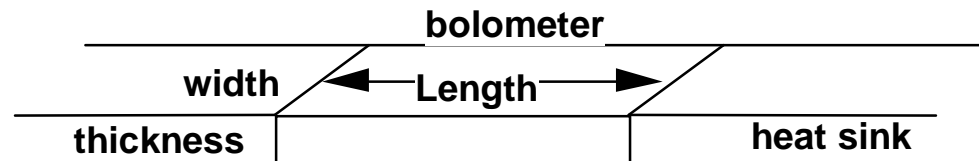
$$R_{thermal} = \frac{L}{12 \cdot t \cdot w \cdot \kappa_{bol}} \quad C_{thermal} = \rho \cdot t \cdot w \cdot L \cdot C_{bol}$$

$$\omega_{cut-off} \approx 1/R_{thermal} C_{thermal} = \frac{12 \cdot \kappa_{bol}}{\rho \cdot C_{bol} \cdot L^2}$$

Small bolometers: heat conduction directly through device leads

- assume heat sink at ends of bolometer

$$C_{\text{thermal}} = \rho \cdot t \cdot w \cdot L \cdot C_{\text{bol}}$$



$$R_{\text{thermal}} = \frac{L}{12 \cdot t \cdot w \cdot \kappa_{\text{bol}}} = \frac{1}{12} \cdot \frac{\sigma}{\kappa} \cdot R_{\text{bolom electrical}}$$

$$\omega_{\text{cut-off}} \approx \frac{12 \cdot \kappa_{\text{bol}}}{\rho \cdot C_{\text{bol}} \cdot L^2}$$

- thermal resistance directly proportional to electrical resistance, regardless of material!
- for high thermal R want length to cross-sectional area ratio to be large
- for high speed want L small!

- for silicon bar:

10 μ m x 10 μ m x 0.5 μ m

$R^{\text{thermal}} = 10^3 \text{ K/W}$

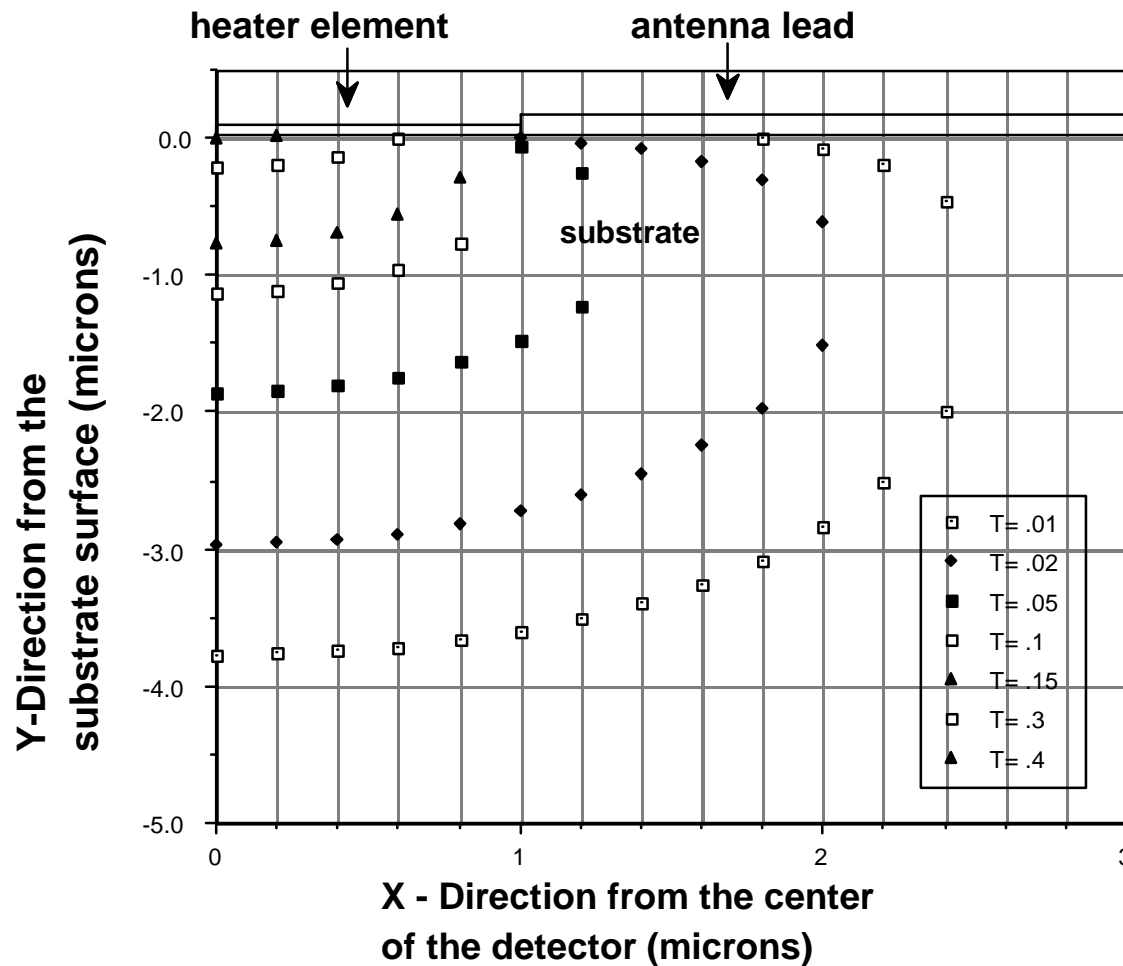
cut-off f = 1.6 MHz

1 μ m x 1 μ m x 0.5 μ m

$R^{\text{thermal}} = 10^3 \text{ K/W}$

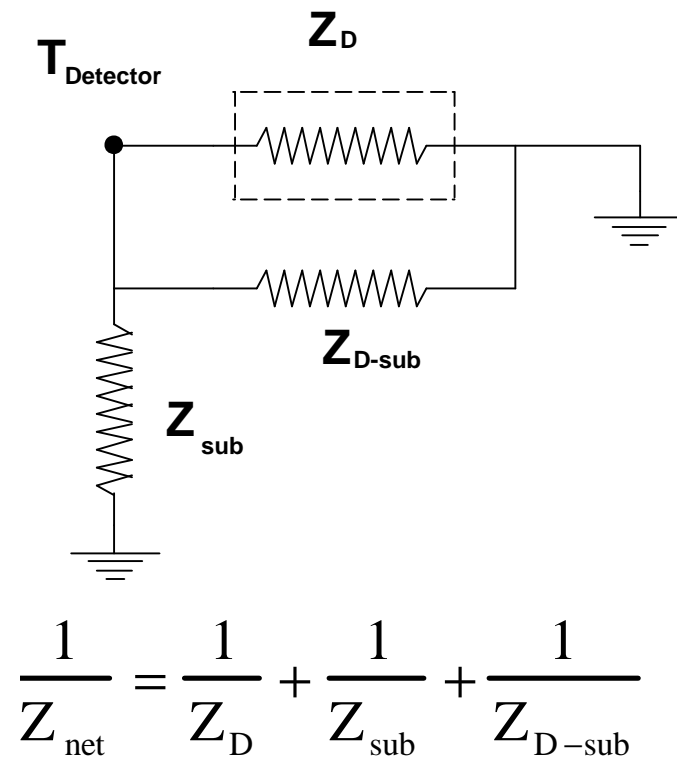
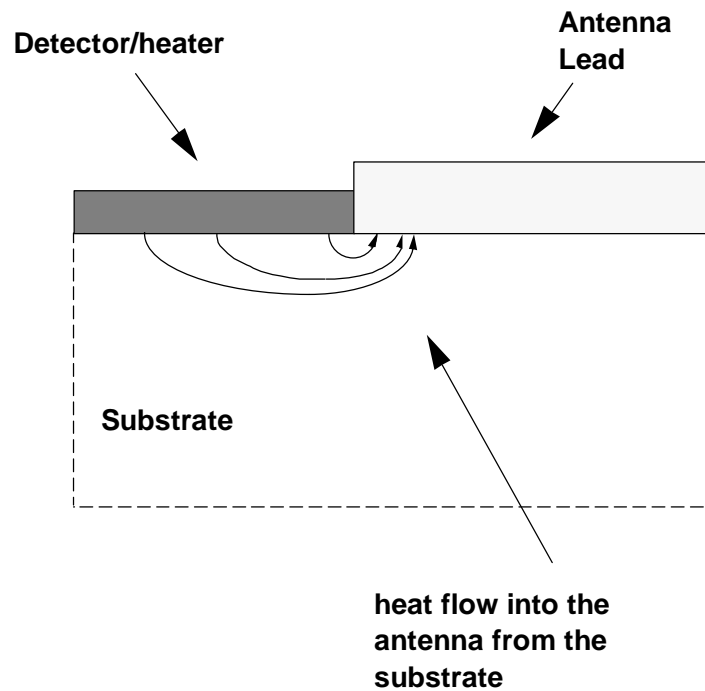
? cut-off f = 160 MHz

Actual simulation results for full three-D geometry: Isothermal Profile into Substrate



- Bismuth Load
- Quartz Substrate
- Operating Conditions
 - Input power = 4 μ W
 - Length = 4 μ m
 - Width = 2 μ m

Fringe Heat Conduction into Leads



- thermal resistance and speed increase as bolometer shrinks

Thermal impedance summary

- convection to air above bolometer

$$R_{\text{convect}}^{\text{thermal}} \approx \frac{1}{8\pi \cdot \kappa_{\text{air}} \cdot \sqrt{\text{area}}}$$

- conduction to “substrate”
 - substrate under bolometer

$$R_{\text{substrate}}^{\text{thermal}} \approx \frac{1}{\sqrt{2\pi} \cdot \kappa_{\text{substrate}} \cdot \sqrt{\text{area}}}$$

- air above bolometer

$$R_{\text{air}}^{\text{thermal}} \approx \frac{1}{\sqrt{2\pi} \cdot \kappa_{\text{air}} \cdot \sqrt{\text{area}}}$$

- conduction out “arms” of bolometer

$$R_{\text{arms}}^{\text{thermal}} = \frac{L}{12 \cdot \text{area} \cdot \kappa_{\text{bol}}}$$

- total from parallel combination (smallest R dominates)

$$R_{\text{thermal}} = \left[\sum \frac{1}{R_i^{\text{thermal}}} \right]^{-1}$$

- clearly R_{thermal} gets bigger as device area gets smaller
- speed gets higher as volume of device shrinks

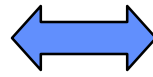
“Micro” bolometers

- **originally this term was coined by Hwang and Schwarz, and referred to bolometers that were smaller than a wavelength**
 - T.-L. Hwang, S. E. Schwarz, and D. B. Rutledge, “Microbolometers for infrared detection,” *Applied Physics Letters*, vol. 34, pp. 773, 1979.
 - **required antenna for coupling**
- **to increase thermal resistance need to decrease cross sectional area, and increase length, of “thermal link”**
- **can use micromachining to form "free standing" films to “remove” the substrate**
 - **bulk or sacrificial layer processes can be used**

Basic classes of antenna coupled microbolometers

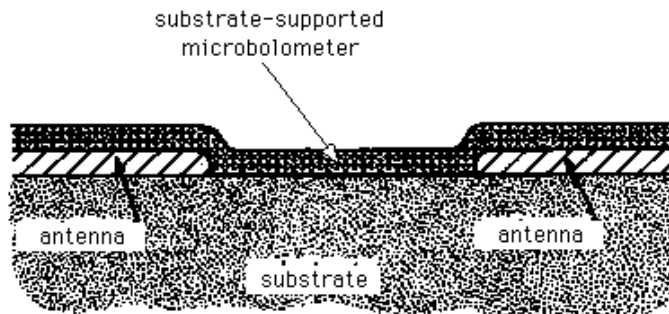
- main classification set by dominant heat transport mechanism

$$R_{\text{substrate}}^{\text{thermal}} \approx \frac{1}{\sqrt{2\pi} \cdot \kappa_{\text{substrate}} \cdot \sqrt{\text{area}}}$$



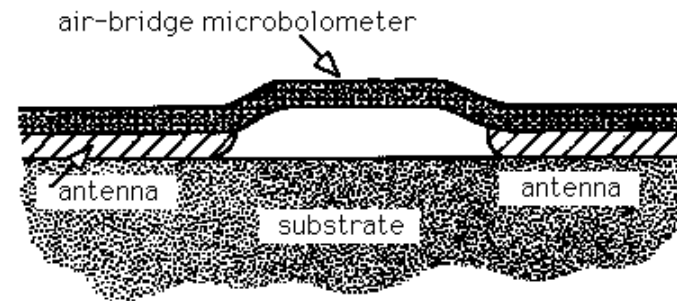
$$R_{\text{arms}}^{\text{thermal}} = \frac{L}{12 \cdot \text{area} \cdot \kappa_{\text{bol}}}$$

- “substrate supported”: main heat loss to substrate under bolometer
- “air-bridge”: main heat loss out ends of bolometer



$$R_{\text{substrate}}^{\text{thermal}} < R_{\text{arms}}^{\text{thermal}}$$

$$1 < \frac{\sqrt{2\pi}}{12} \cdot \frac{L}{\sqrt{\text{area}}} \cdot \frac{\kappa_{\text{substrate}}}{\kappa_{\text{bol}}}$$



$$R_{\text{substrate}}^{\text{thermal}} > R_{\text{arms}}^{\text{thermal}}$$

$$\frac{\sqrt{2\pi}}{12} \cdot \frac{L}{\sqrt{\text{area}}} \cdot \frac{\kappa_{\text{substrate}}}{\kappa_{\text{bol}}} < 1$$

“Air-bridge” bolometers

- need

$$\frac{\sqrt{2\pi}}{12} \cdot \frac{L}{\sqrt{\text{area}}} \cdot \frac{\kappa_{\text{substrate}}}{\kappa_{\text{bol}}} < 1$$

- easiest way to get this is to have $\kappa_{\text{sub}} \ll \kappa_{\text{bol}}$
- use micromachining to form "free standing" films to “remove” the substrate
 - bulk or sacrificial layer processes can be used

- thermal resistance is then

$$R_{\text{arms}}^{\text{thermal}} = \frac{L}{12 \cdot \text{area} \cdot \kappa_{\text{bol}}}$$

- increase by decreasing cross sectional area, increasing length

Optimizing Responsivity

$$\mathfrak{R} = \frac{V}{P_{\text{incident}}} = I_b \cdot \frac{dR}{dT} \frac{dT}{dP} \cdot \frac{P_{\text{absorbed}}}{P_{\text{incident}}} = I_b \cdot Z_{\text{thermal}} \cdot \frac{dR}{dT} \cdot \eta$$

- clearly want max Z_{thermal} , but improvement is not unbounded
- bias current limitations

from I^2R heating: $I_{\text{max}}^2 \cdot R = P_{\text{max}} = (T_{\text{max}} - T_{\text{amb}})/Z_{\text{thermal}}$

$$r \approx \sqrt{T_{\text{max}} - T_{\text{ambient}}} \cdot \sqrt{R_{\text{bol}}} \cdot \alpha_{\text{bol}} \cdot \sqrt{R_{\text{bol}}^{\text{thermal}}}$$

- current density (electromigration/critical currents)

$$r \approx \frac{J_{\text{max}} \cdot \alpha_{\text{bol}} \cdot l \cdot R_{\text{bol}}^{\text{thermal}}}{\sigma_{\text{bol}}}$$

$$r \approx \frac{J_{\text{max}} \cdot \alpha_{\text{bol}}}{2\sqrt{\pi} \cdot \sigma_{\text{bol}} \cdot \kappa_{\text{sub}}} \cdot \sqrt{\frac{l}{w}} \quad \text{substrate-dominated}$$

- detector instability (problem only if α is positive)

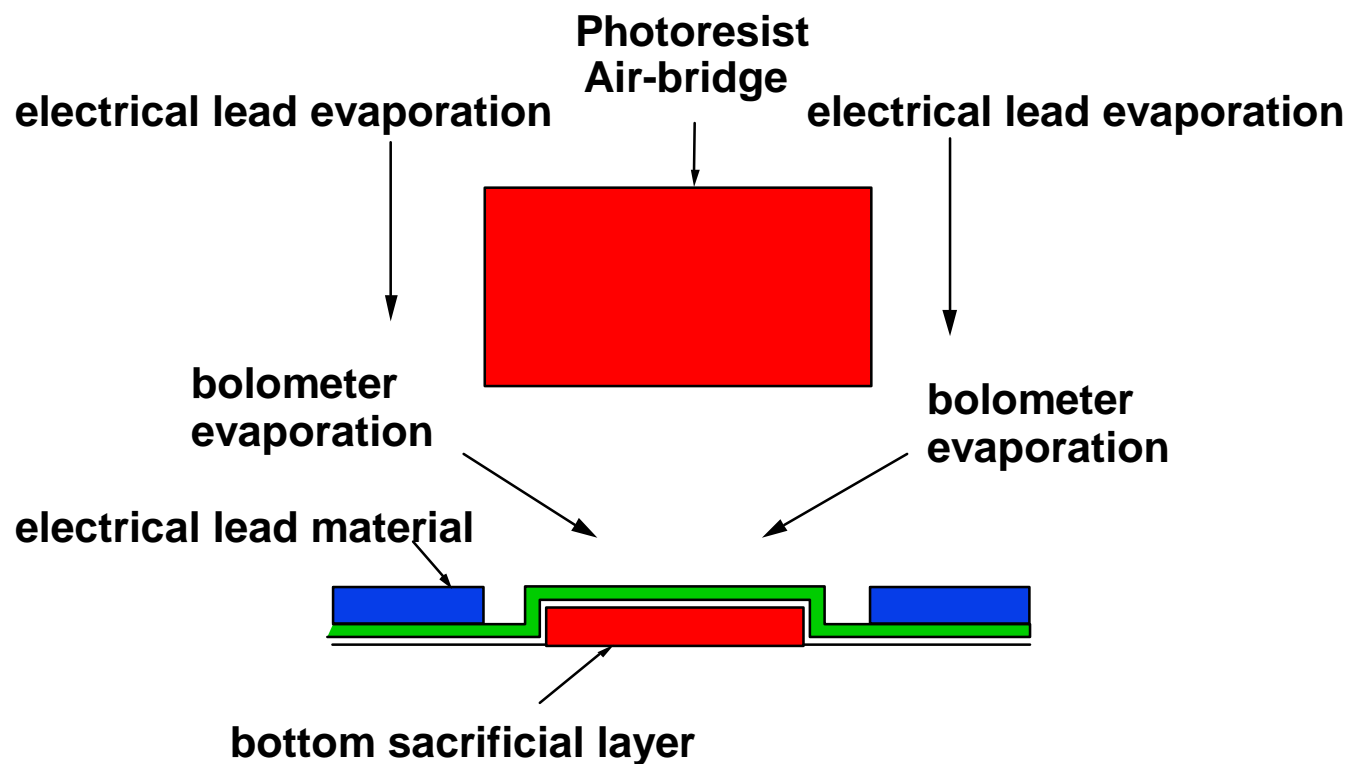
$$r \cdot I_{\text{bias}} < 1 \Rightarrow (I_{\text{bias}})^2 \cdot \frac{dR}{dT} < \frac{1}{R_{\text{bol}}^{\text{thermal}}}$$

$$r < \sqrt{R_{\text{bol}} \cdot \alpha_{\text{bol}} \cdot R_{\text{bol}}^{\text{thermal}}}$$

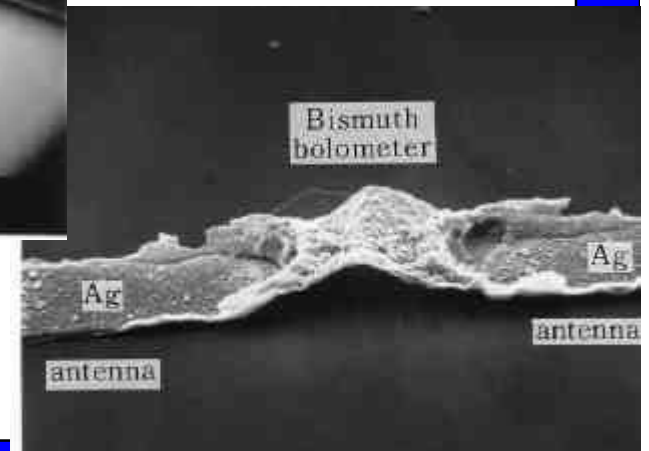
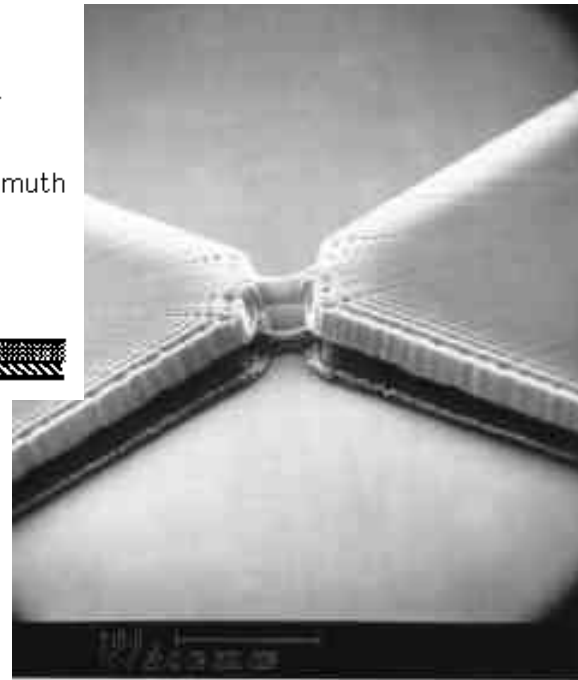
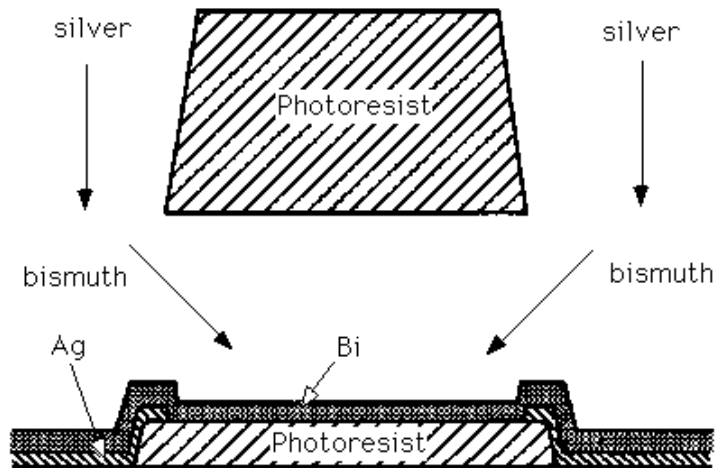
alpha positive

Tri-layer sacrificial resist process

- **use photoresist as sacrificial layer**
 - tri-layer resist, middle layer soluble, top and bottom patterned
- **lift-off patterning of materials**



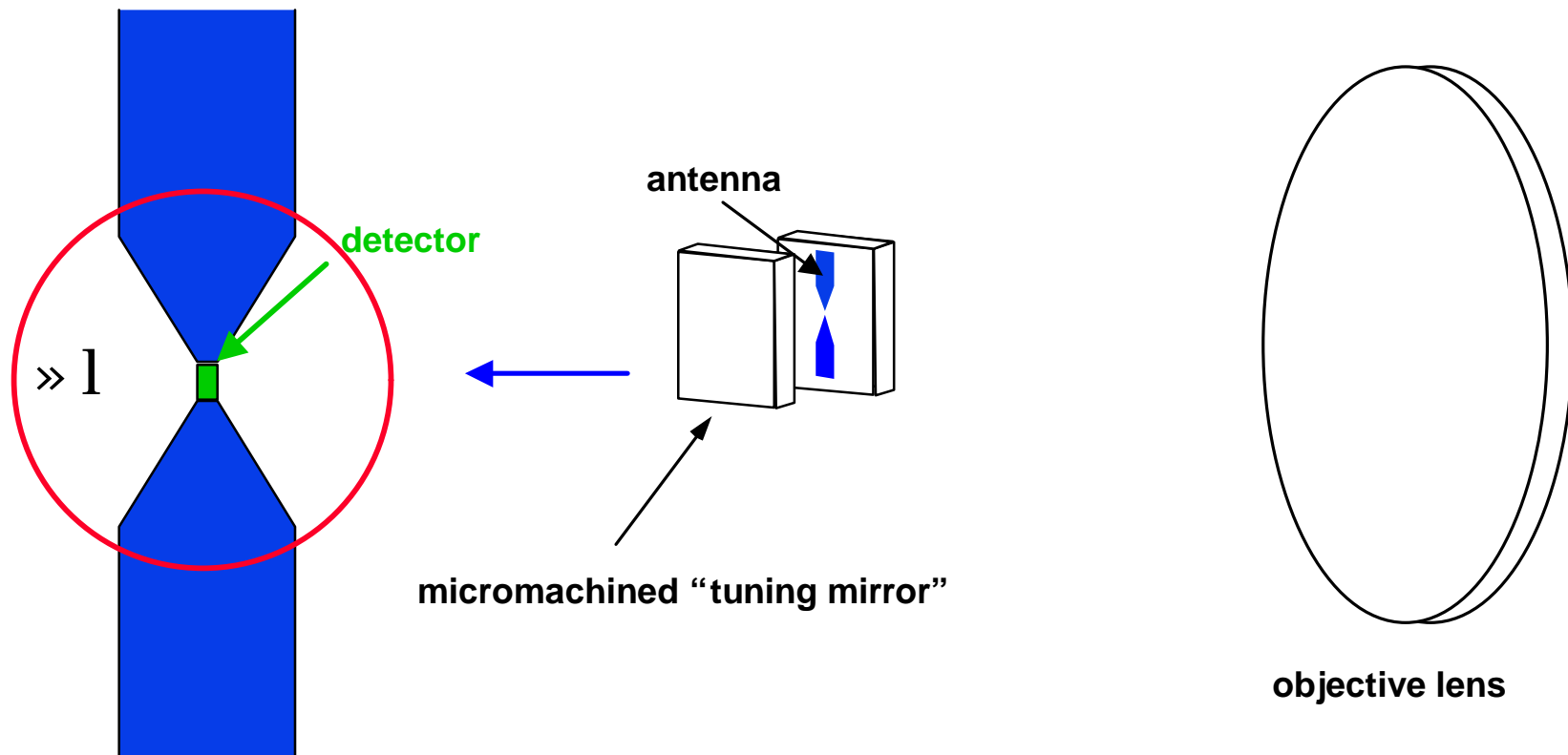
Air-bridge Lithographic Technique



Behavior in IR (~1 - ~10 mm)

- **antenna-coupled microbolometer**
 - requires sub-micron size for lumped model to apply
- **conductor losses in antenna**
 - use "non-resonant" design: simple bow-tie
 - achieve wavelength selectivity using “back short” (integral micromachined mirror)
- **substrate absorption impacts efficiency**
 - micromachining removes substrate from antenna

Quasi-Optical Detection System



Impedance Matching: Composite Microbolometers

- size and conductivity

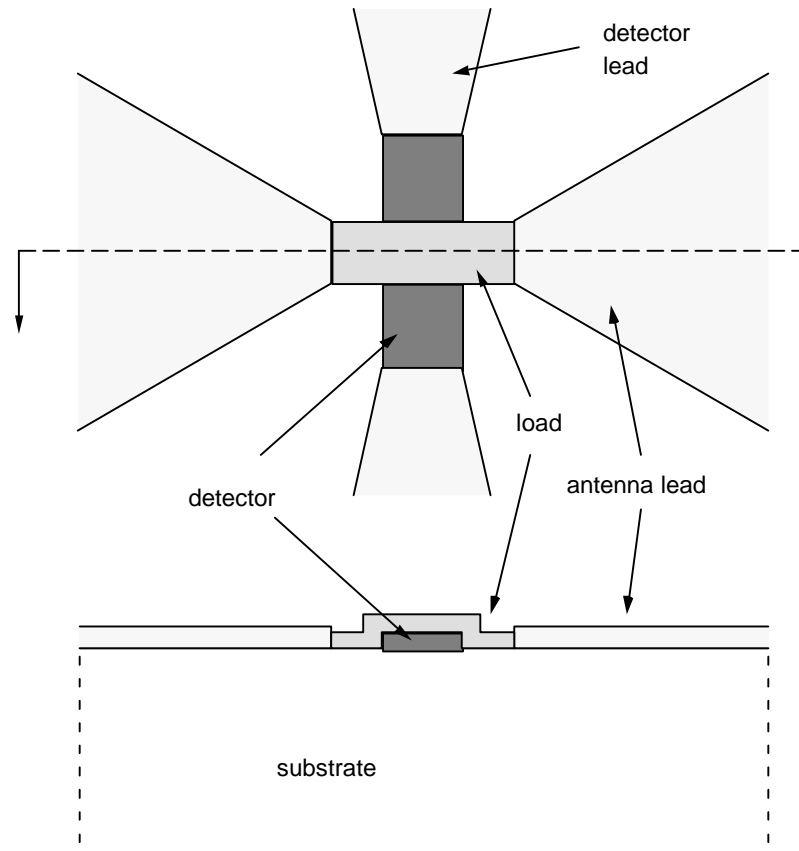
constraint: $R_{bol} \sim 50-100?$

- cannot use very low or very high conductivity materials

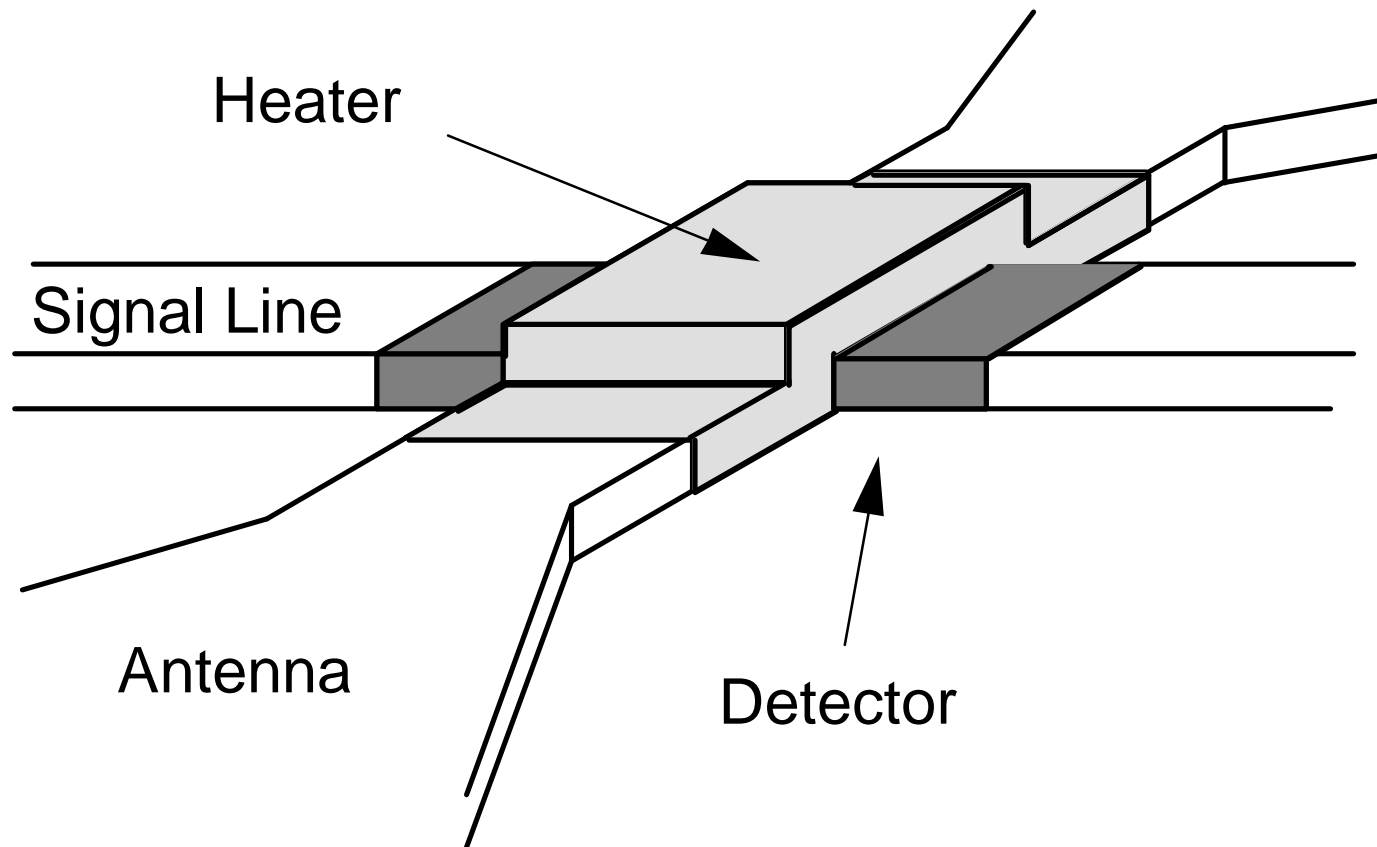
- separate function of load and temperature sensor

- matched "heater"

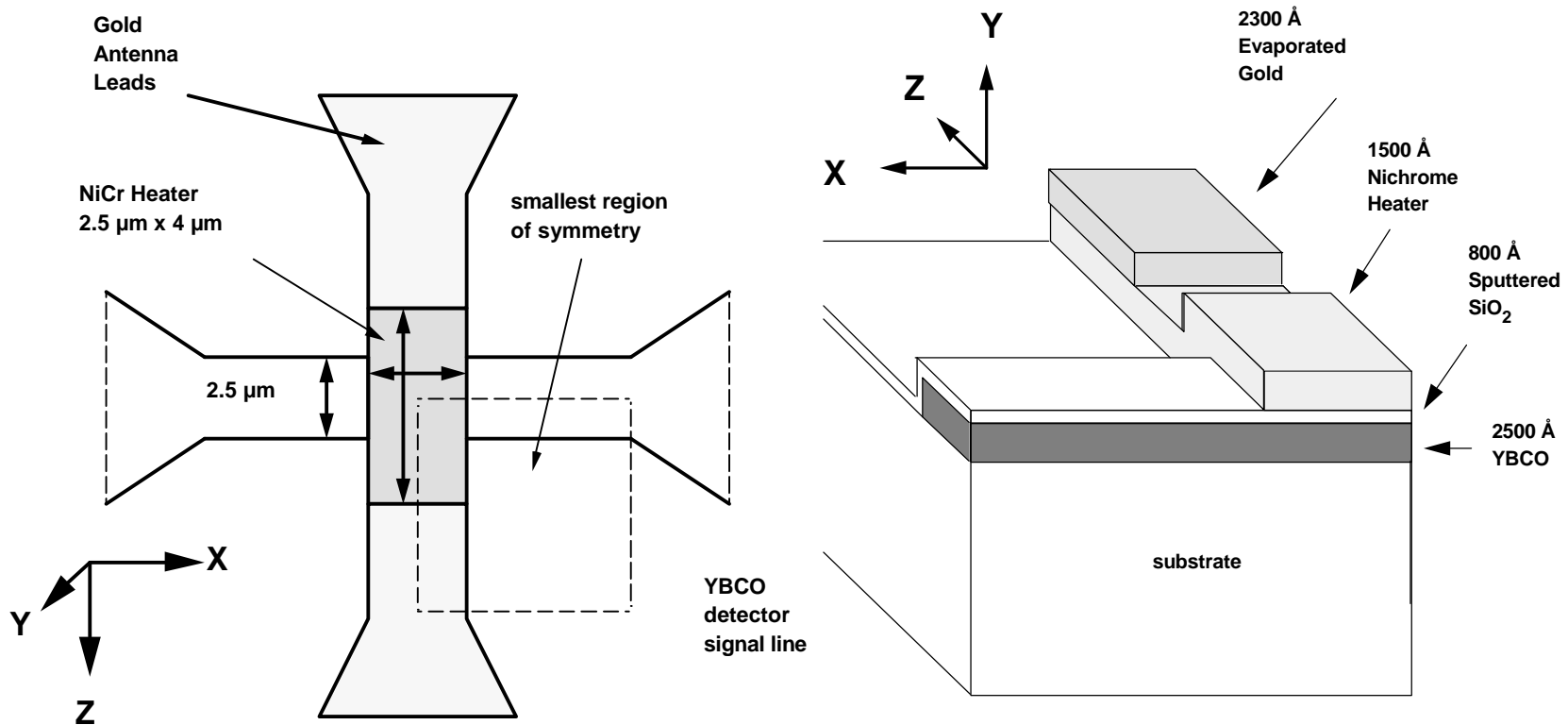
- high alpha "detector"



Composite Microbolometer



Layout of Simulated Devices



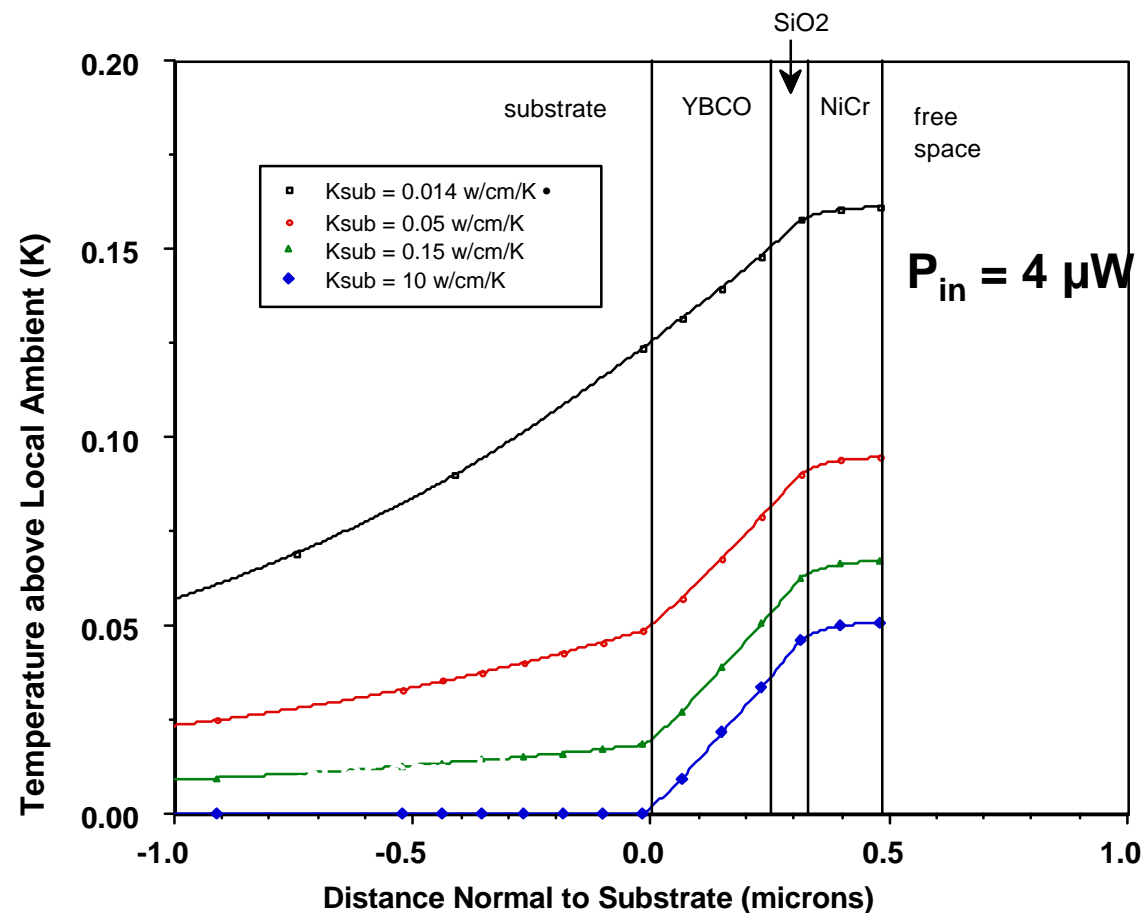
Temperature profiles for various substrates

- YBCO substrates:

MgO, YSZ, LaAlO₃

- with buffer layer: Si,
sapphire

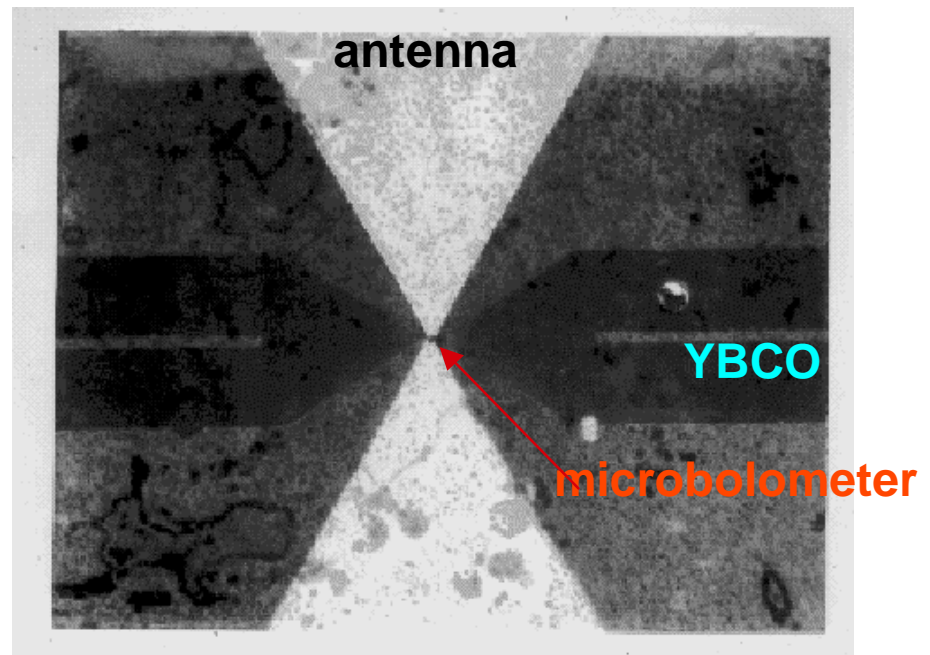
-most have either
high κ or high ϵ_r



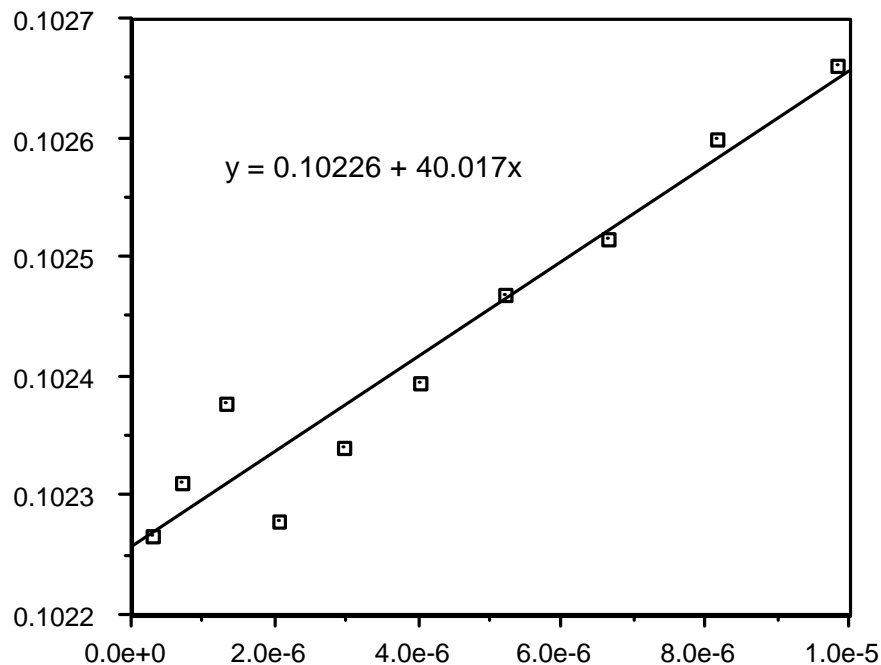
YBCO Composite Microbolometer

- YBCO films

- grown on 400 Å MgO buffer
- sapphire substrate
- courtesy: Alex deLozanne,
UT-Austin



Responsivity Measurement



- bolometers are easily calibrated from dc I-V

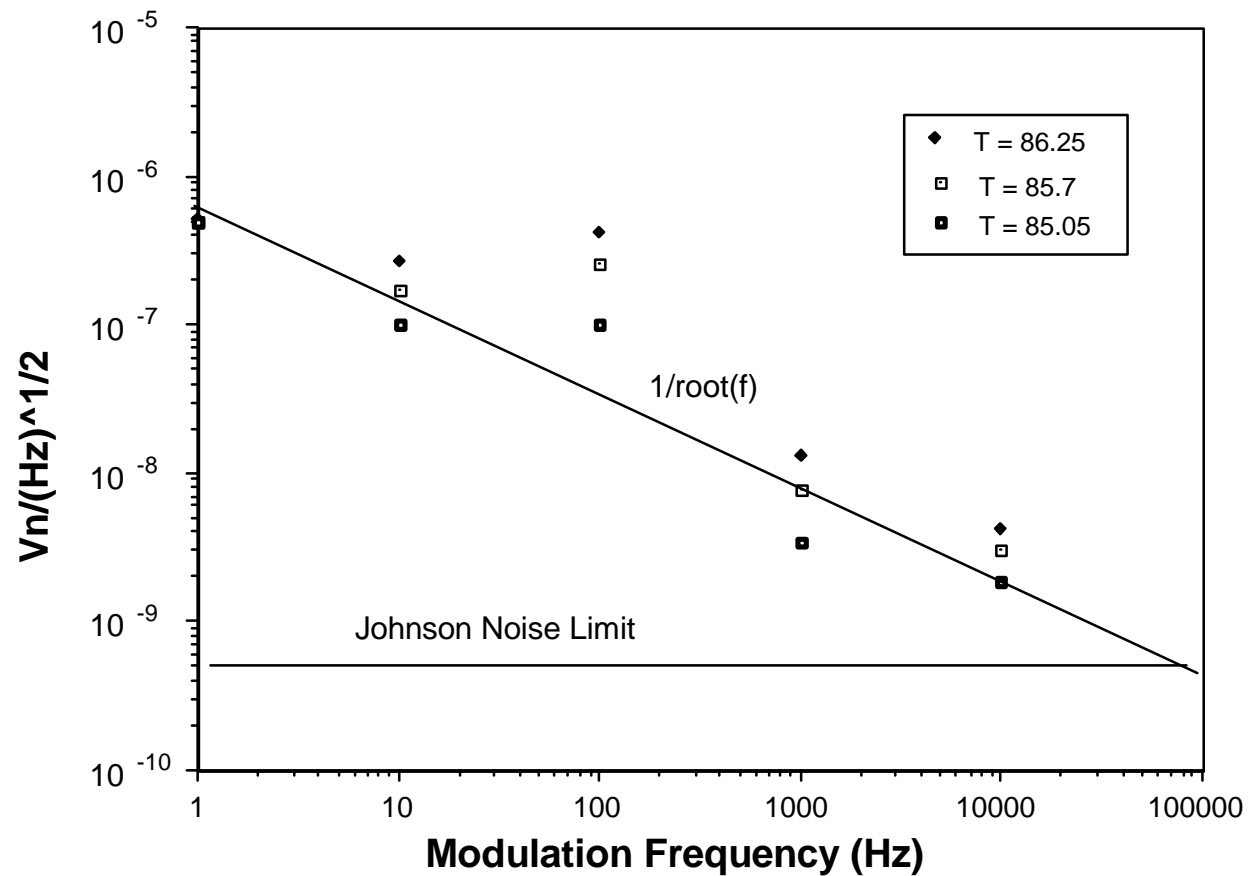
- slope of resistance versus power curve

- plot V/I versus $I \cdot V$

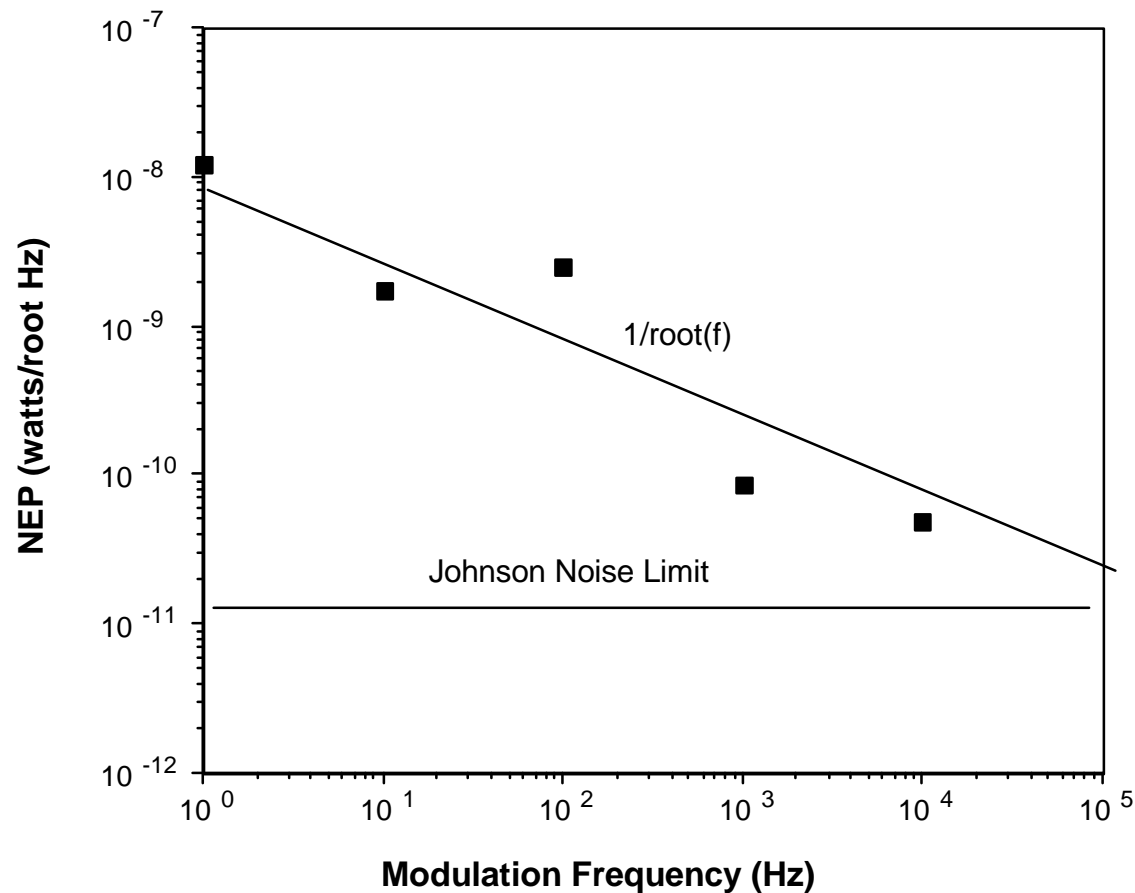
- for composite bolometer plot detector voltage versus power in heater

- YBCO / heater : 40 V/Watt

Noise Voltage



Noise Equivalent Power (NEP)



- YBCO composite structure

$\sim 3 \times 10^{-11}$ W/ $\sqrt{\text{Hz}}$

- conventional Bi microbolometer

$\sim 10^{-10}$ W/ $\sqrt{\text{Hz}}$ at room temperature

“Micro” bolometers

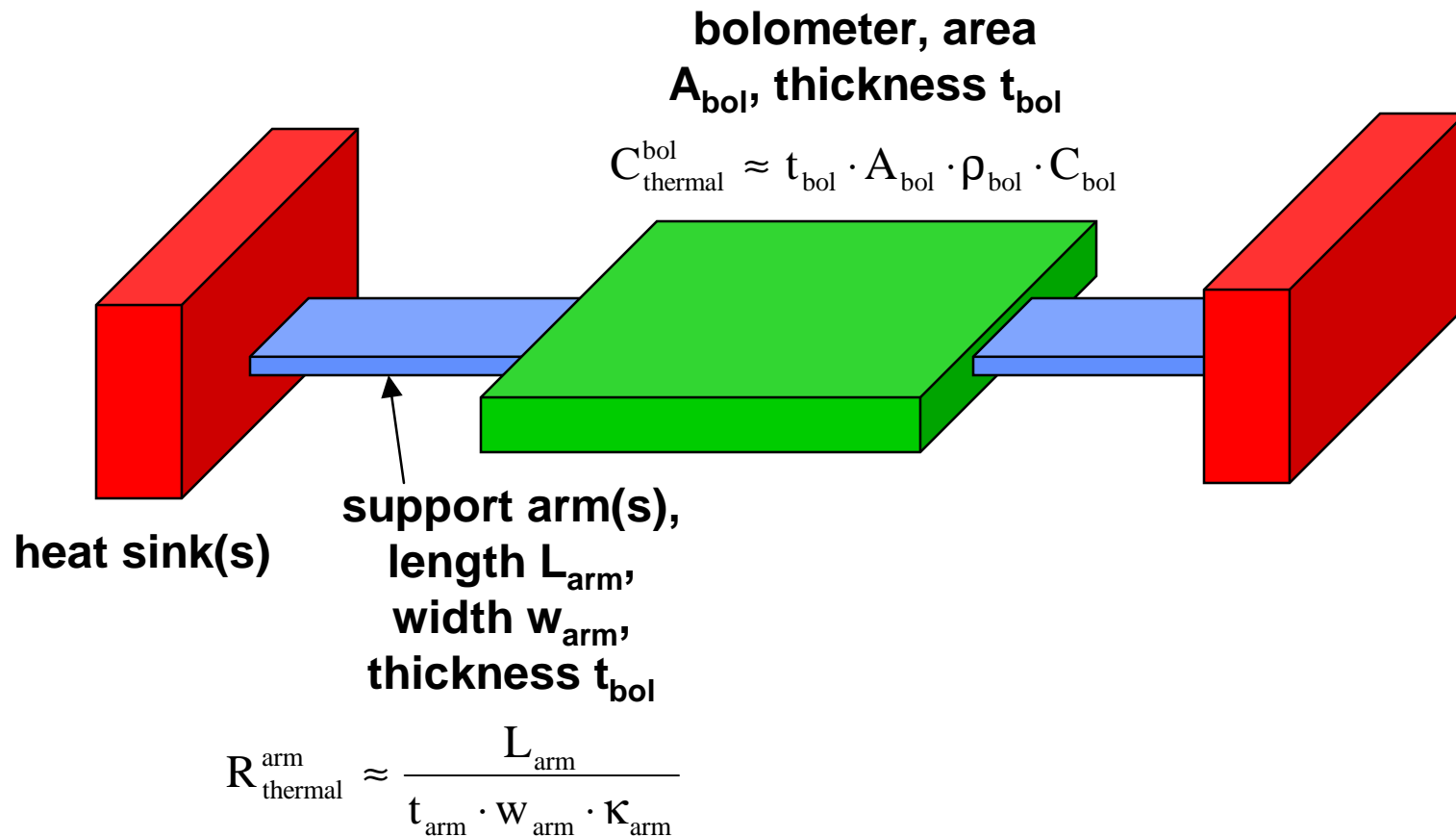
- **originally this term referred to bolometers that were smaller than a wavelength**
 - required antenna for coupling
- **but even for “large area” devices, to increase thermal resistance, need to decrease cross sectional area, and increase length, of “thermal link”**
 - if too large will be slow
- **use micromachining to form "free standing" films to “remove” the substrate**
 - bulk or sacrificial layer processes can be used

“classical” micromachined bolometers

- **device area $\gg \lambda^2$**
- **if use CMOS compatible processing can combine with other electronics**
 - **J.-S. Shie and P. K. Weng, “Fabrication of micro-bolometer on silicon substrate by anisotropic etching technique,” presented at Transducers '91 1991 International Conference on Solid-State Sensors and Actuators, San Francisco, CA, 1991.**
 - **R. A. Wood, “High-Performance Infrared Thermal Imaging with Monolithic Silicon Focal Planes Operating at Room Temperature,” presented at IEEE International Electron Devices Meeting, Washington, DC, 1993.**
- **these devices are now widely referred to as “microbolometers”**

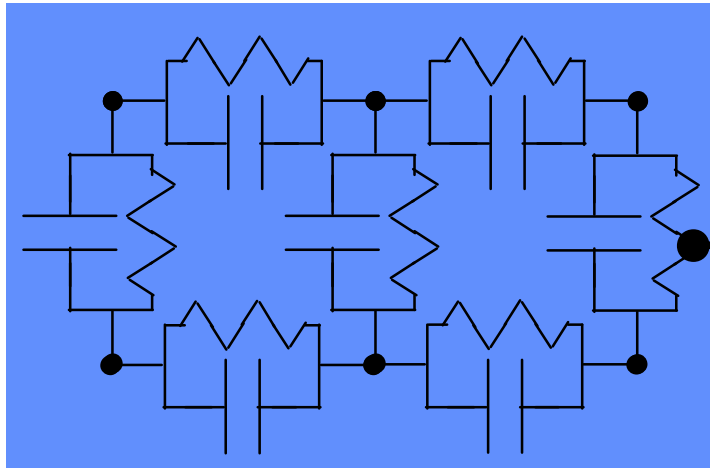
Simple model of “large” microbolometer

- assume absorbing region absorbs power uniformly over its entire area

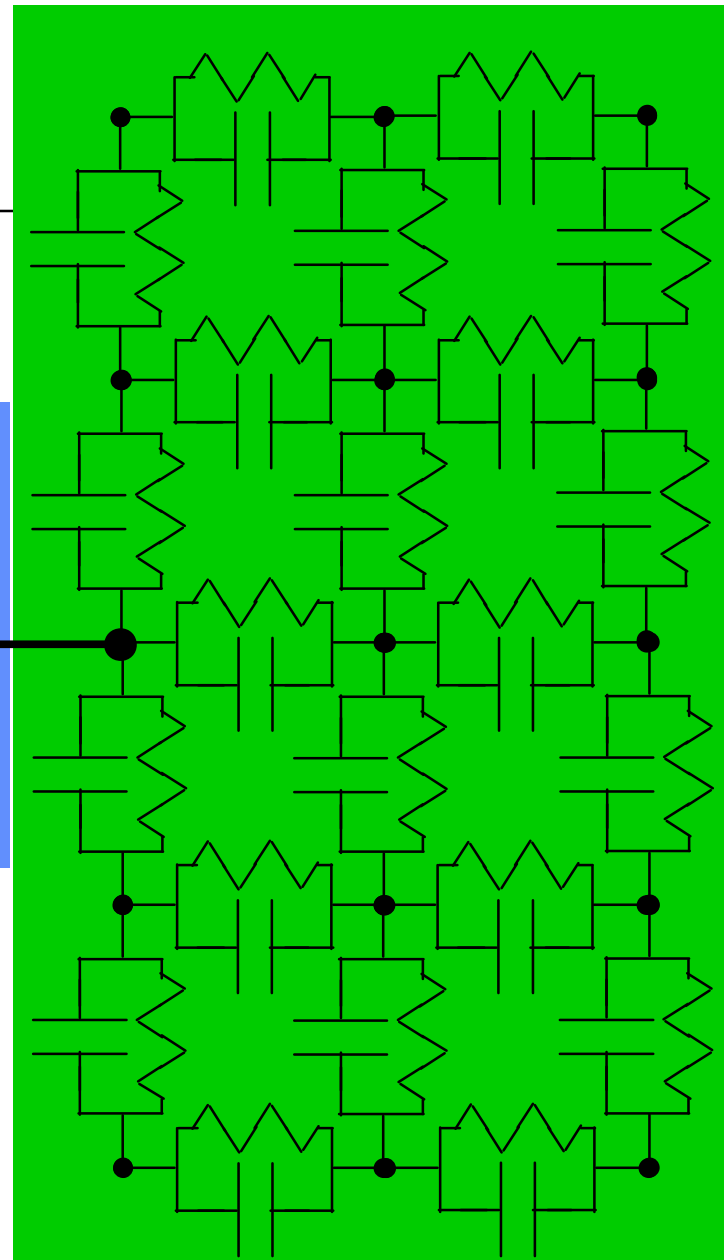


Equivalent thermal circuit

- bolometer is REALLY “distributed”

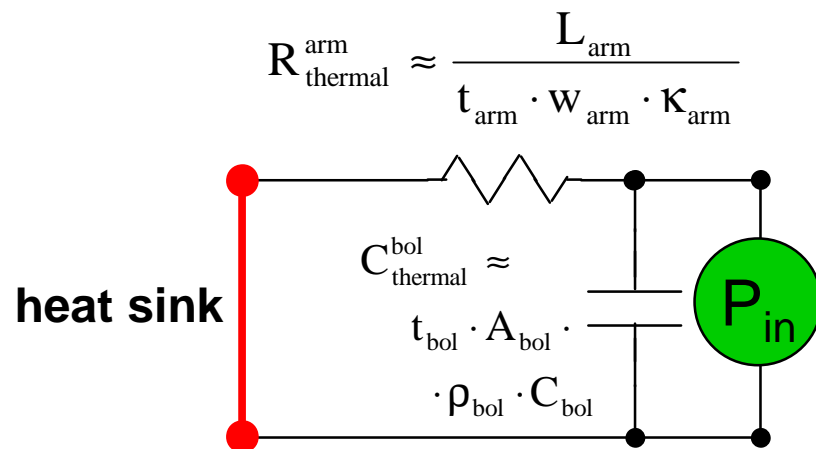


- but if assume:
 - power uniformly deposited across bolometer
 - thermal resistance of arm is much larger than that of bolometer
 - bolometer area is approximately isothermal



Simplified thermal equivalent circuit

- surface of bolometer is approximately isothermal
 - mainly contributes thermal capacitance
- arm thermal resistance is large



$$Z_{\text{thermal}} \approx \left[\frac{1}{R_{\text{thermal}}^{\text{arm}}} + j \cdot \omega \cdot C_{\text{thermal}}^{\text{bol}} \right]^{-1}$$

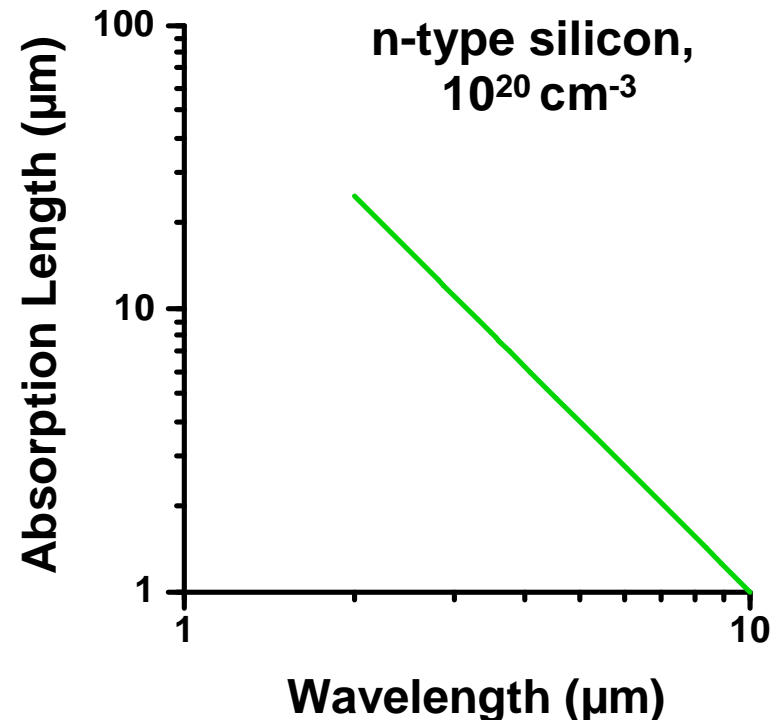
$$= \frac{R_{\text{thermal}}^{\text{arm}} \cdot (1 - j \cdot \omega \cdot R_{\text{thermal}}^{\text{arm}} \cdot C_{\text{thermal}}^{\text{bol}})}{1 + (\omega \cdot R_{\text{thermal}}^{\text{arm}} \cdot C_{\text{thermal}}^{\text{bol}})^2}$$

- conclusions:
 - make arm length-to-cross section ratio LARGE
 - make thickness of bolometer small (area already set by wavelength)

Bolometer absorber material choices

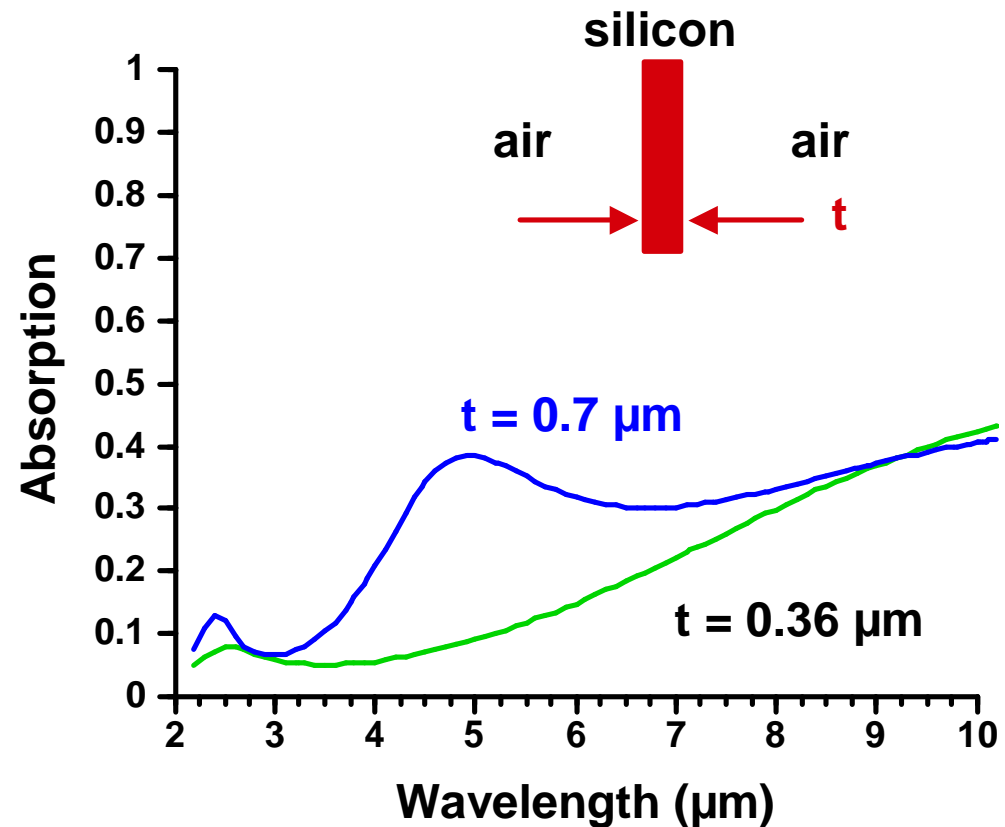
- **metals**
 - skin depth $\sim 10\text{nm}$ @ $\lambda_0 = 5\text{ }\mu\text{m}$
 - impedance matching requires very thin sheets
 - tens of \AA \sim few ohms/square
- **semiconductors**
 - below-gap absorption weak
 - free carrier absorption
 - absorption constant $\alpha \gg n \cdot l^2$
- **would appear very thick layers necessary for efficient absorption**
 - heavy doping also required

Free Carrier Absorption in Silicon

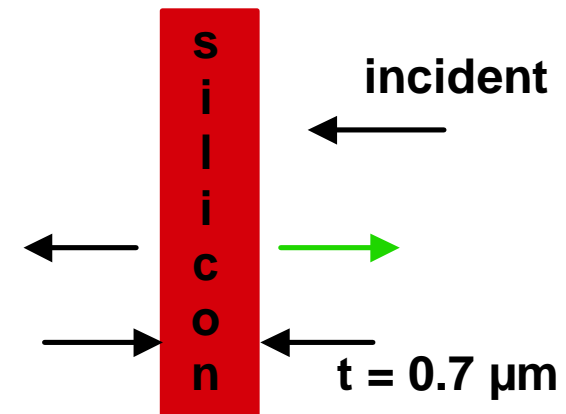
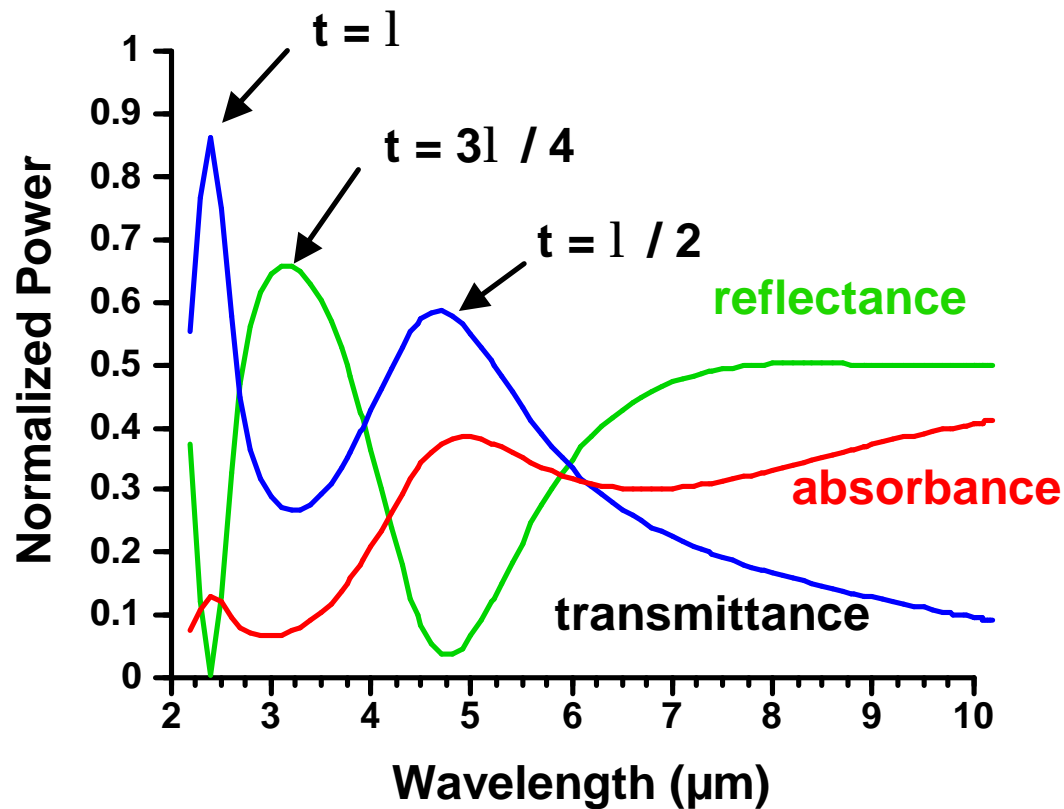


Free carrier absorption in thin silicon films

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



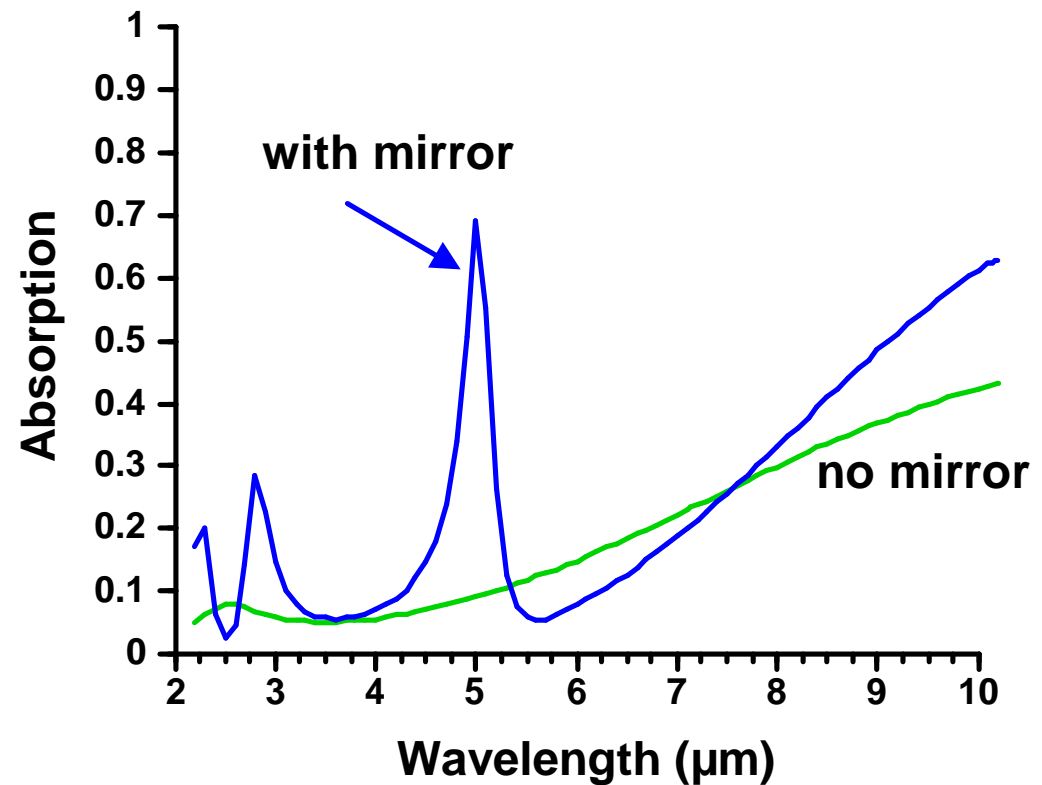
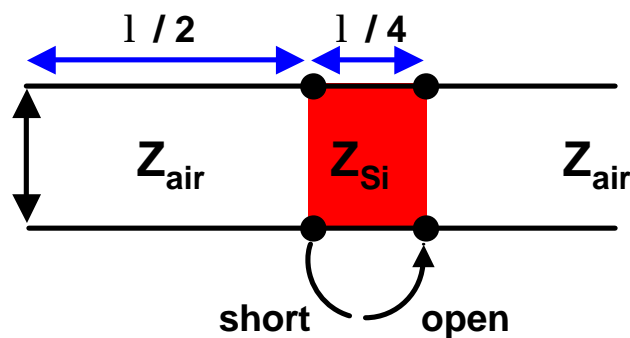
Interference effects in moderately absorbing films



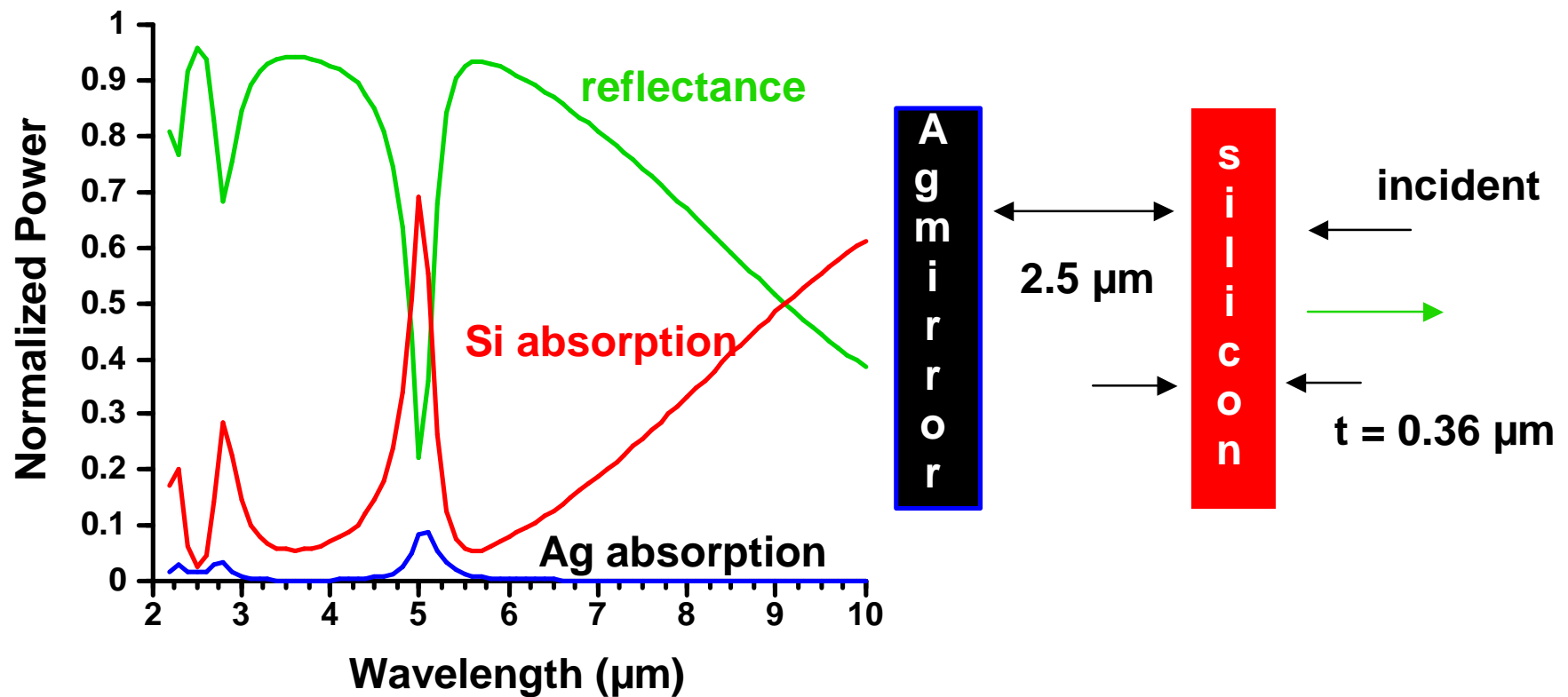
- $t = l / 2 \text{ } \lambda$ half wave window
- $t = 3l / 4 \text{ } \lambda$ impedance inverter
- $t = l \text{ } \lambda$ full wave window

Impedance Matching using "Backshorts"

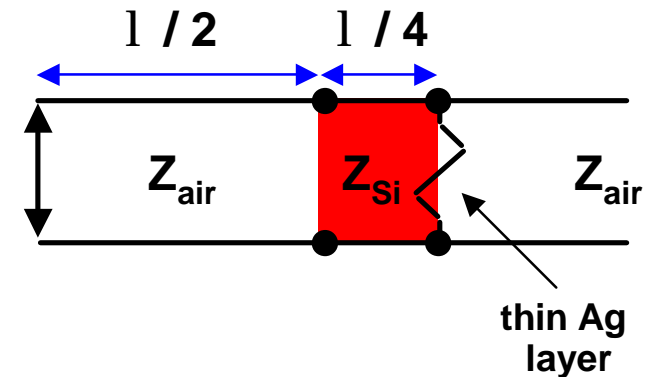
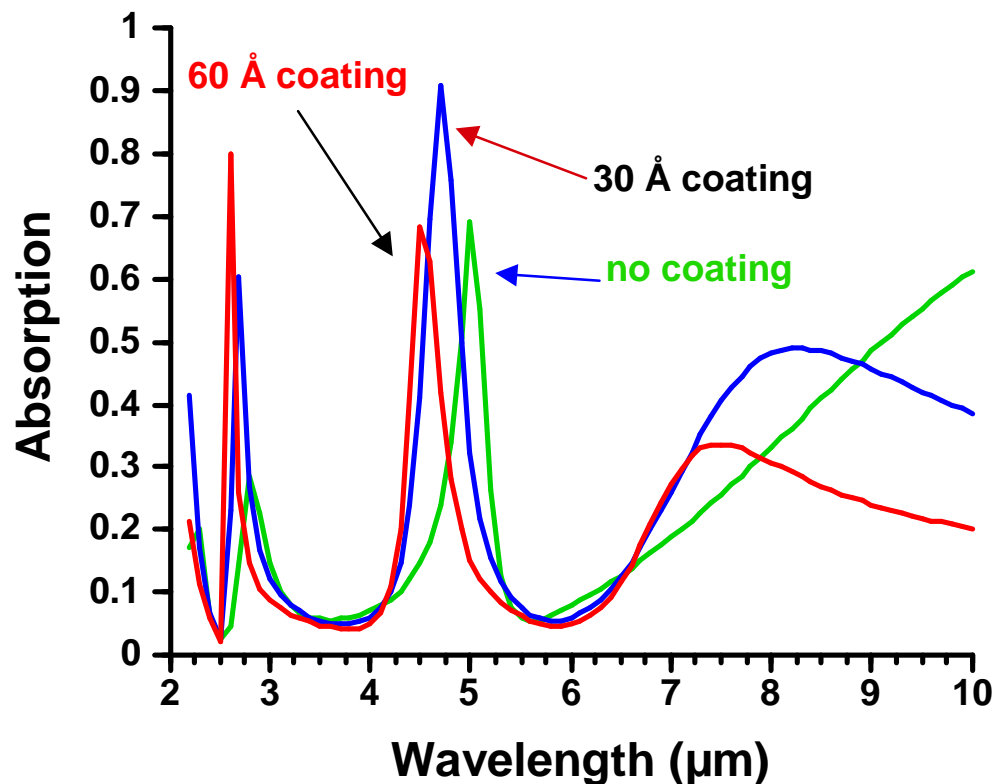
- 0.36 μm thick silicon sheet
 $-R_s^{\text{dc}} \sim 83 \text{ } \Omega/\text{square}$
- silver mirror place 2.5 μm behind sheet
- at $\lambda_o = 5 \text{ } \mu\text{m}$:



0.36 μm Silicon Film with Mirror



Enhanced Absorption using "Resistive" Coating



- 0.36 μm Si film, Ag mirror 2.5 μm behind
- front surface coated with thin Ag film

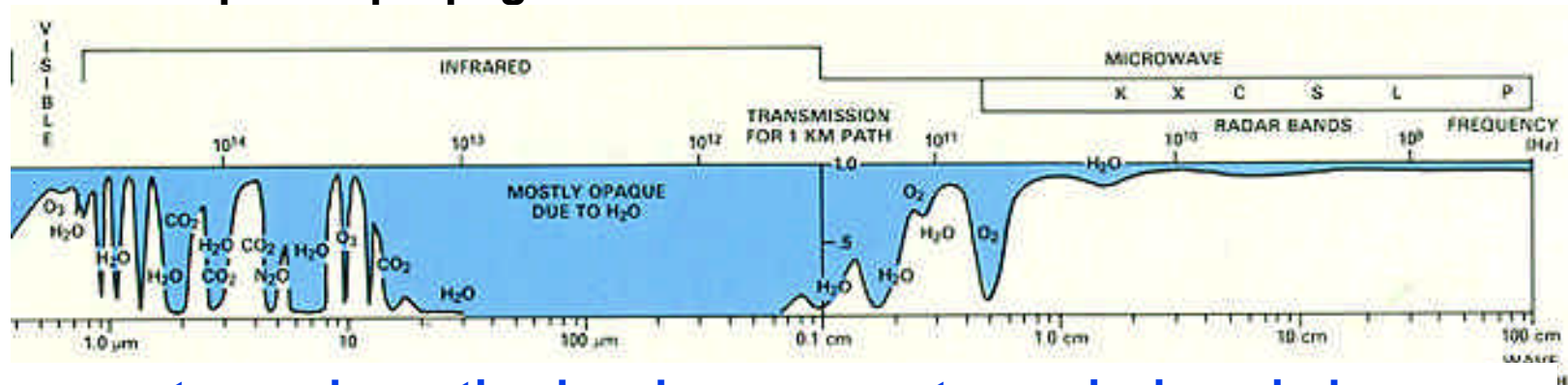
-no coating

$$-30 \text{ \AA} \Rightarrow R_s^{\text{dc}} \sim 6.7 \text{ ? /?}$$

$$-60 \text{ \AA} \Rightarrow R_s^{\text{dc}} \sim 3.3 \text{ ? /?}$$

Is wavelength selectivity important?

- visible wavelength sensors: object “reflectivity” dominates
 - reflectivity/absorption are functions of wavelength
 - produces “color” in the image
- most energy emitted by an object at terrestrial temp. (300K) falls in the 3 - 14 mm range
 - “mid” to “far” IR sensing: emissivity of object dominates
 - emissivity is also a function of wavelength
- atmospheric propagation also influences band choice



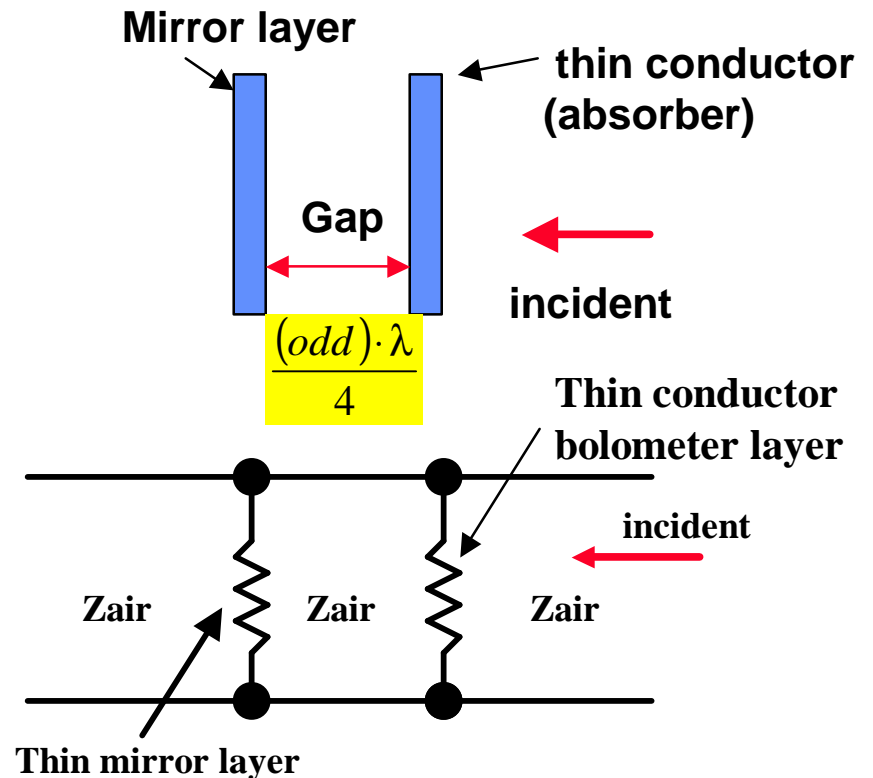
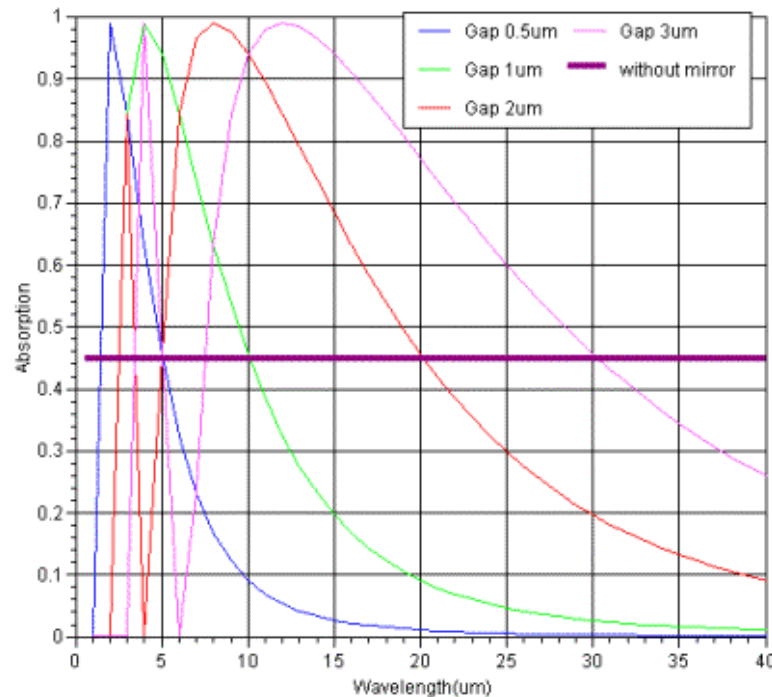
- strong absorption bands

- H₂O (2.6, 2.7, 6.3 mm)
- CO₂ (2.7, 4.3, 15 mm)

- transmission windows:

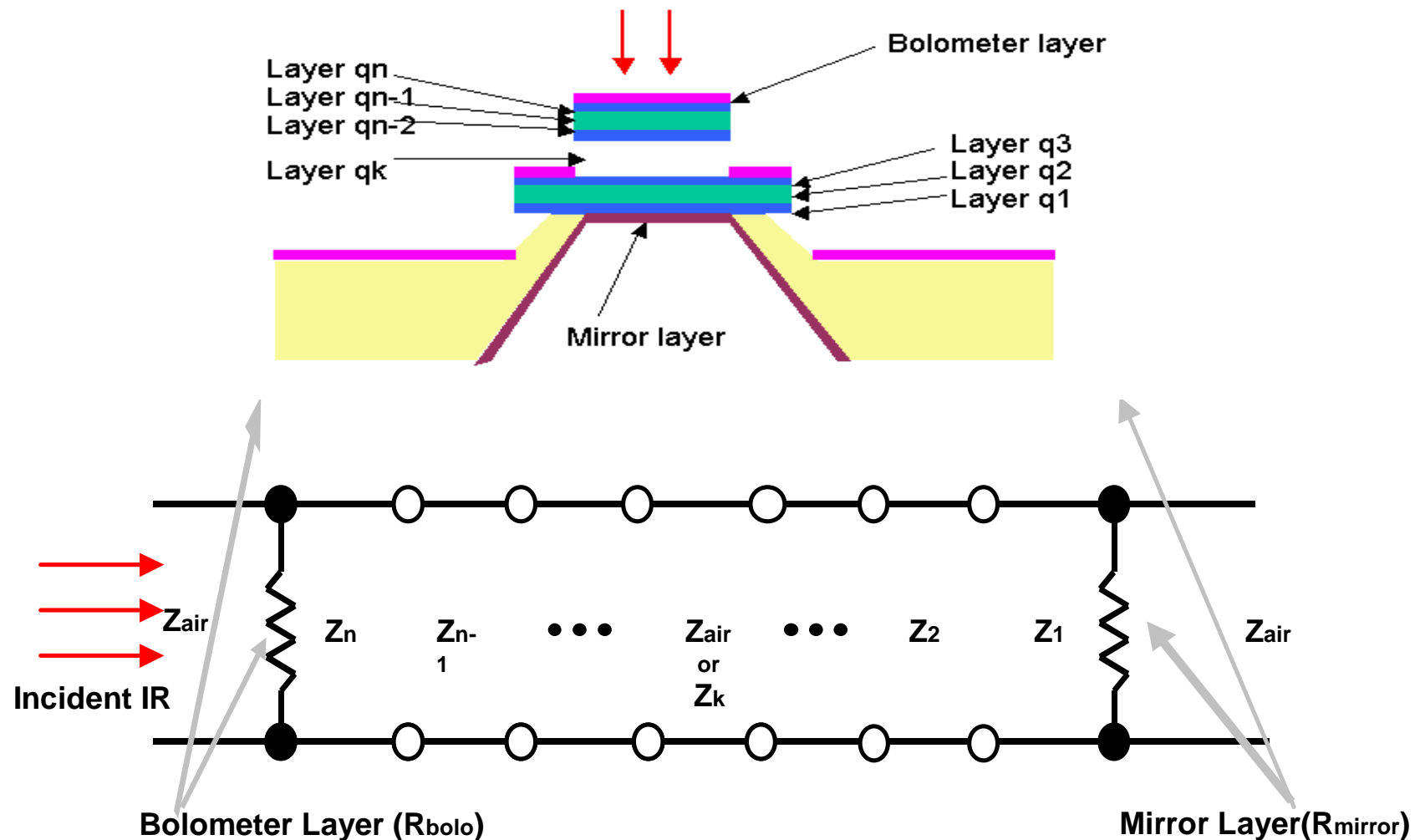
- 3-5 mm (MWIR)
- 8-14 mm (LWIR) window

“Enhanced” absorption in microbolometers

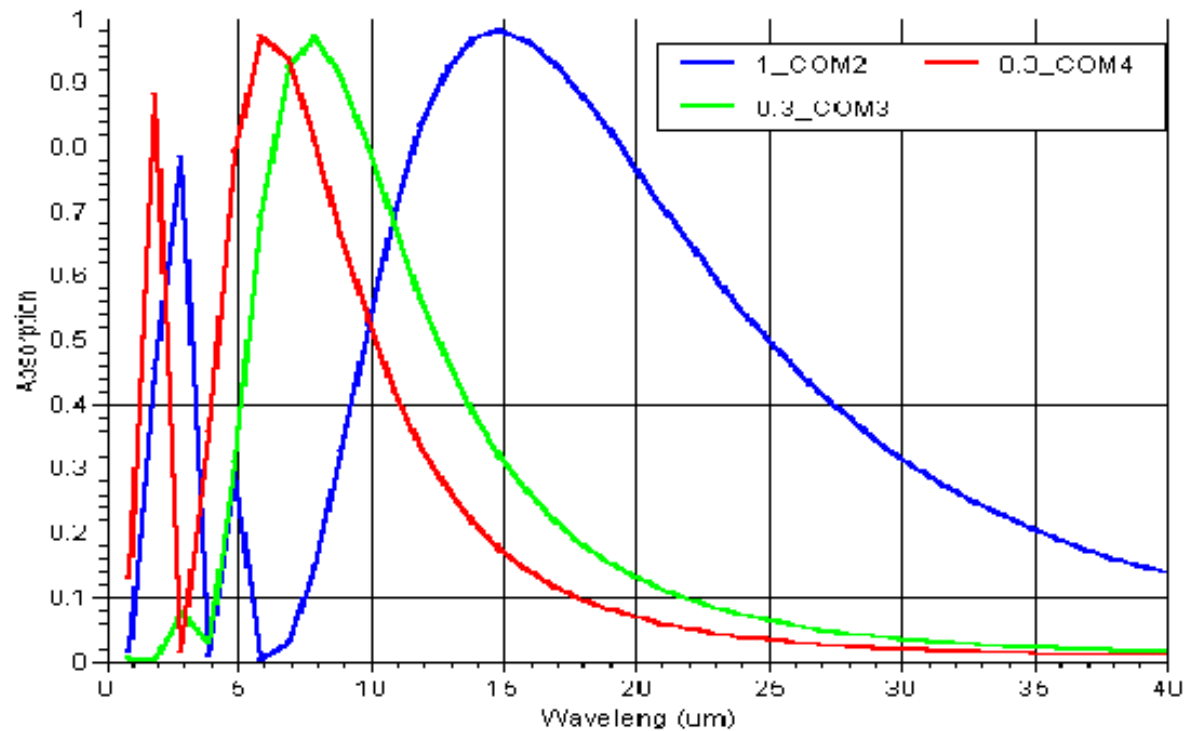


- to “match” an absorber to free space requires
 - absorber: thin conductor with sheet resistance 377 ohms
 - mirror placed $[(odd\ integer)/4] \cdot \lambda$ behind absorbing layer
 - essentially a Fabry-Perot cavity

IR wavelength selective structure and transmission line equivalent model



Simulation of absorption of microbolometer



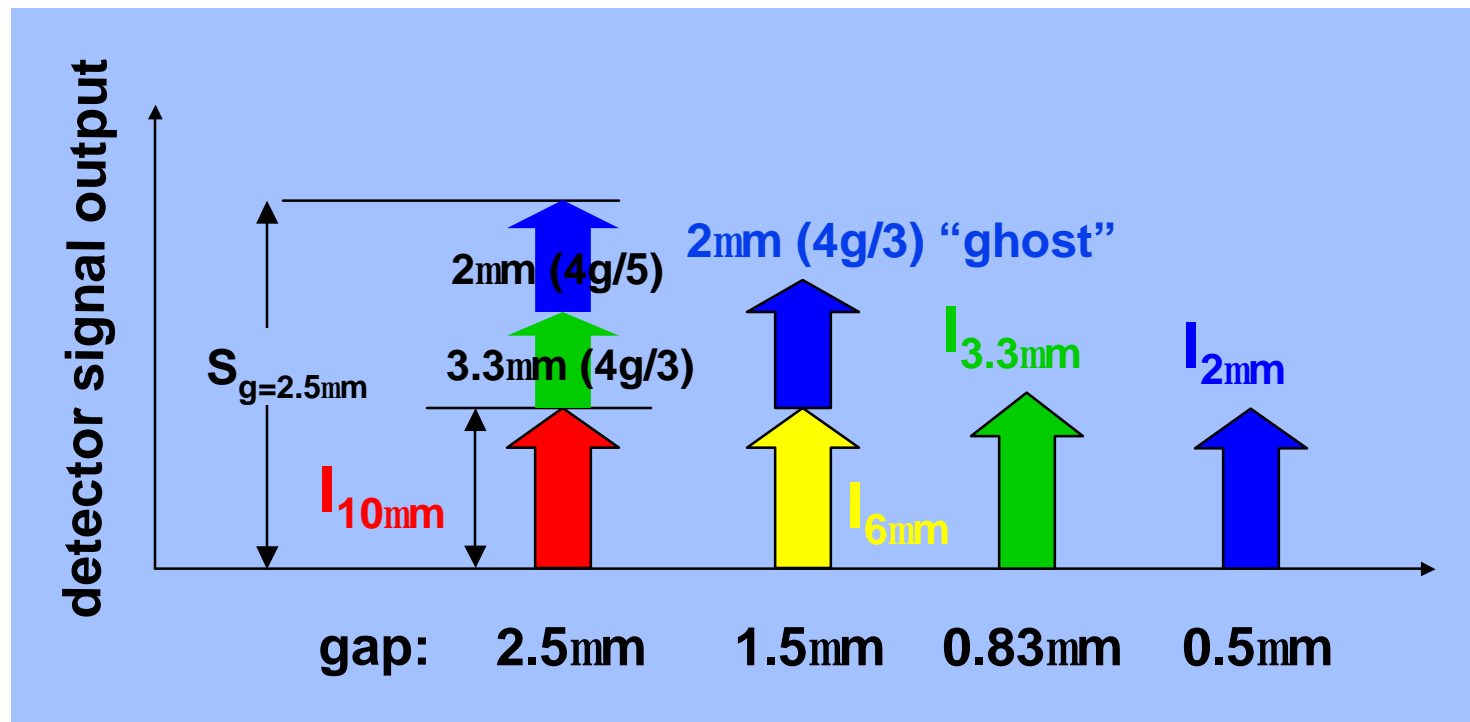
	Si ₃ N ₄	SiO ₂	Si ₃ N ₄	Air Gap	Si ₃ N ₄	SiO ₂	Si ₃ N ₄
1_COM2	750	4000	750	10000	750	4000	750
0.3_COM3	400	2800	400	3000	400	2800	400
0.3_COM4	300	2100	300	3000	300	2100	300

Unit: Å

Resolving multi-wavelength ambiguities

- for a given gap, response occurs at all wavelengths where $\lambda = 4 \cdot \text{gap} / (\text{odd integer})$
- four “color” detector array
 - gap (air equivalent): 2.5 mm $\rightarrow \lambda_1 = 10$ mm
 - “ghost” response at 3.3 mm, 2 mm, etc.
 - gap: 1.5 mm $\rightarrow \lambda_1 = 6$ mm
 - “ghost” response at 2 mm & shorter
 - gap: 0.83 mm $\rightarrow \lambda_1 = 3.3$ mm
 - all “ghost” responses below 2 mm
 - gap: 0.5 mm $\rightarrow \lambda_1 = 2$ mm
 - all “ghost” responses below 2 mm
- assume external bandpass from just less than 2 mm to just over 10 mm

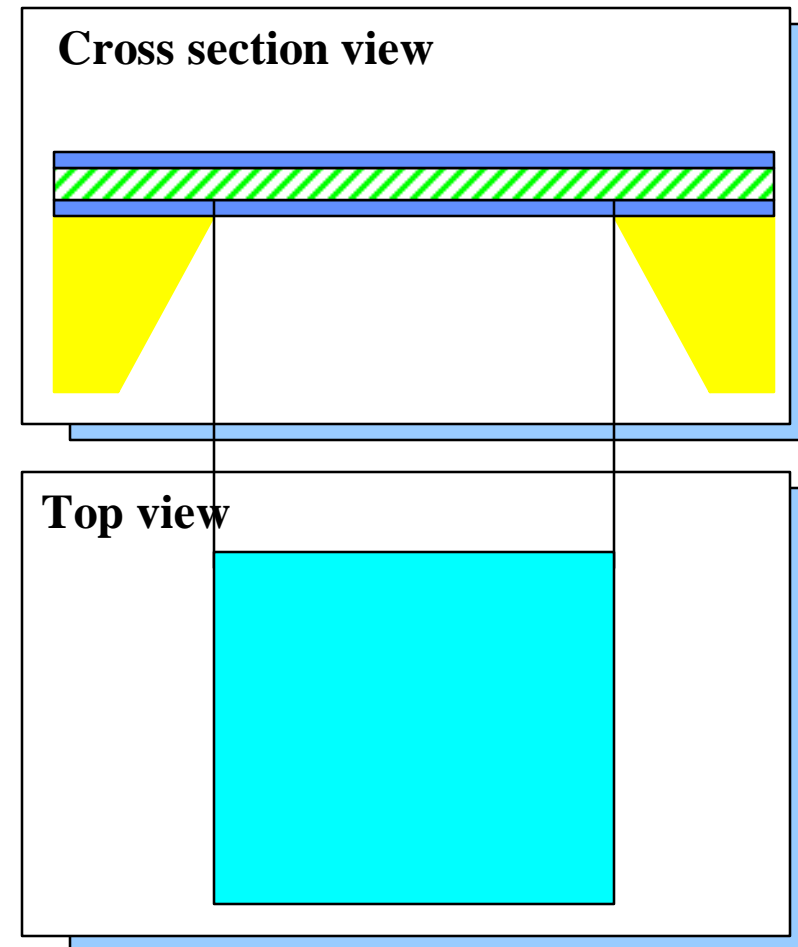
Resolving multi-wavelength ambiguities



- $I_{10\text{mm}} = S_{g=2.5\text{mm}} - m_{3.3 \rightarrow 10} \cdot S_{g=.83\text{mm}} - m_{2 \rightarrow 10} \cdot S_{g=.5\text{mm}}$
- $I_{6\text{mm}} = S_{g=1.5\text{mm}} - m_{2 \rightarrow 6} \cdot S_{g=.5\text{mm}}$

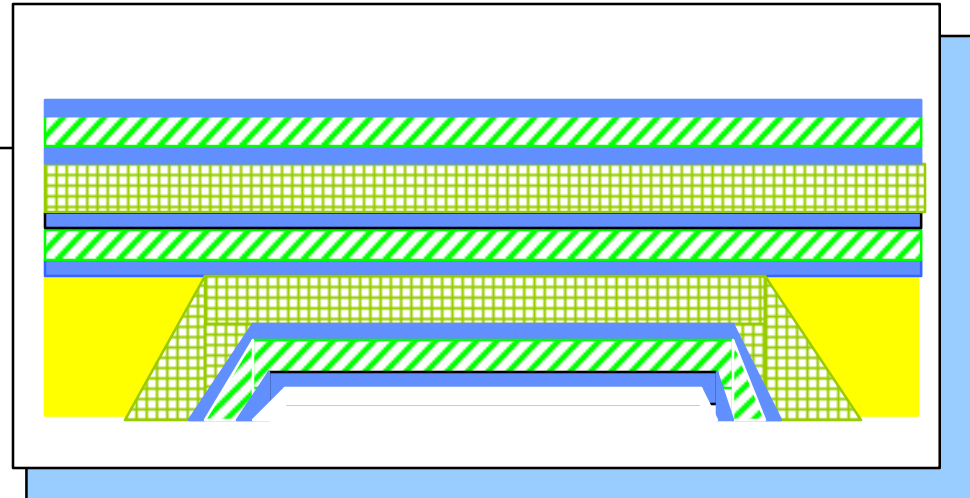
fabrication procedure

- **STEP 1: formation of bottom membrane**
 - deposition of bottom membrane layers ($\text{Si}_3\text{N}_4/\text{LTO}/\text{Si}_3\text{N}_4$)
 - multi-lare stack used to compensate for stress in deposited films
 - nitride in tension
 - oxide in compression
 - backside masking & RIE
 - anisotropic KOH etching



- **STEP 2: formation of sacrificial layer and top membrane**

- deposition of sacrificial layer (LPCVD polysilicon deposition)
- deposition of top membrane layers ($\text{Si}_3\text{N}_4/\text{LTO}/\text{Si}_3\text{N}_4$)

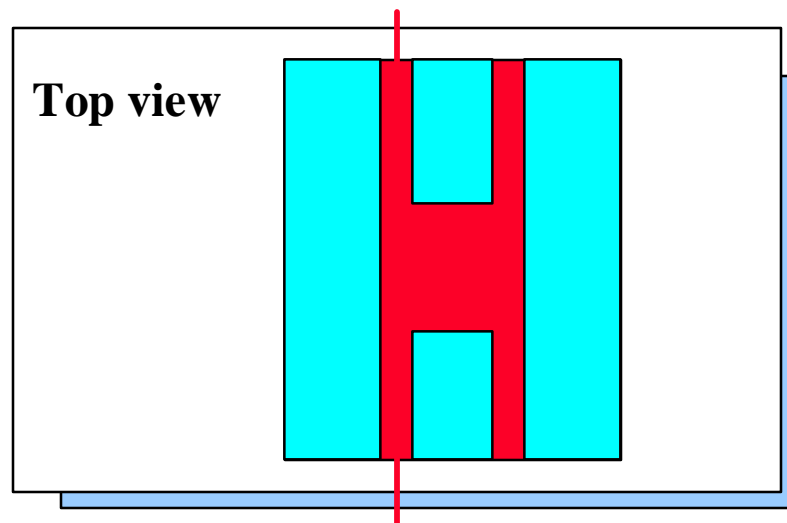
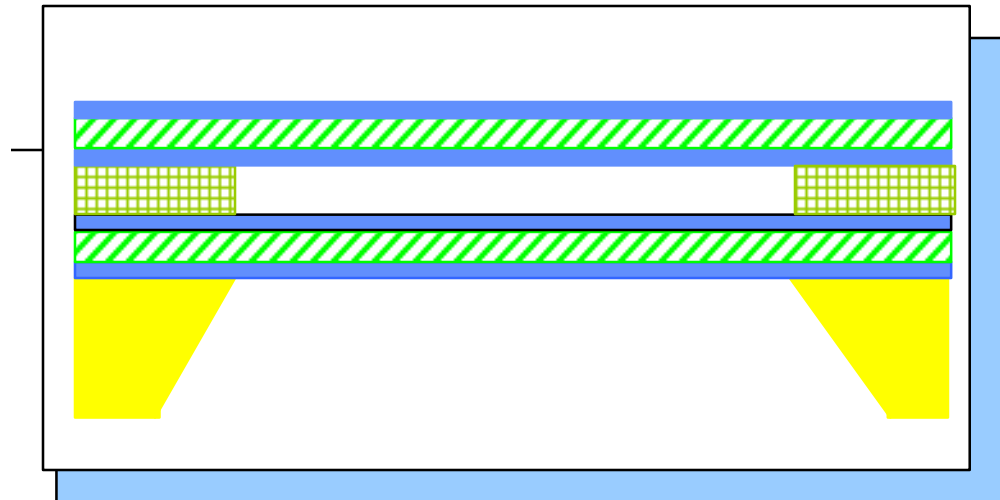


Top view



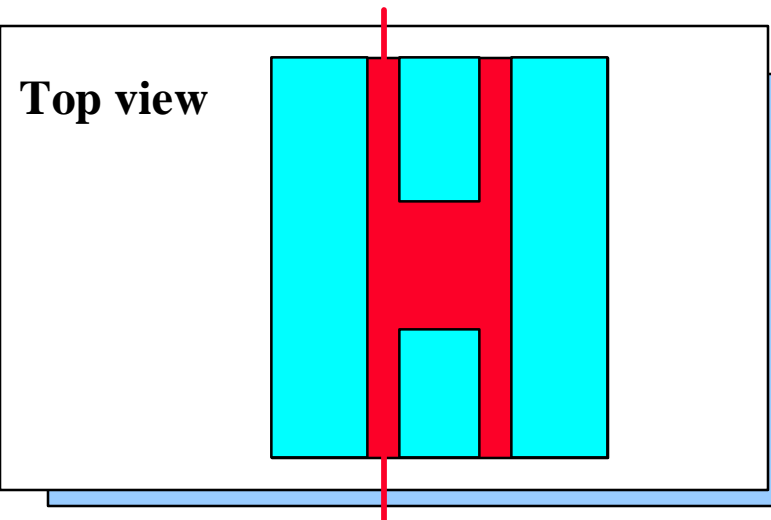
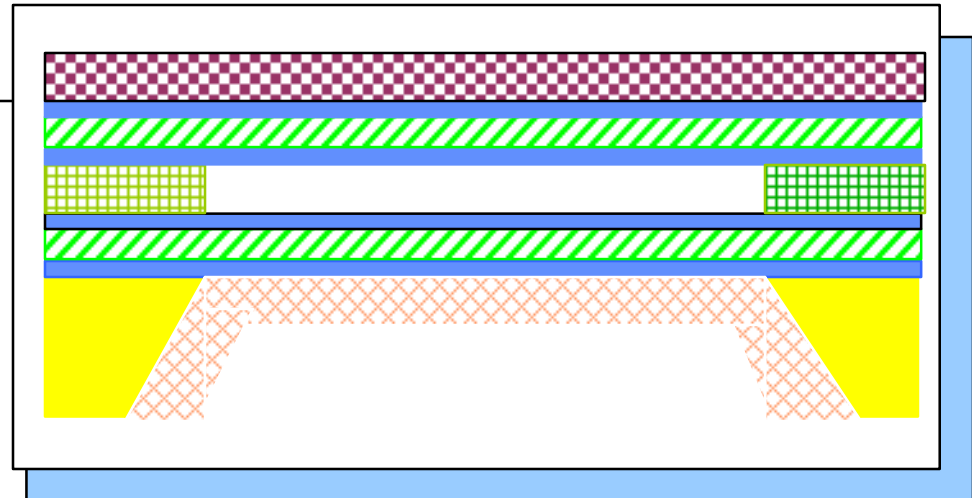
- **STEP 3: back side removal of poly, removal of sacrificial layer**

- remove backside $\text{Si}_3\text{N}_4/\text{LTO}/\text{Si}_3\text{N}_4$ layers by RIE
- polysilicon by KOH
- patterning & RIE to remove top $\text{Si}_3\text{N}_4/\text{LTO}/\text{Si}_3\text{N}_4$
- remove sacrificial polysilicon by KOH

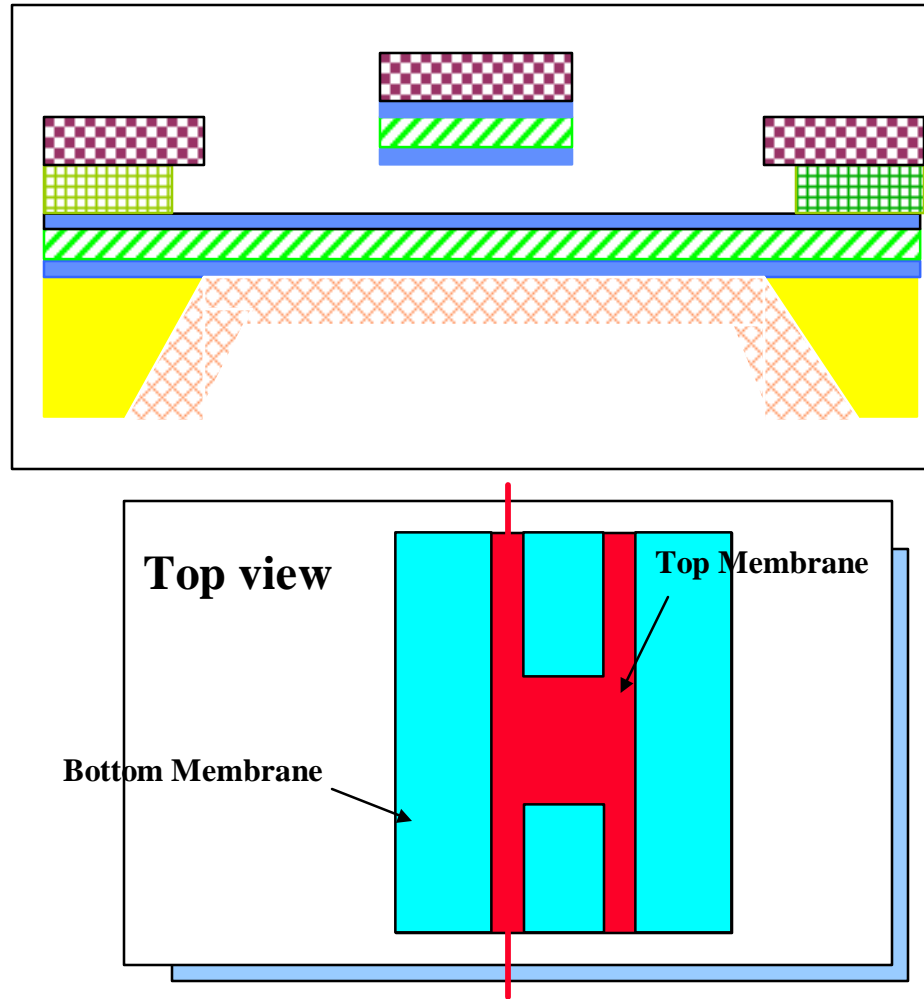


- **STEP 4: “self-aligned” microbolometer structure**

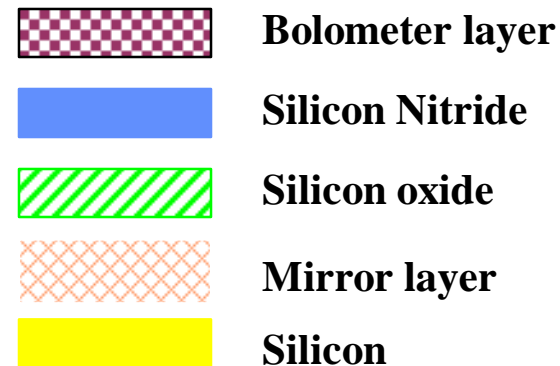
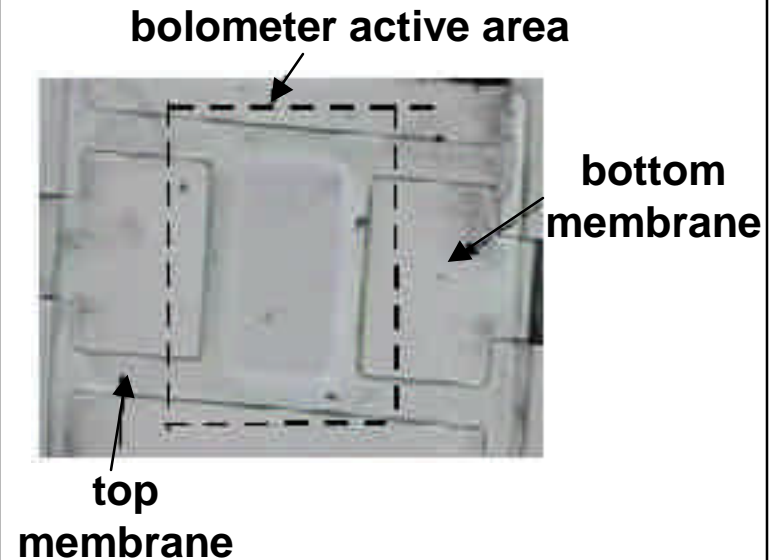
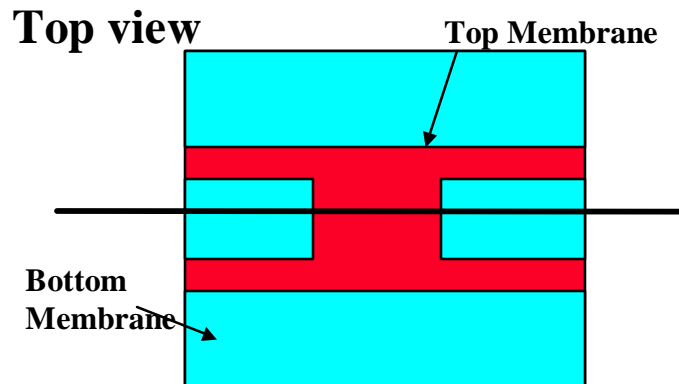
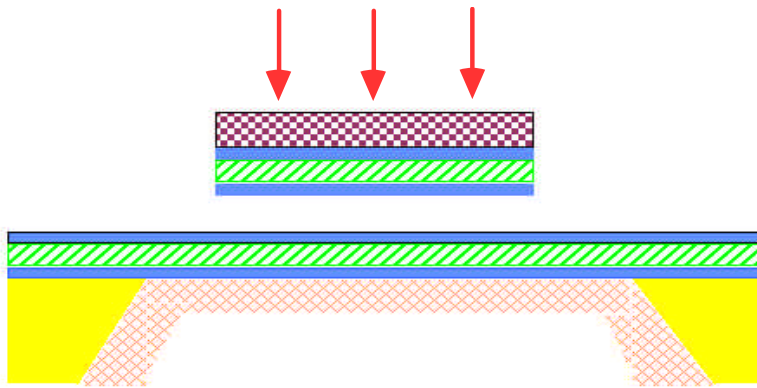
- deposition of back side mirror coating layer by evaporator
- deposition temperature sensitive bolometer layer



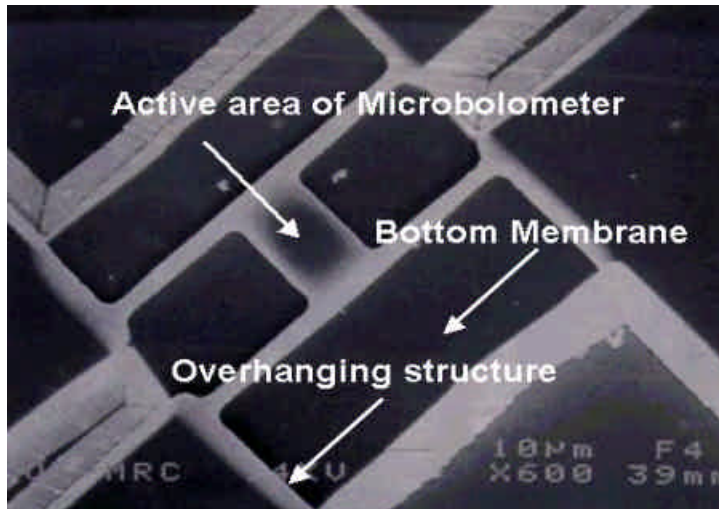
Wavelength selective micromachined IR sensors



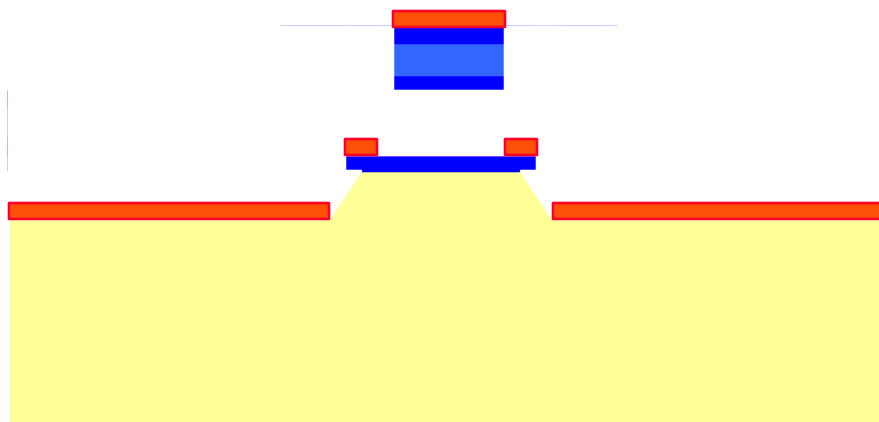
Fabrication of proposed structure using IC comparable micromachining techniques



Fabrication process for micromachined microbolometer

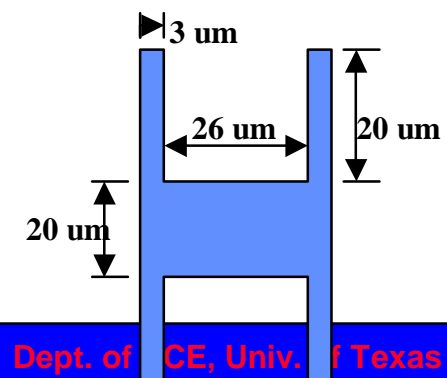


- Deposition of silicon nitride as barrier layer
- Deposition of sacrificial poly and patterning
- Deposition of membrane layers ($\text{Si}_3\text{N}_4/\text{LTO}/\text{Si}_3\text{N}_4$)
- Patterning of membrane layers using RIE
- Poly etching and Self-aligned undercutting etching process
- Deposition of bolometer layer

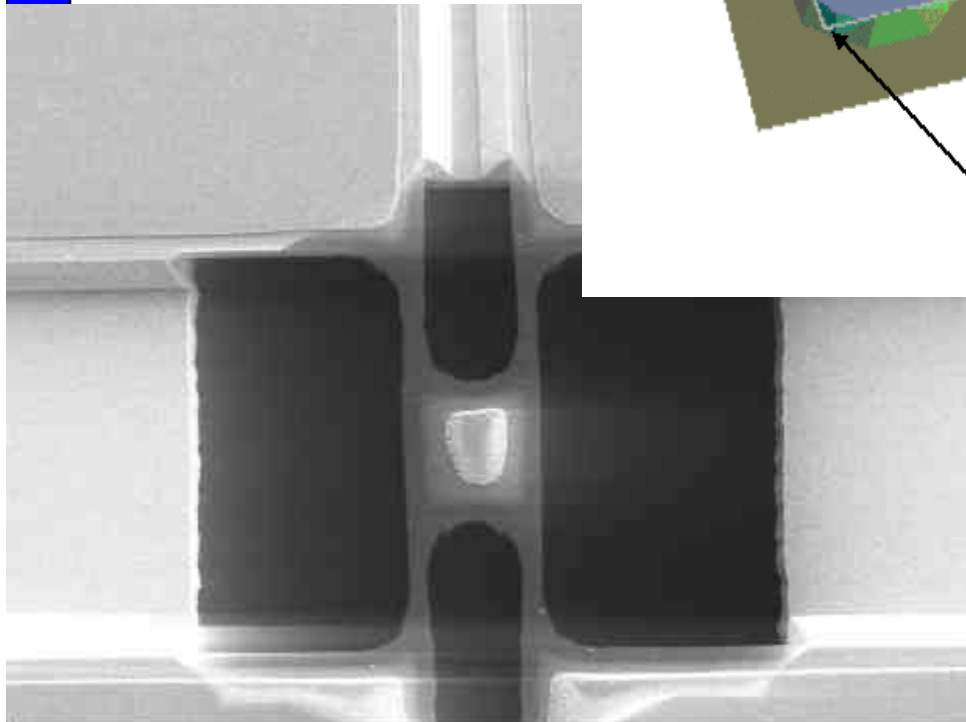
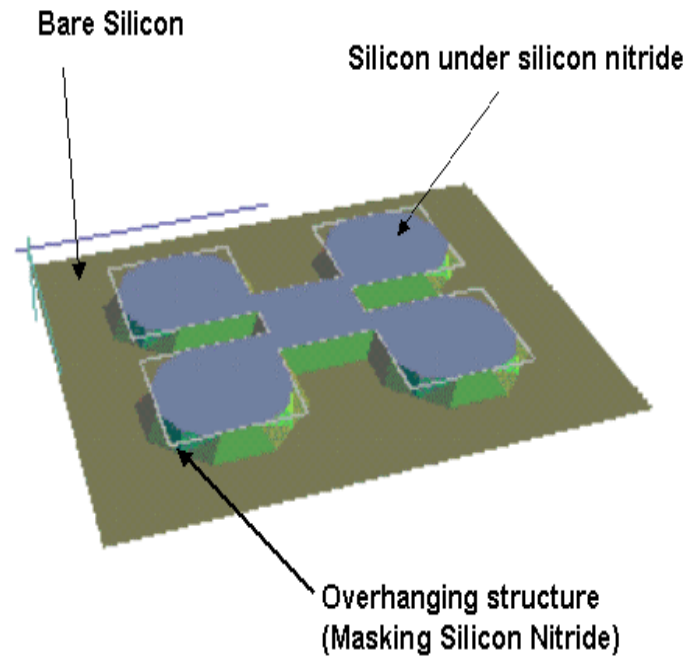


Active area 26 mm x 20 mm, 20 mm leg length, 3 mm leg width

Si substrate
 Si_3N_4
 Poly
 SiO_2
 Cr



Self aligned undercutting structure



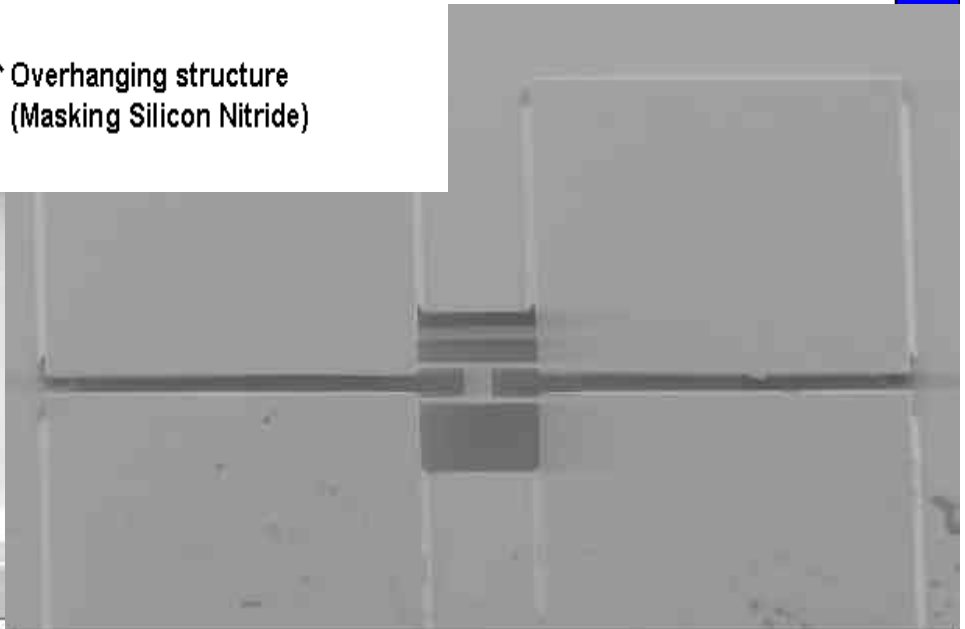
Mag = 425 X

30µm

EHT = 10.00 kV
WD = 8 mm

Signal A = SE2
Photo No. = 233

Date : 19 Feb
Time : 10:32



Mag = 457 X

100µm

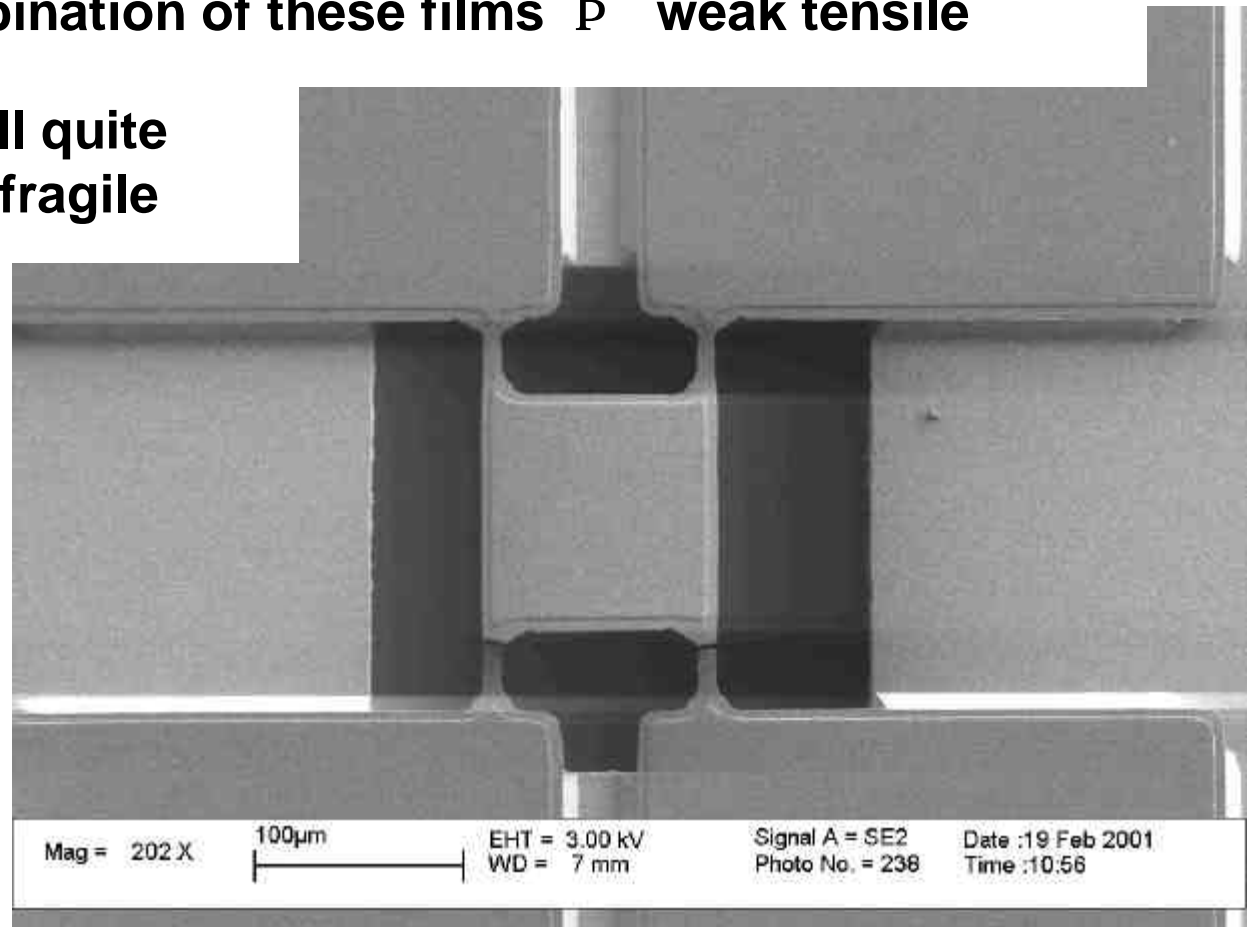
EHT = 5.00 kV
WD = 7 mm

Signal A = SE2
Photo No. = 237

Date : 16 Nov 2000
Time : 16:47

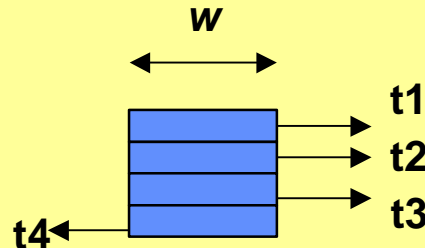
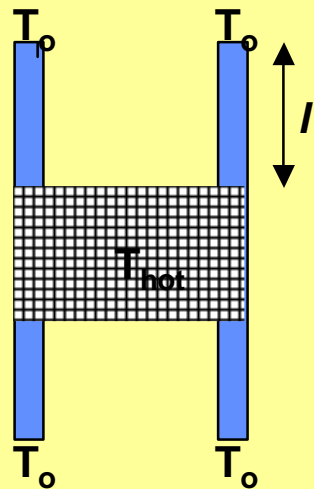
Fabrication issues

- mechanical stability issues
 - tensile nature of Si_3N_4 + compressive nature of SiO_2
 - combination of these films \Rightarrow weak tensile
- legs are still quite compliant, fragile



Thermal impedance approximation

- Active area 26 mm x 20 mm, 20 mm leg length, 3 mm leg width



$$w = 3 \text{ mm}, l = 20 \text{ mm}$$

	Thermal Conductivity	Thickness
Chromium	0.019 W/cm-K	300 Å
Silicon Nitride	0.0032 W/cm-K	1500 Å
Silicon dioxide	0.014 W/cm-K	10000 Å
Silicon Nitride	0.015 W/cm-K	1500 Å

$$\frac{1}{R_{leg}} = \left(\frac{1}{R_{t1}} + \frac{1}{R_{t2}} + \dots + \frac{1}{R_{t4}} \right)$$

Where $R_t \approx \frac{l}{t \cdot w \cdot k}$

$$R_{leg} \gg 4.3 \times 10^6 \text{ K/W}$$

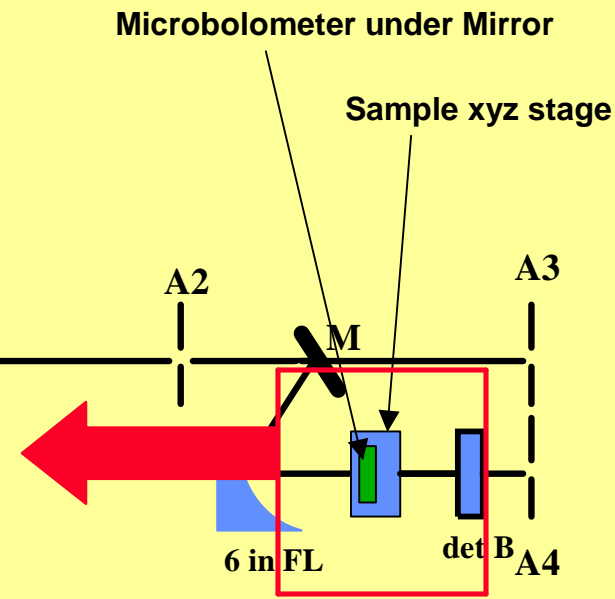
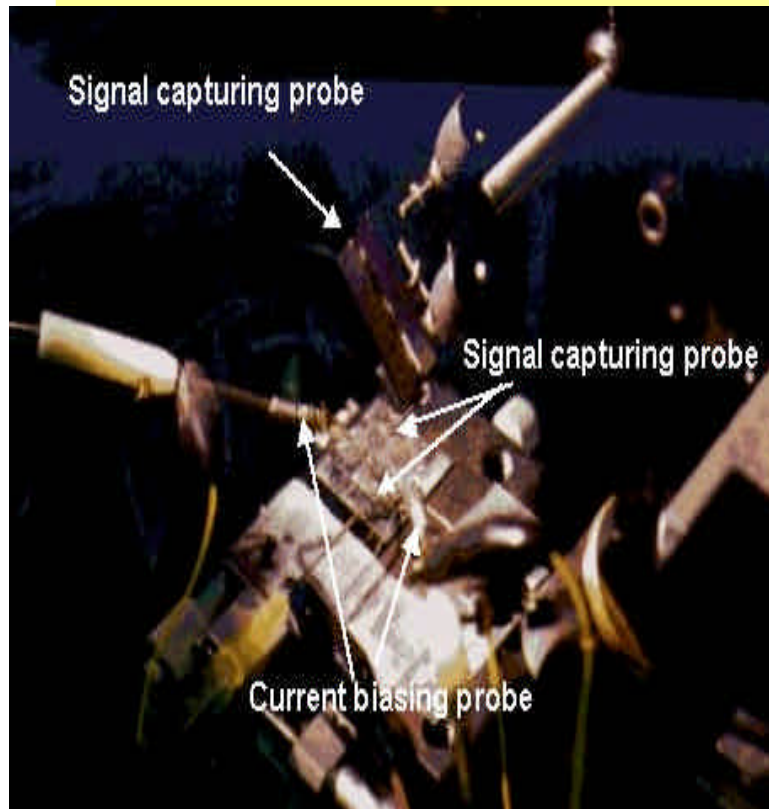
$$Z_{bolometer} \approx \frac{R_{leg}}{4}$$

$$Z_{bolometer} \gg 1.1 \times 10^6 \text{ K/W}$$

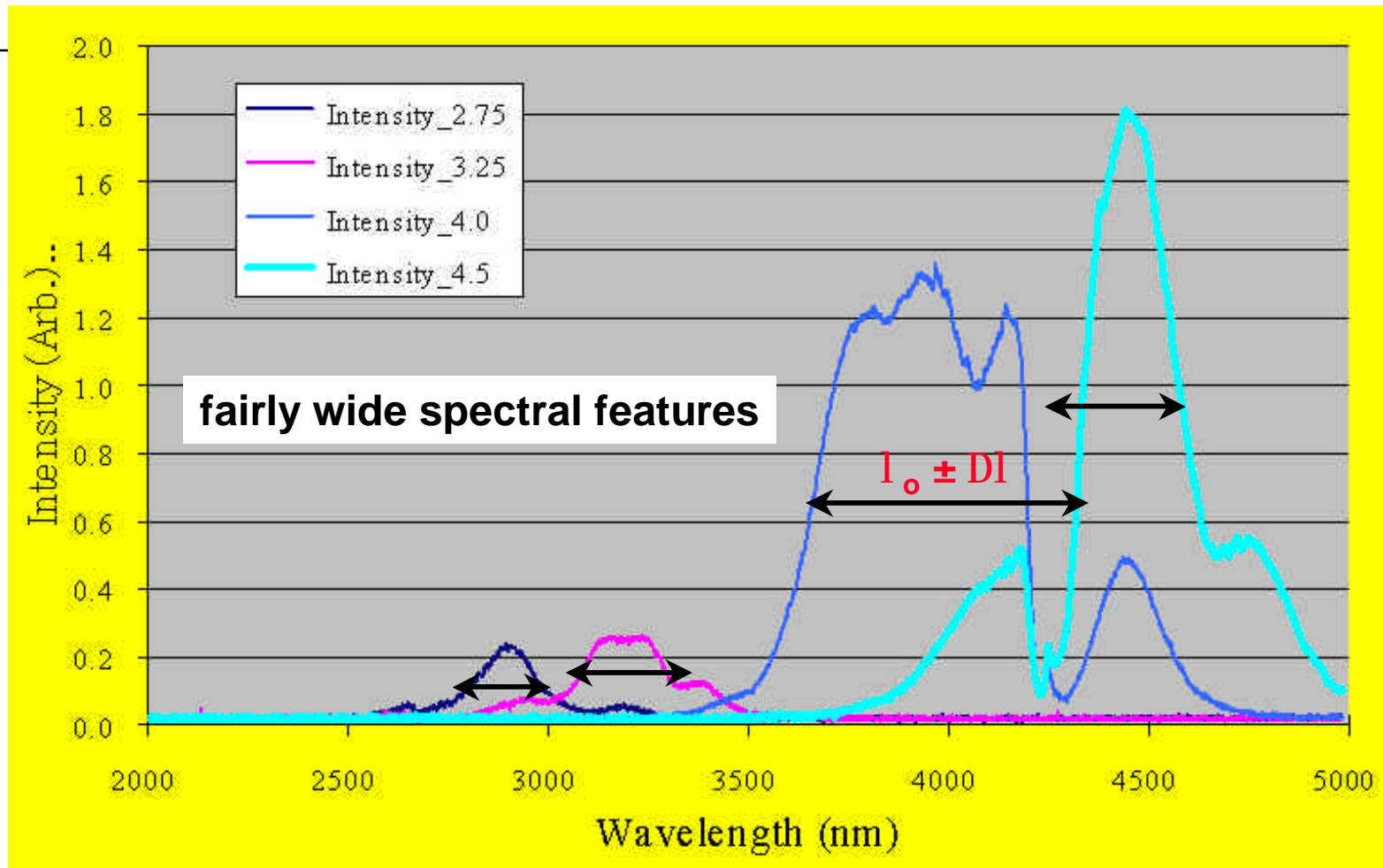
- measured thermal impedance under ambient pressure is $6 \times 10^4 \text{ K/W}$ vs. calculated thermal impedance $1 \times 10^6 \text{ K/W}$
 - simple “still air” estimate gives thermal resistance of about $2 \times 10^5 \text{ K/W}$
 - past work supports two-order reduction due to thermal losses to air at ambient pressure

Optical setup used for IR testing of microbolometers

- set-up in A. J. Welch's lab, with thanks to Dan Hammer
- two device types tested
 - resonant cavity bolometer WITH mirror for enhanced wavelength dependent absorption, first resonance at 3 mm
 - simple bolometer WITHOUT mirror

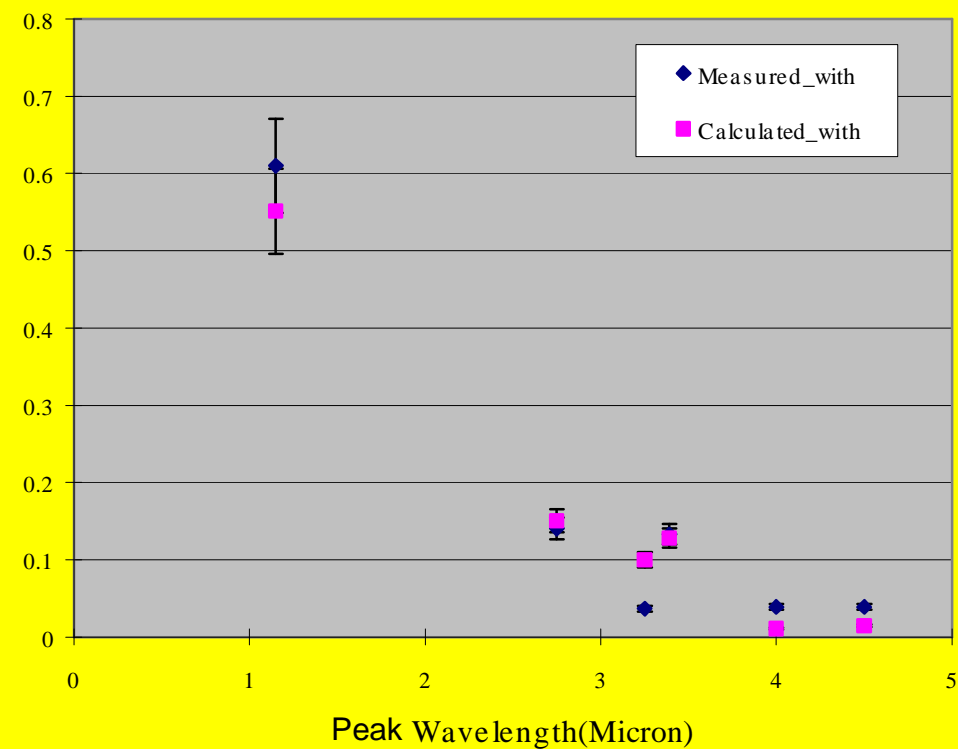
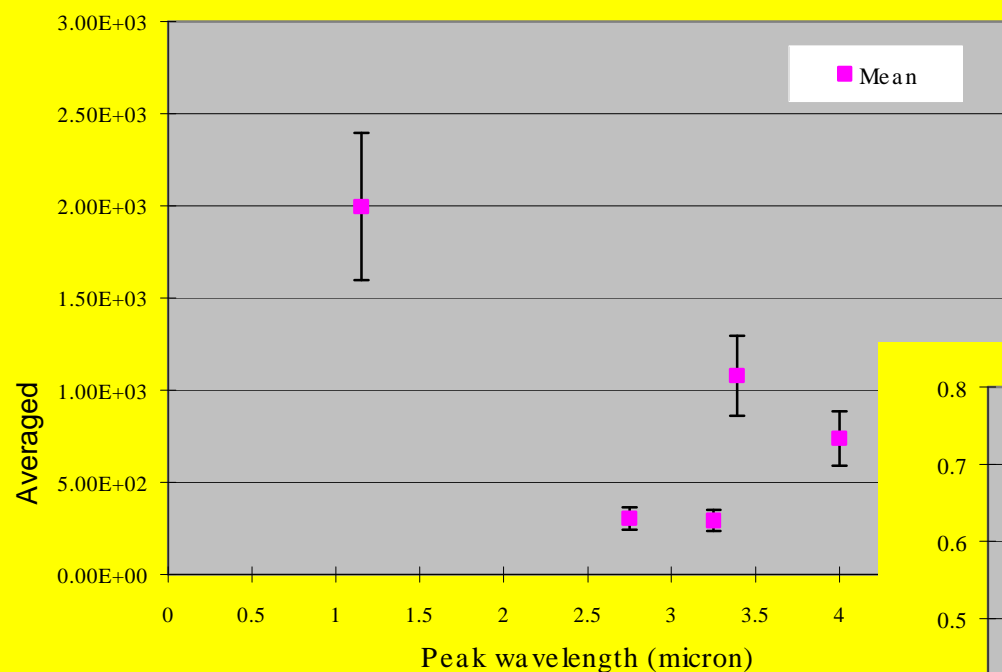


IR spectrum of ultrafast laser system

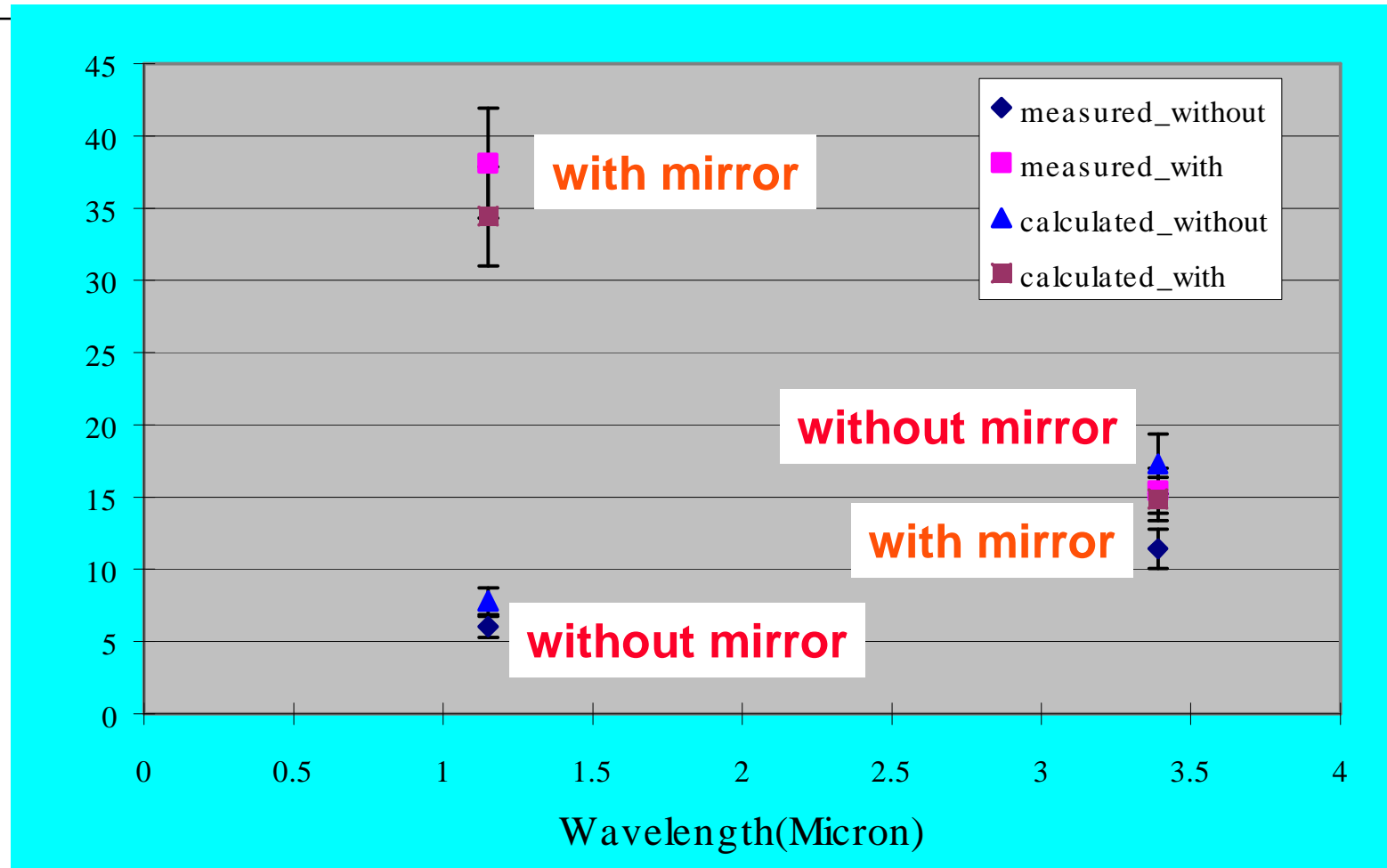


bolometer response μ $P_{\text{absorbed}} = \int dx \int dy \int d\lambda \cdot \eta(\lambda) \cdot S(\lambda, x, y)$

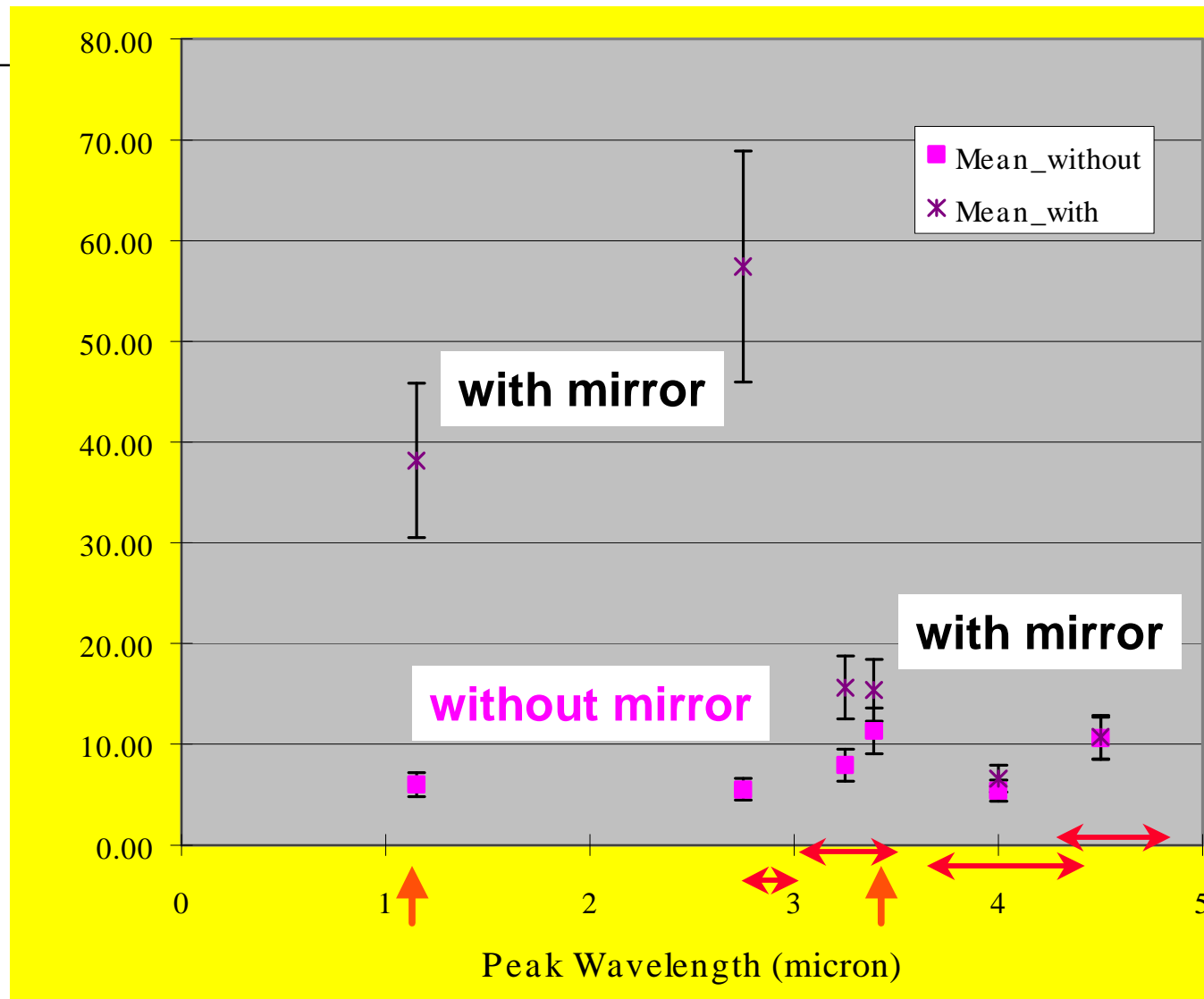
Irradiance on and output voltage of resonant cavity microbolometer



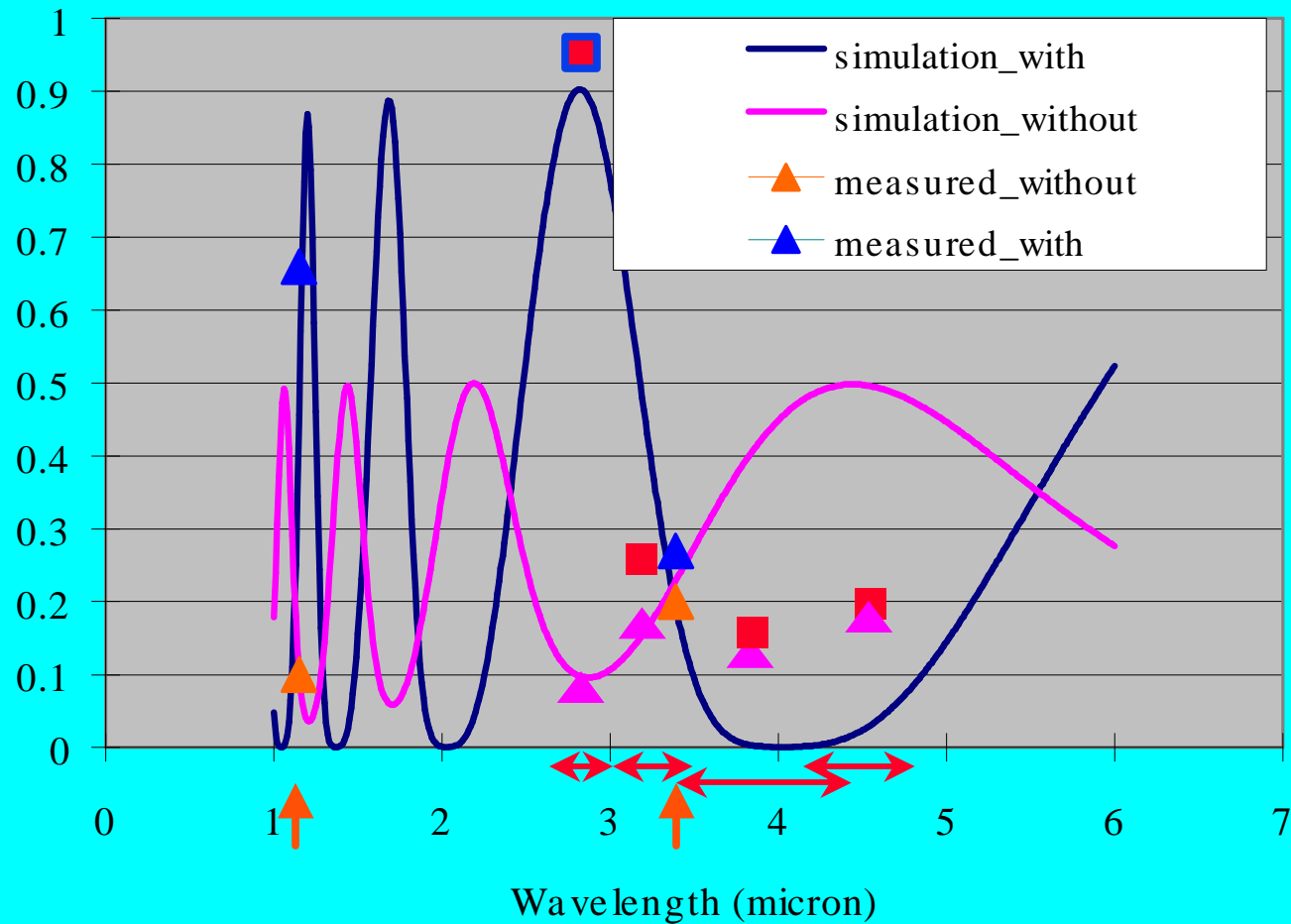
Responsivity at 1.15 and 3.39 μm , narrow-band excitation



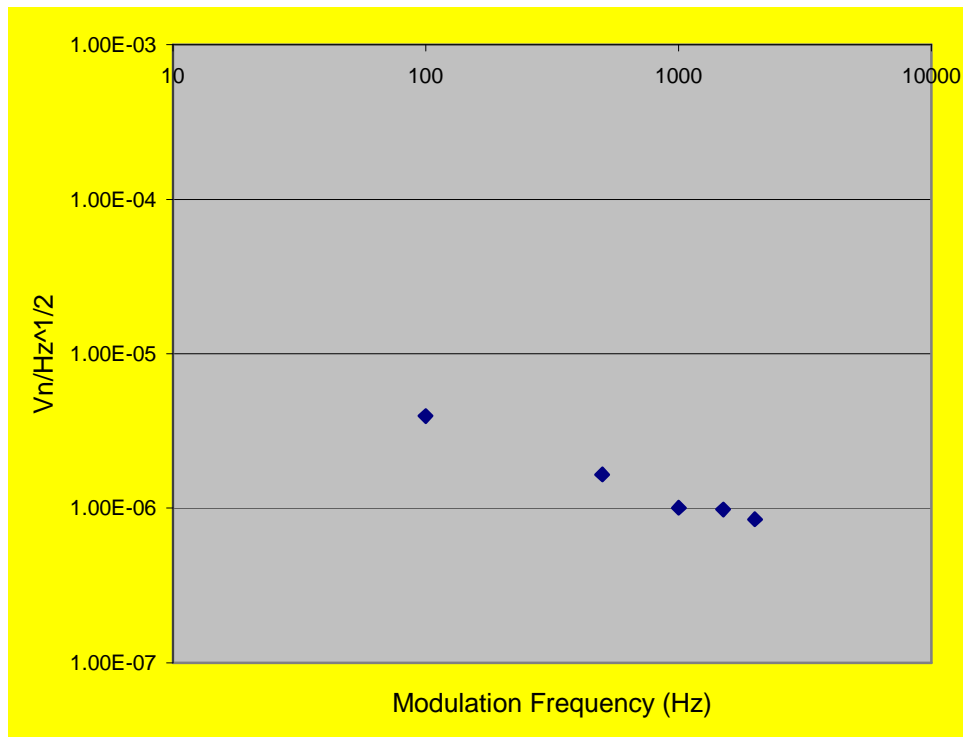
Measured responsivity of resonant cavity microbolometer



Power coupling efficiency



Noise measurement of the resonant dielectric cavity microbolometer



1/f noise dominant

NEP (Noise Equivalent Power) at 1500 Hz

– $\sim 5 \times 10^{-8} \text{ W}/(\text{Hz})^{1/2}$

Detectivity (D^*) at 1500 Hz

– $6.9 \times 10^4 \text{ cm } (\text{Hz})^{1/2} / \text{W}$

Noise equivalent temperature difference (NETD)

- smallest temperature change in object space that can be resolved assuming a unit signal to noise ratio

$$\text{NETD} \propto \frac{T}{\eta R_{\text{thermal}} \sqrt{C_{\text{thermal}}}} \quad \text{Where } T: \text{temperature, } h: \text{absorptivity, and } C: \text{thermal capacitance}$$

- temperature resolution for IR “microbolometer” systems
 - NETD of uncooled camera: claim that 0.039 C° is enough for “TV quality”
 - public results
 - SBRC (1996) : 110 mK
 - Mitubishi Electronics (1996) : 500 mK
 - Lockheed Martin (1998): less than 100 mK

-

Comparison of current commercial IR detectors

Summary of Important Specification of IR detectors

	Near Infrared	Mid Infrared Antimonide	Uncooled Microbolometer	Microbolometer	Long QWIP
Type	InGaAs	InSb	Microbolometer	Microbolometer	GaAs QWIP
Spectral range	0.9 – 1.68 μm	1 – 5.5 μm	7 – 14 μm	7 – 14 μm	8 – 9.2 μm
Array format	320 x 240	320 x 240	320 x 240	160 x 128	320 x 240
Size	30 x 30 μm	30 x 30 μm	51 x 51 μm	51 x 51 μm	30 x 30 μm
Operating Temperature	291 K Uncooled	77 K Cooled	313 K or 293 K Uncooled	300 K Uncooled	77 K or less Cooled
NedT		< 20 mK	< 100 mK	< 100 mK	< 30 mK