Device-level vacuum-packaged infrared sensors on flexible substrates

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Outline

- Introduction
  - MEMS
  - Infrared radiation and detection
  - Bolometers
  - Flexible substrates
- Bolometers on flexible substrates
- Device-level vacuum-packaged microbolometers
- Fabry Perot cavity based tunable infrared microspectrometer

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Microelectromechanical Systems (MEMS)

- *Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common substrate through microfabrication technology*.

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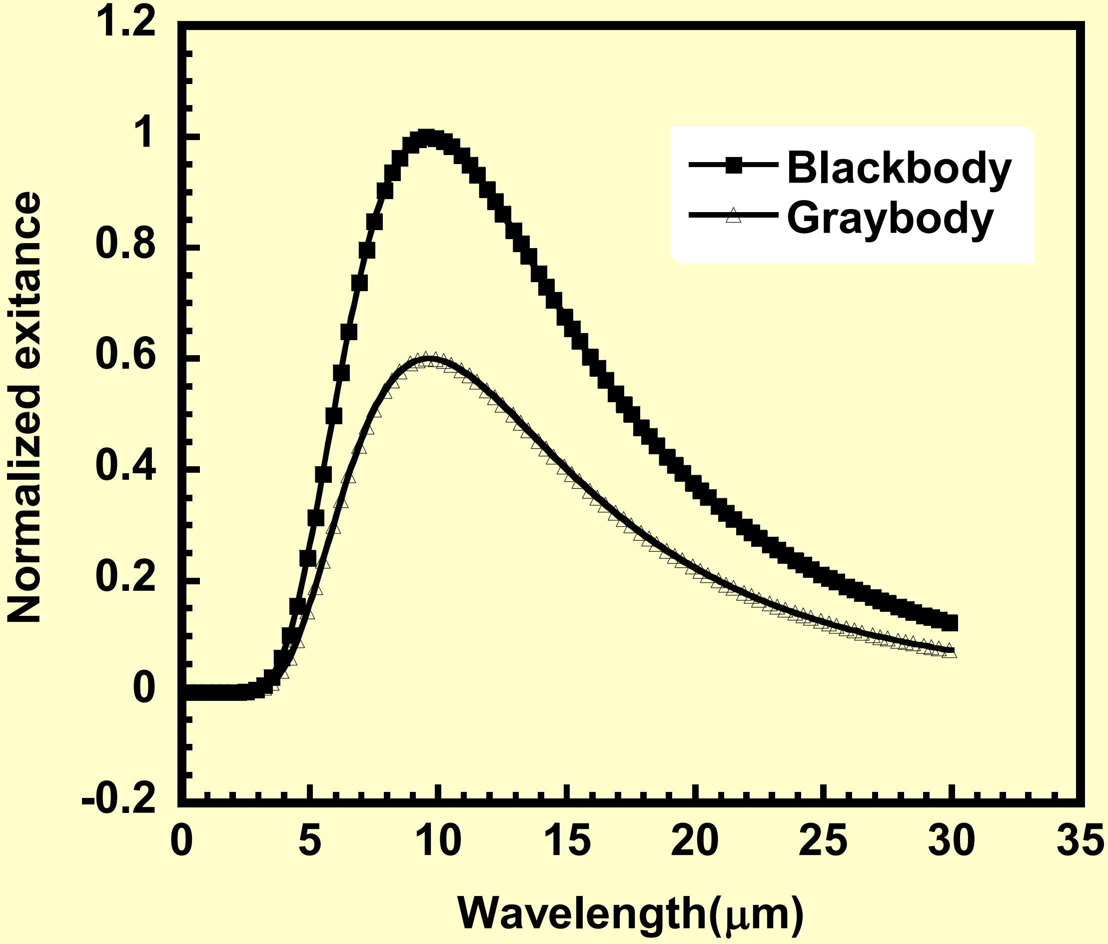
Infrared radiation
Planck's law



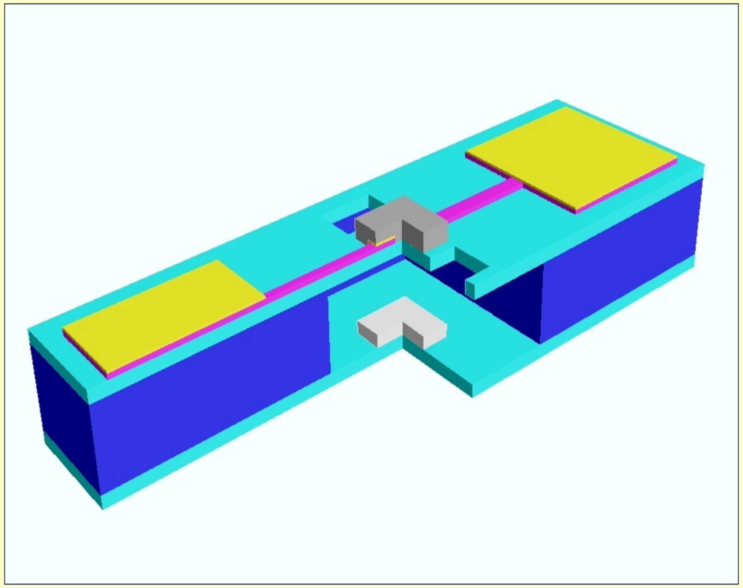
Infrared Detectors

- **Photon Detectors**
  - Incident radiation generates photo carriers
    - Photovoltaic detectors
    - Photoconductive detectors
    - Photoemissive detectors
- **Thermal Detectors**
  - Incident radiation causes change in temperature that causes a change in a detector property e.g.
    - Bolometers *(change in temperature causes the detector resistance to change)*
    - Pyroelectric detectors *(change in temperature causes the detector capacitance to change)*
    - Thermocouples *(use Seebeck effect)*

Bolometers and IR detection

$$\Delta T_{ac} = \frac{\eta P_{signal}}{G_{eff}\sqrt{1+(\omega\tau_{th})^2}}$$

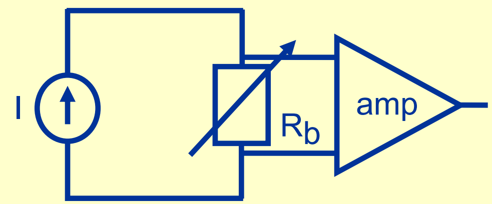
$$\tau_{th} = \frac{C_{th}}{G_{eff}}$$



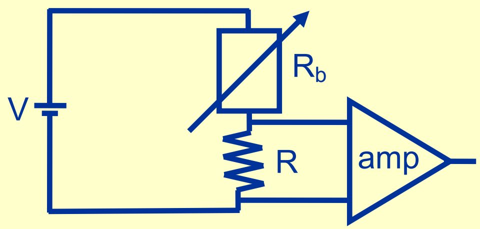
Bolometers and IR detection

- Temperature induces a change in the detector resistance

$$\Delta V = \eta \frac{\alpha I R_b}{G_{eff}(1+\omega^2\tau^2)^{1/2}} P_{signal}$$



$$\Delta I = \eta \frac{R_b}{(R+R_b)^2} \frac{V\alpha}{G_{eff}(1+\omega^2\tau^2)^{1/2}} P_{signal}$$



η = absorptivity, ω = angular frequency of incident radiation, τ = detector thermal time constant, P_{signal} = the magnitude of the incident flux fluctuation

Bolometer Figures of Merit

Temperature coefficient of resistance

Normalized change in resistance w.r.t. temperature

$$\alpha = TCR = \frac{1}{R}\frac{dR}{dT}$$

Responsivity

Output/Input

$$\Re_V = \frac{\Delta V}{P_{signal}} = \eta \frac{\alpha I R_b}{G_{eff}(1+\omega^2\tau^2)^{1/2}}$$

$$\Re_I = \frac{\Delta I}{P_{signal}} = \eta \frac{R_b}{(R+R_b)^2} \frac{V\alpha}{G_{eff}(1+\omega^2\tau^2)^{1/2}}$$

Bolometer Figures of Merit

Detectivity

Signal-to-noise ratio normalized to the detector area and frequency bandwidth

$$D_V = \Re_V \frac{\sqrt{\Delta f \times A}}{V_n}$$

$$D_I = \Re_I \frac{\sqrt{\Delta f \times A}}{I_n}$$

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Bolometer materials

Material	TCR (300K)	Salient features
YBCO	**-3 to -3.5 %K^{-1}**	**Room temp sputtering, no heat treatment**
VO_x	**-2 %K^{-1}**	**Low noise**
A-Si	**-2.7 %K^{-1}**	**High doping with impurities, Crystalization by high temp annealing**
P-Si	**-1 to -2 %K^{-1}**	**High temperature annealing**
P-Si_Ge alloy	**~ -2 %K^{-1}**	**High temperature deposition**

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Flexible substrates

Property	Units	Polyimide	Polyester
Thickness Range	mils	0.3 - 5	0.25 - 14
Dielectric Constant	1 Mhz	3.4	3.2
Volume Resistivity	Ω–cm	10^{18}	10^{18}
Tensile Strength (at 25°C)	psi	40 000	27 000
Tear Initiation Strength	gms	800	1200
Operational Temperature	min/max °C	.-200 to +300	.-60 to +105
Coefficient of Thermal Expansion (at 20 °C)	1/°C	10×10^{-6}	20×10^{-6}
Change in Linear Dimension(150 °C, 30min)	%	>0.15	>1.5
Acid Resistance	_	Good	Good
Alkali Resistance	_	Poor	Poor
Grease/Oil Resistance	_	Good	Good
Organic Solvent Resistance	_	Good	Good
Water Absorbtion	% (24 hrs.)	3	>0.8

- http://www-ee.uta.edu/zbutler/Smart_skin_for_web.ppt

- Polyester and Polyimide used as flexible substrates
- Polyimide is thermally stable
- Polyimide has a T_g of ~400°C
- Polyimide is chemically resistant to most clean room etchants

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Flexible systems

- Advantages of flexible substrate micro sensors
  - Low cost
  - Lightweight
  - Conformable to non planar surfaces
  - Software based printed IC processes
  - High degree of redundancy

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Flexible systems

- Flexible electronics for personal communication *(flexible electronic paper)*
- Smart clothing *(Wireless communications with smart sensors and actuators in the ambient)*
- BioMEMS *(flexible electrodes for neural prostheses, vision prosthesis)*
- Conductive polymers *(compound eye, piezoresistive strain sensors)*
- Flexible energy sources *(photovoltaic cells, organic solar cells)*

Sensors on flexible substrates
(Smart Skin)

- Sensor Arrays on flexible substrates
  – Infrared sensors
  – Pressure/Tactile Sensors
  – Flow sensors
  – Humidity sensors
  – Velocity sensors

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Evolution of "smart skin" in the micro sensors lab

- First generation (2001-2002)
  - Used solid Kapton sheets pasted on to wafers
- Second generation (2003-2004)
  - Spin on Kapton used (no micromachining, not separated from carrier wafer)
- Third generation (2004)
  - Spin on Kapton used (micromachined devices, peeled off carrier wafer)
- Fourth generation (2005)
  - Vacuum packaging at the device level

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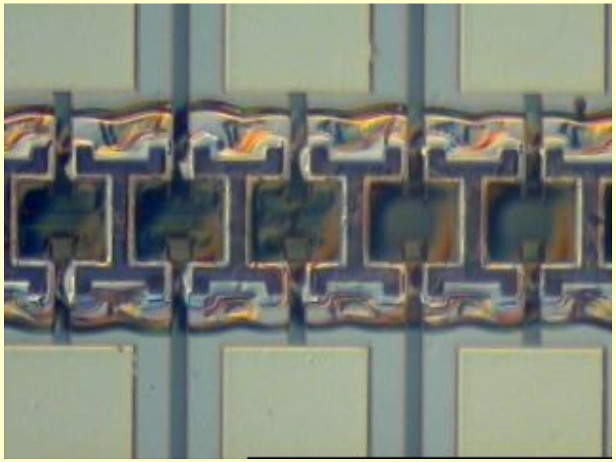
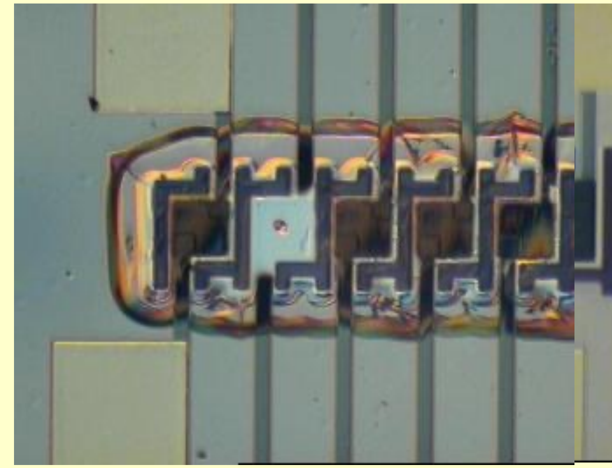
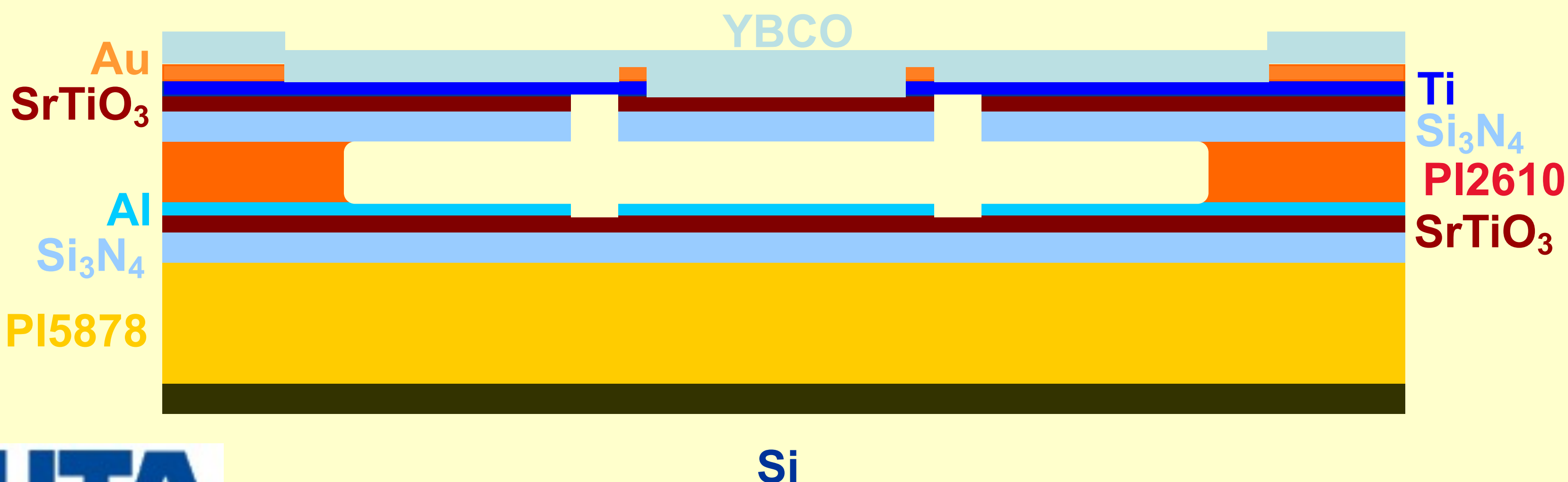
Microbolometers on flexible substrates

Microbolometer Fabrication

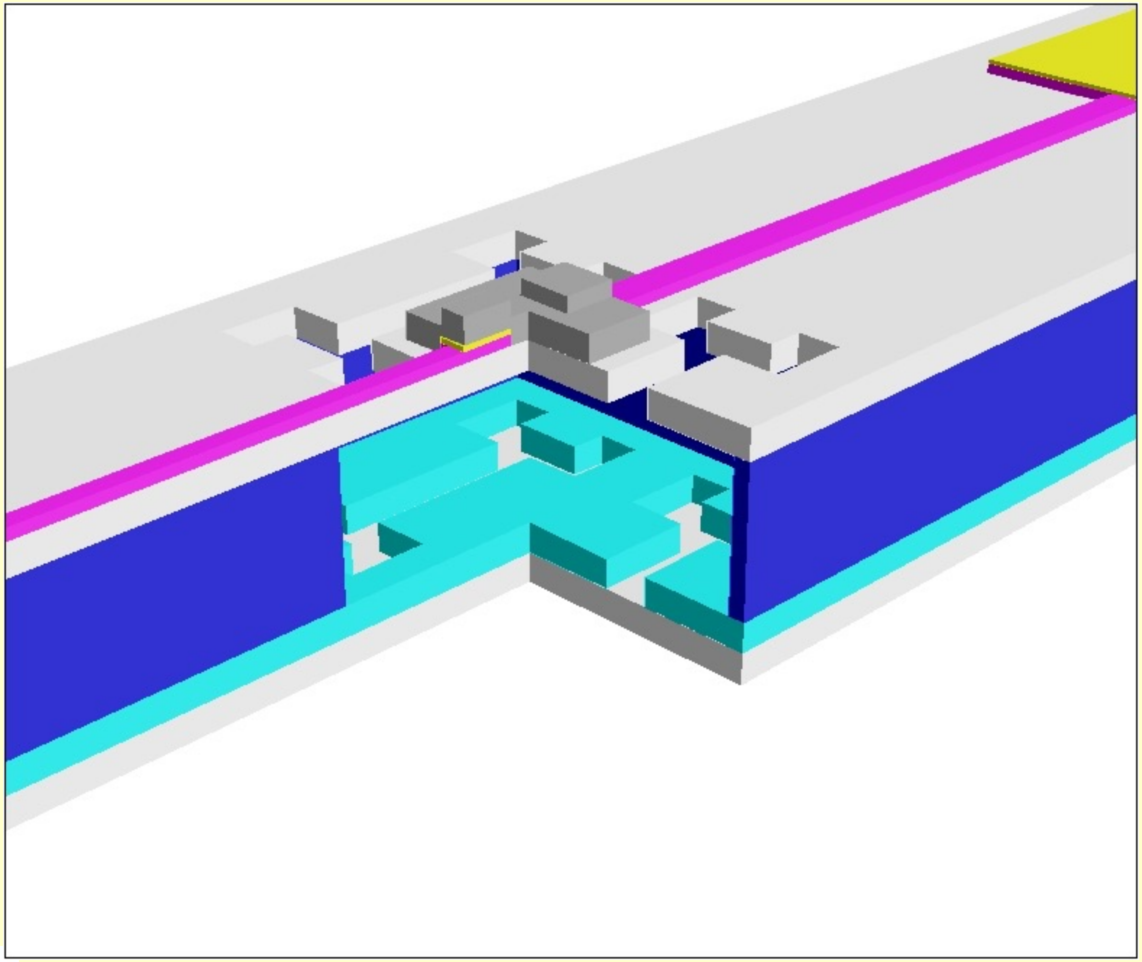
Trench Geometry





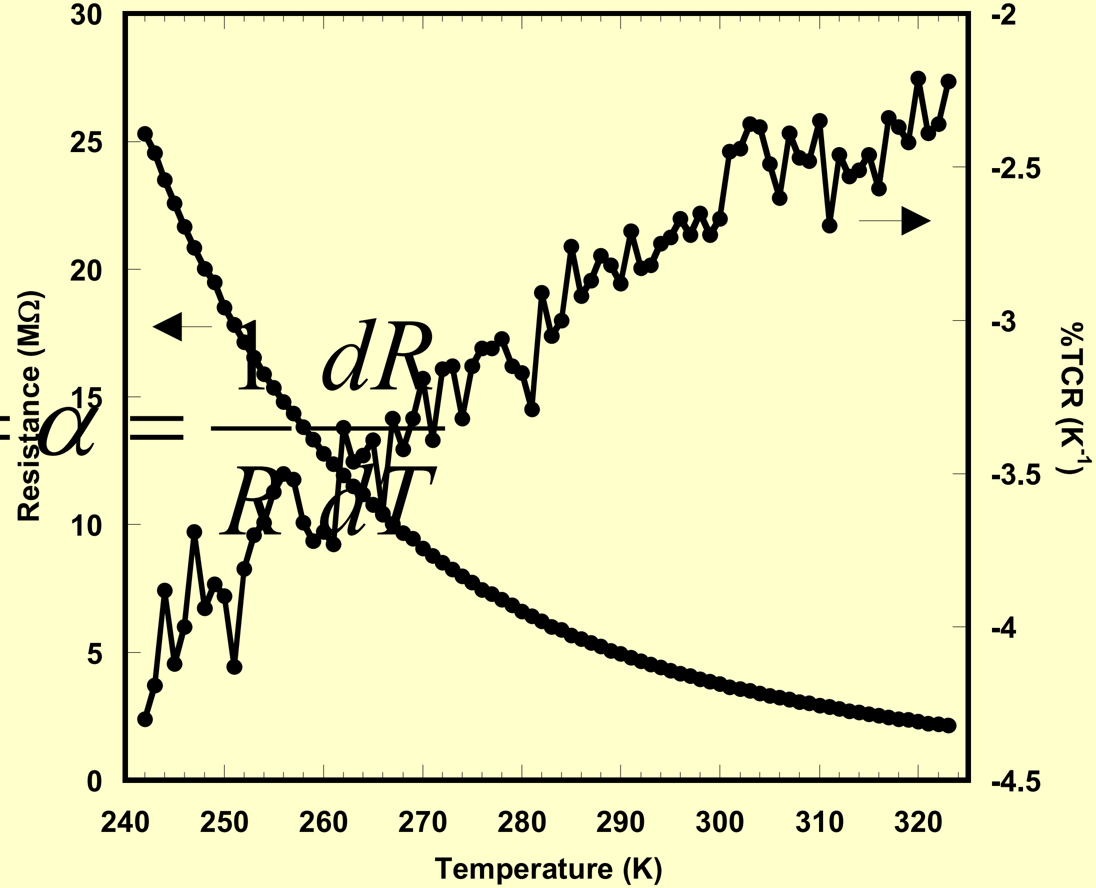


Microbolometers on a flexible substrate

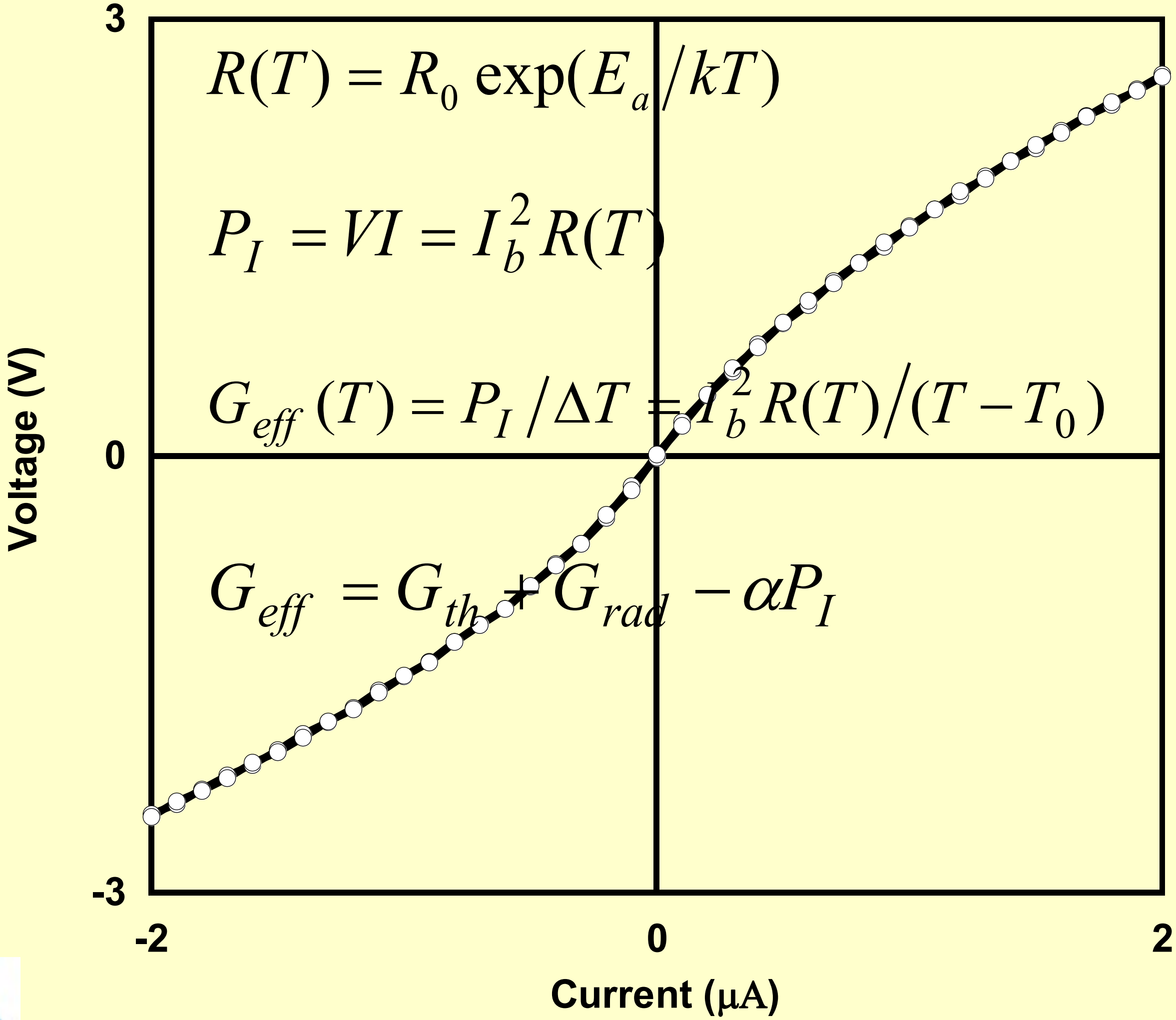


Temperature Coefficient of Resistance (TCR)

$$TCR = \alpha = \frac{1}{R}\frac{dR}{dT}$$



Effects of Joule Heating



$$R(T) = R_0 \exp(E_a / kT)$$

$$P_I = VI = I_b^2 R(T)$$

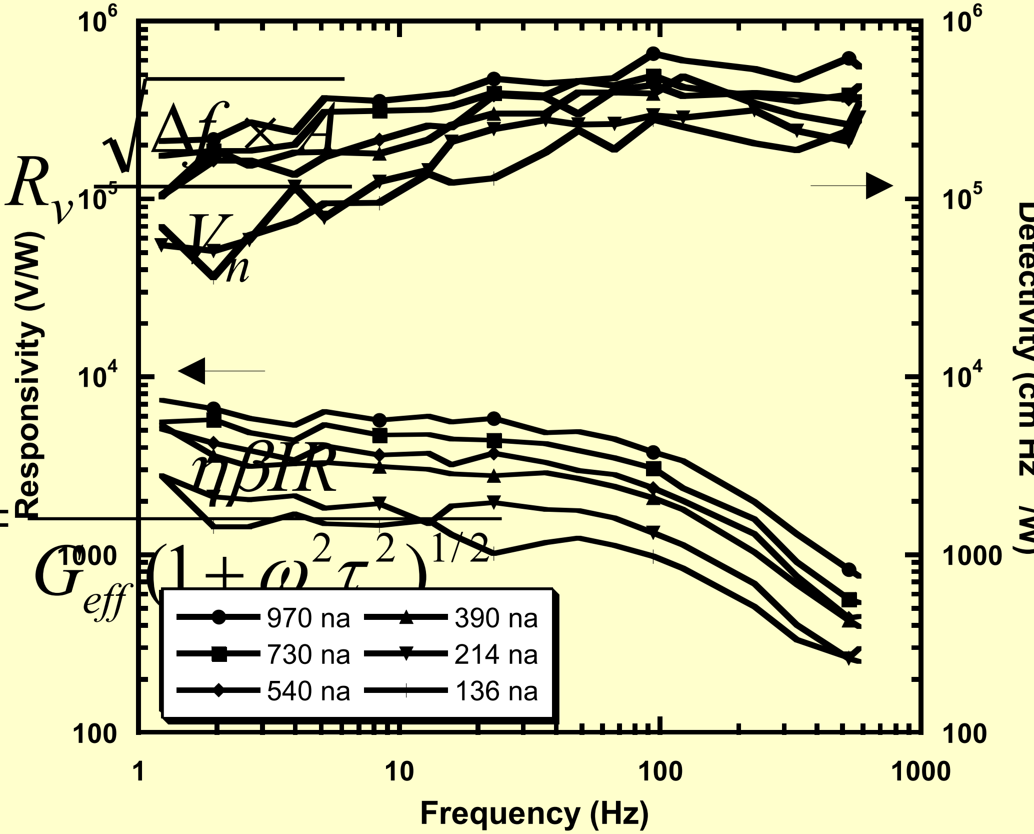
$$G_{eff}(T) = P_I / \Delta T = I_b^2 R(T) / (T - T_0)$$

$$G_{eff} = G_{th} + G_{rad} - \alpha P_I$$

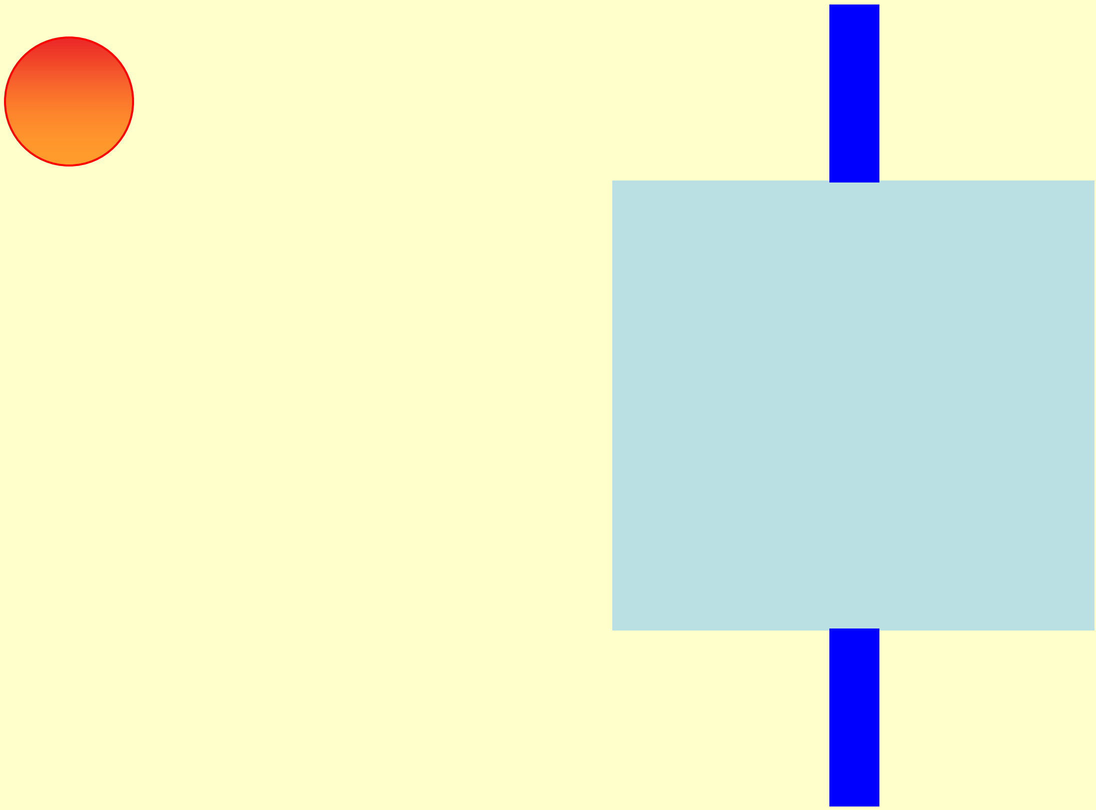
Responsivity/Detectivity

$$D_v = R_v \frac{\sqrt{\Delta f \times A}}{V_n}$$

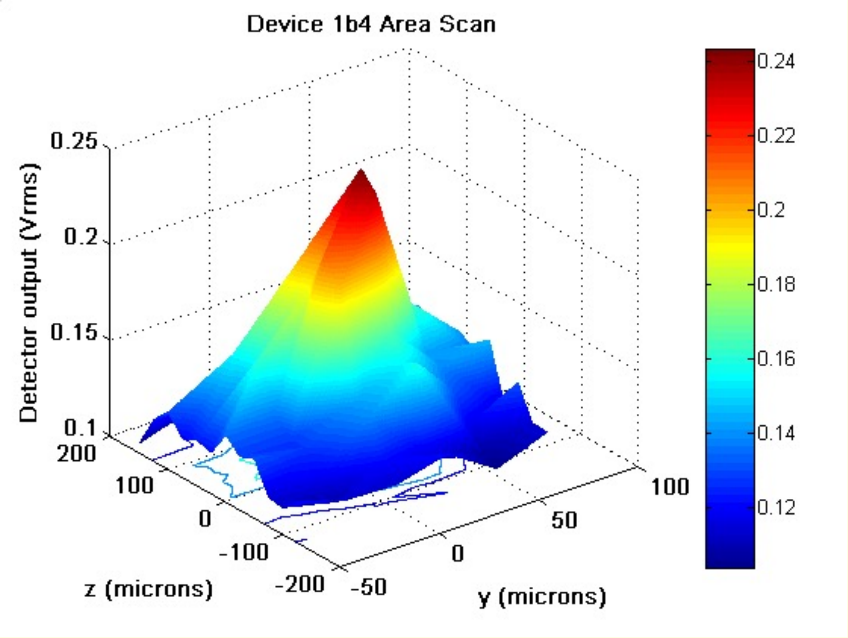
$$R_v = \frac{\Delta V}{\Delta \phi} = \frac{\eta \beta I R}{G_{eff}\left(1+\omega^2\tau^2\right)^{1/2}}$$

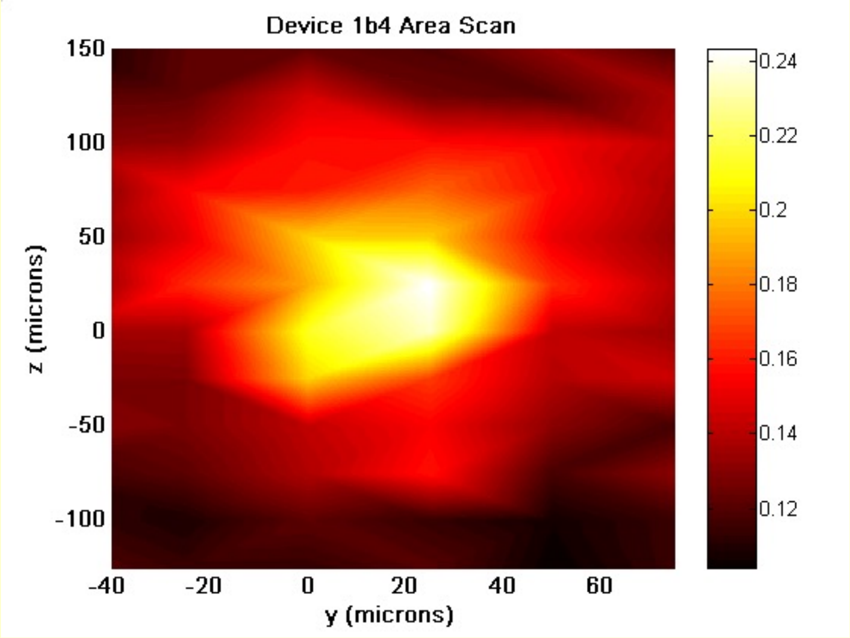


Effects of substrate heating



Area scans of bolometers
Device 1b4 (Trench Geometry)





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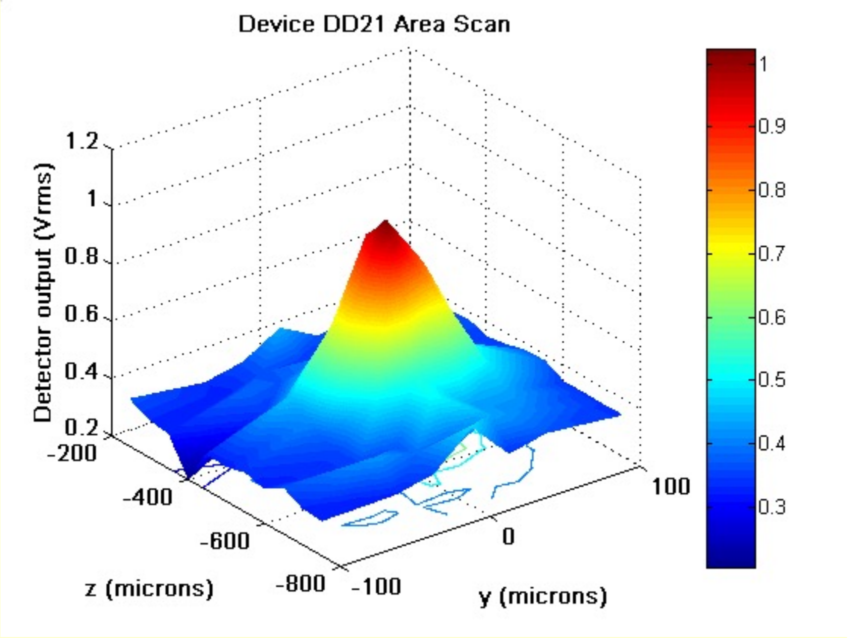
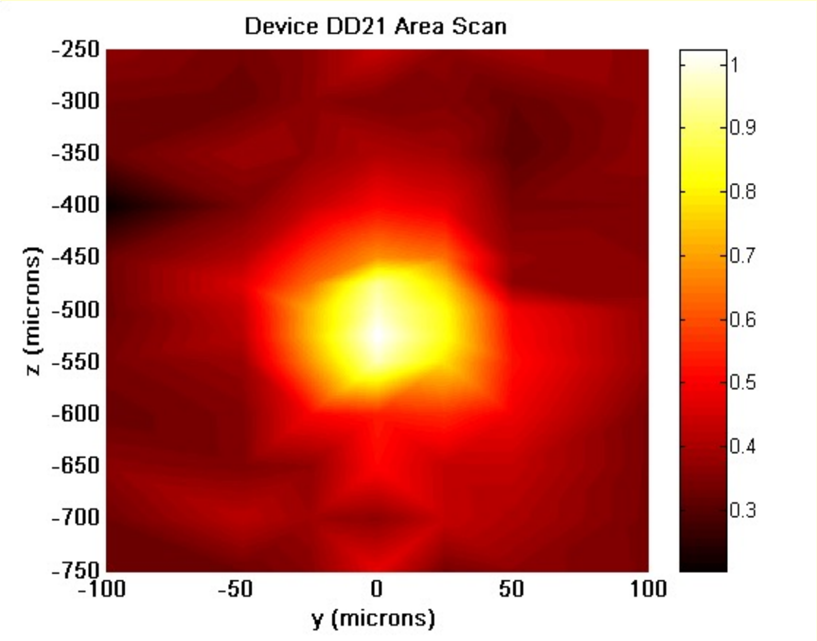
Area scans of bolometers
Device DD15 (Mesa Geometry)





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Conclusion

- Microbolometers on flexible substrates have been fabricated
- Mean measured thermal conductance = 5.61×10^{-7} W/K
- Max room temperature responsivity $R_V = 7.4 \times 10^3$ V/W
- Max room temperature detectivity $D^* = 6.6 \times 10^5$ cmHz$^{1/2}$/W
- Measured room temperature TCR = -2.63%/K
- Measured room temperature resistance = 3.76MΩ

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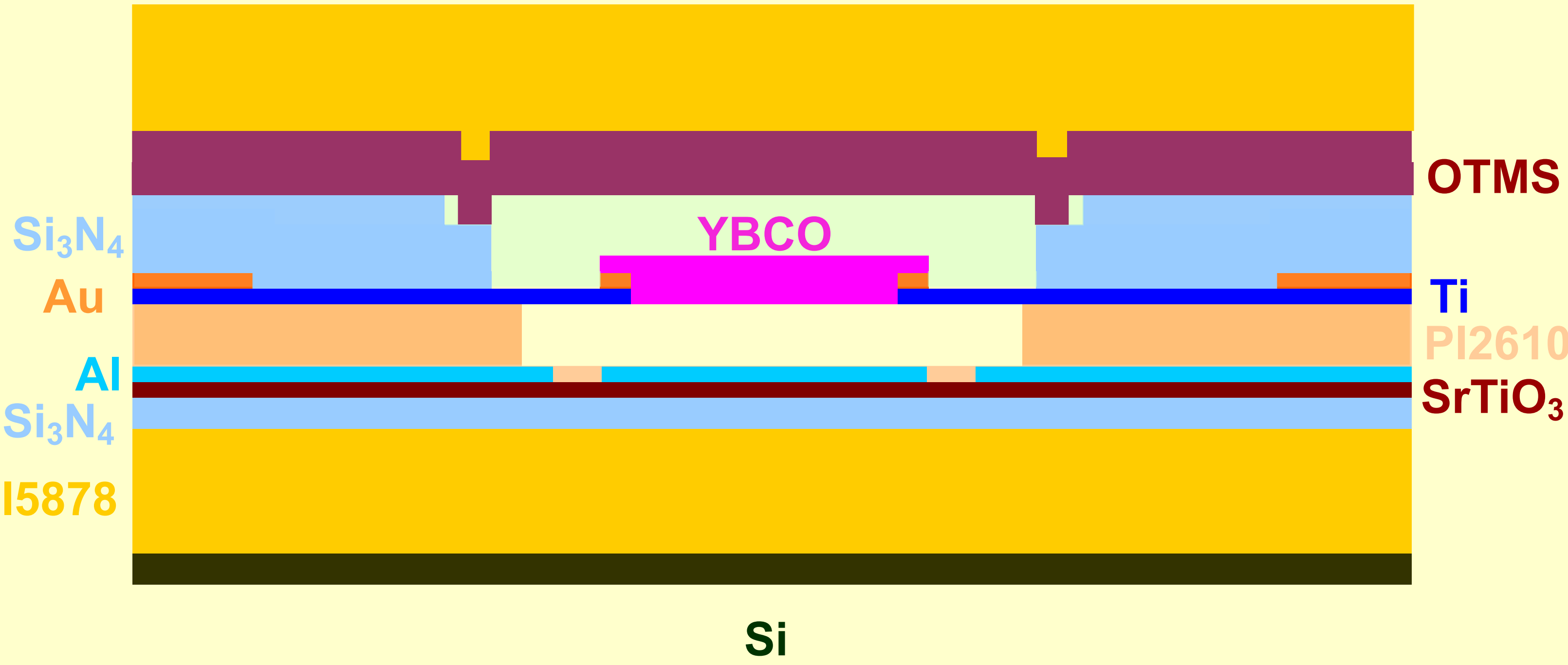
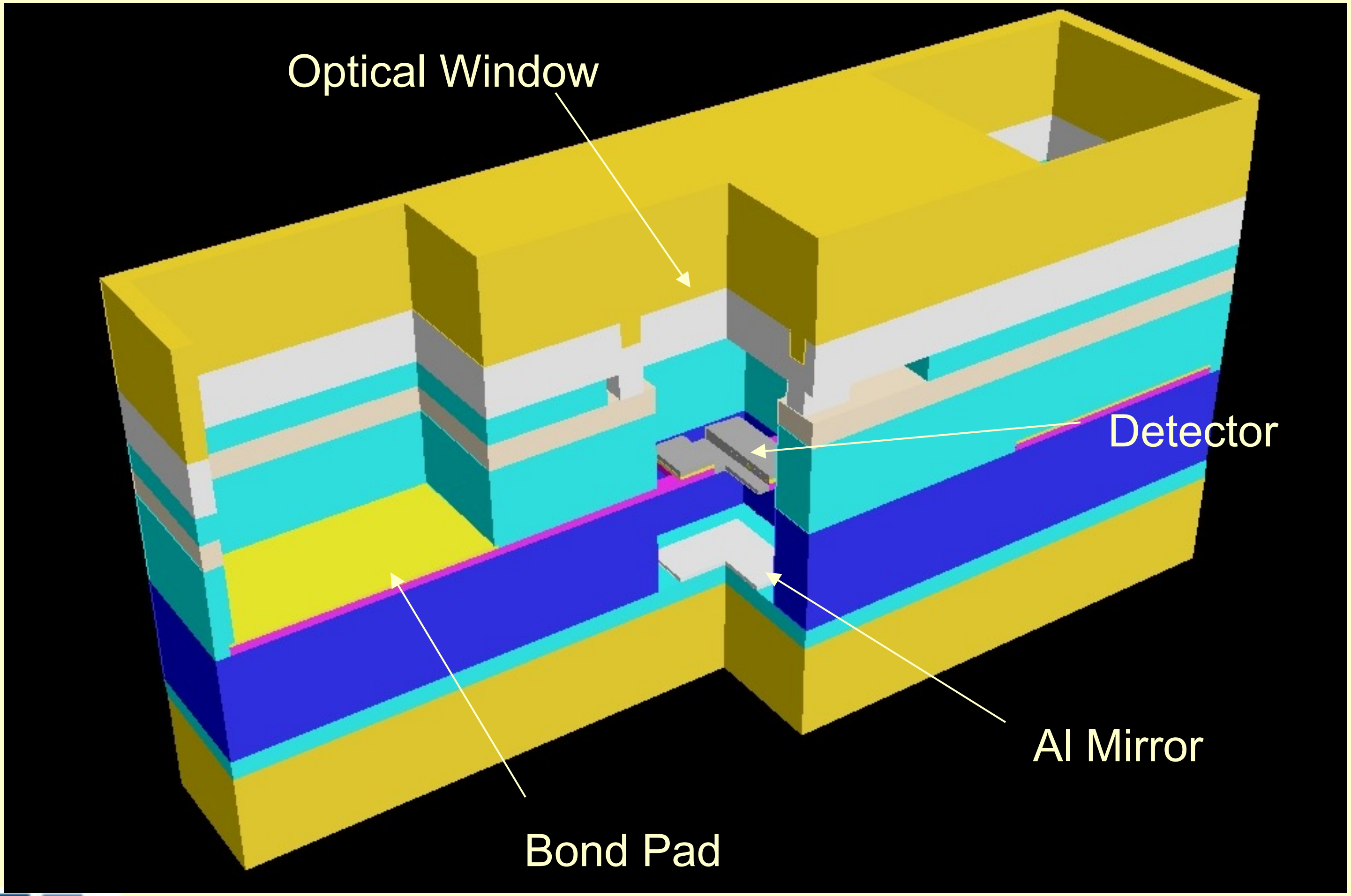
Device-level vacuum-packaging

Device-level vacuum packaging



Device-level vacuum packaging

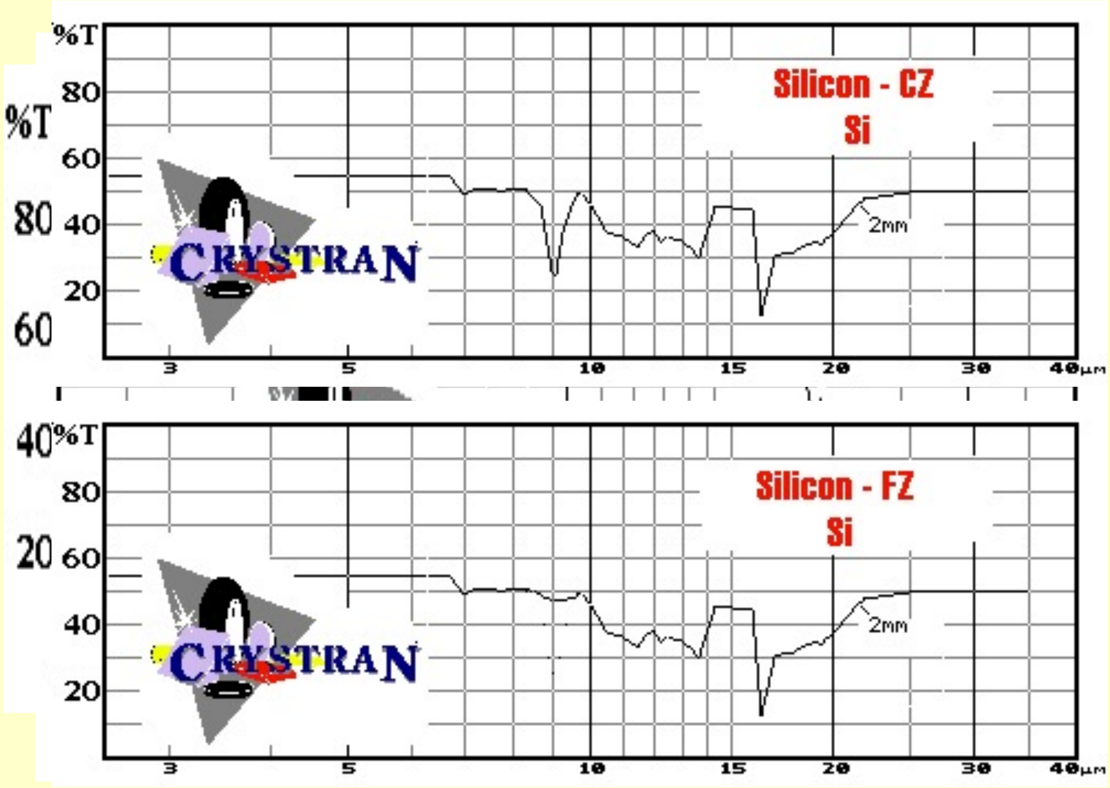


Device-level vacuum packaging

Design Considerations

- Optical window transmission characteristics
- Optical window structural analyses
- Cavity vacuum
- Thermal analyses

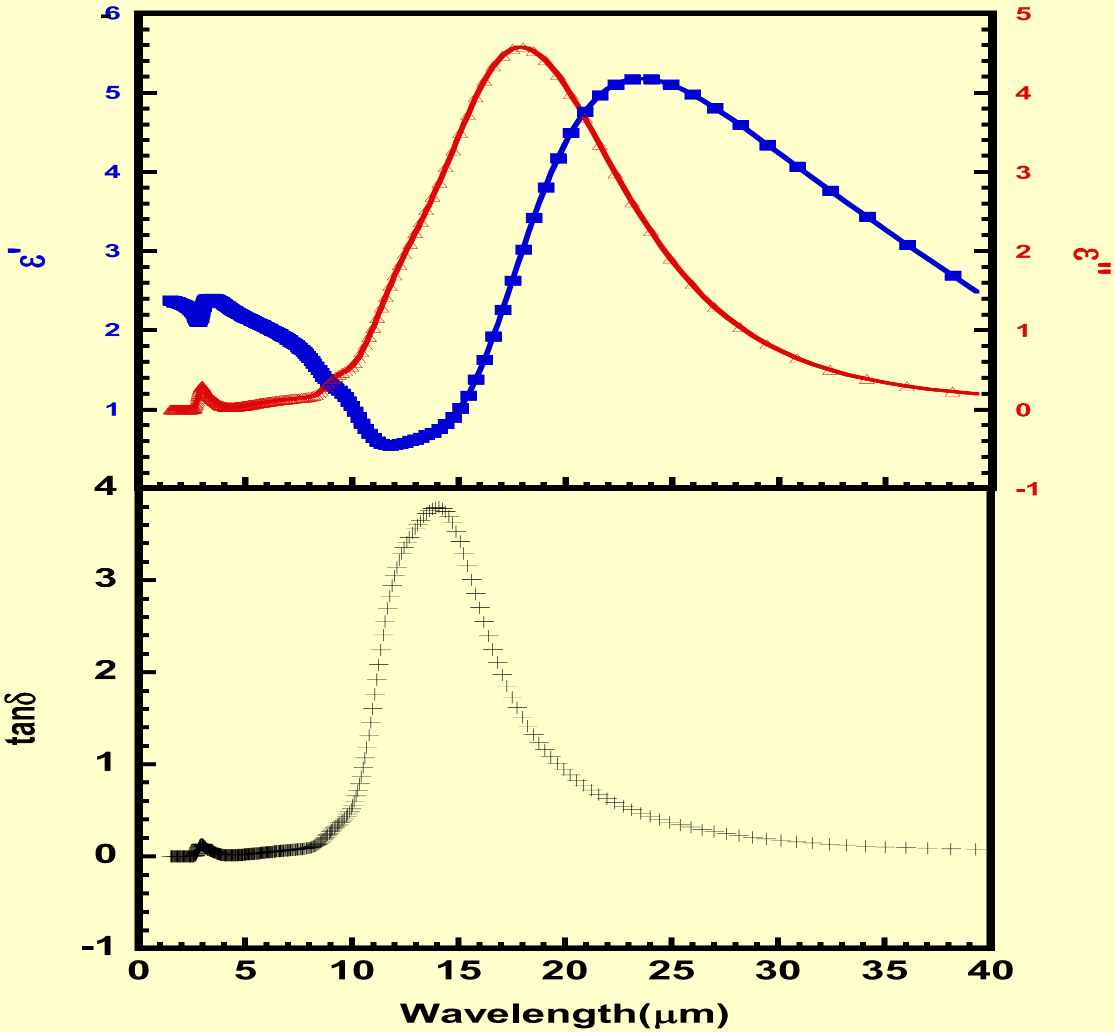
Optical Transmission Characteristics



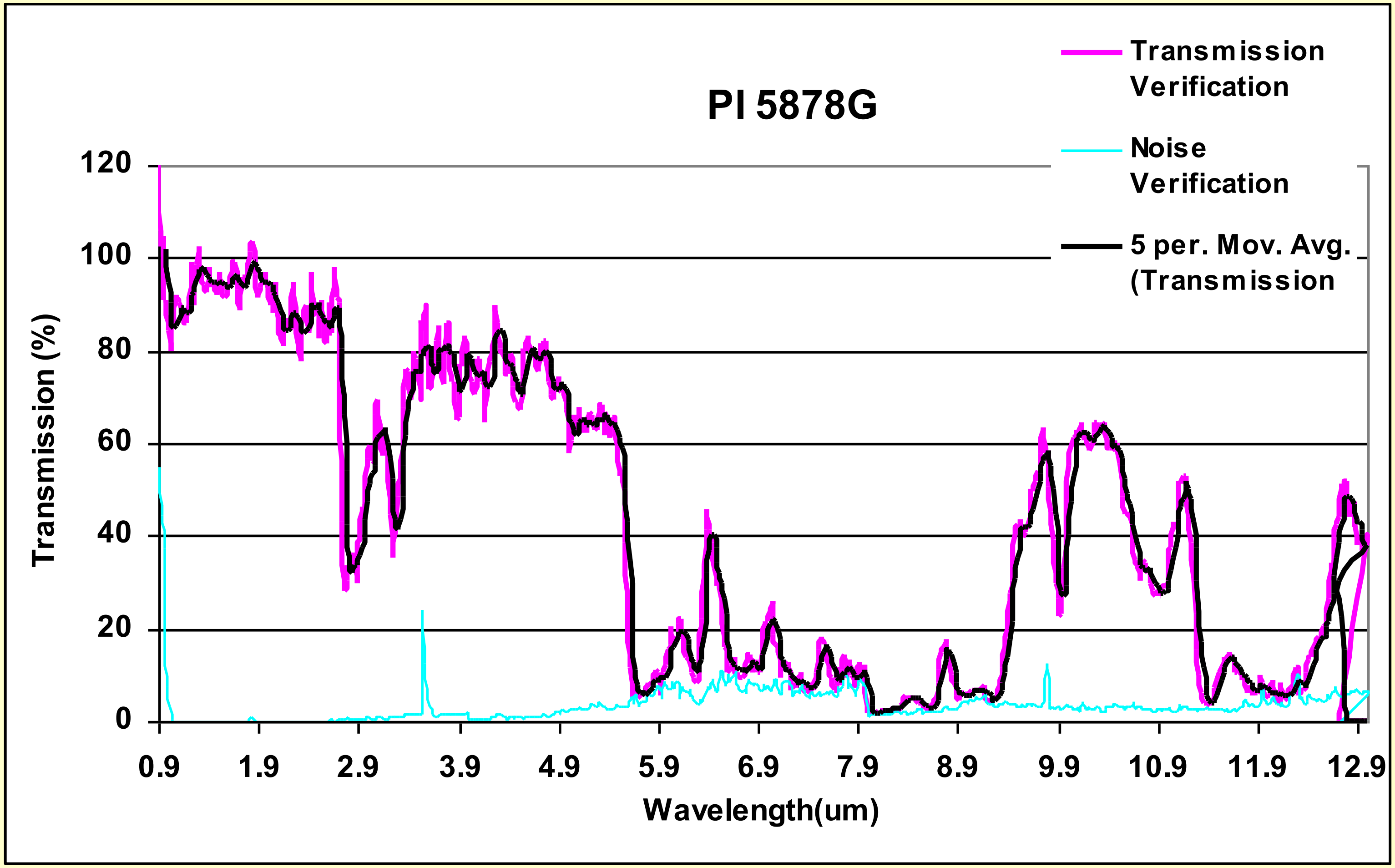
Transmission characteristics of thin Aluminum Oxide film

M. Aguilar-Frutis, M. Garcia, C. Falcony, G. Plesch and S. Jimenez-Sandoval, "A study of the dielectric characteristics of aluminum oxide thin films deposited by spray pyrolysis from Al(acac)3," *Thin Solid Films*, vol 389, Issues 1-2, pp 200-206, 15 June 2001.

Complex relative permittivity of Al_2O_3



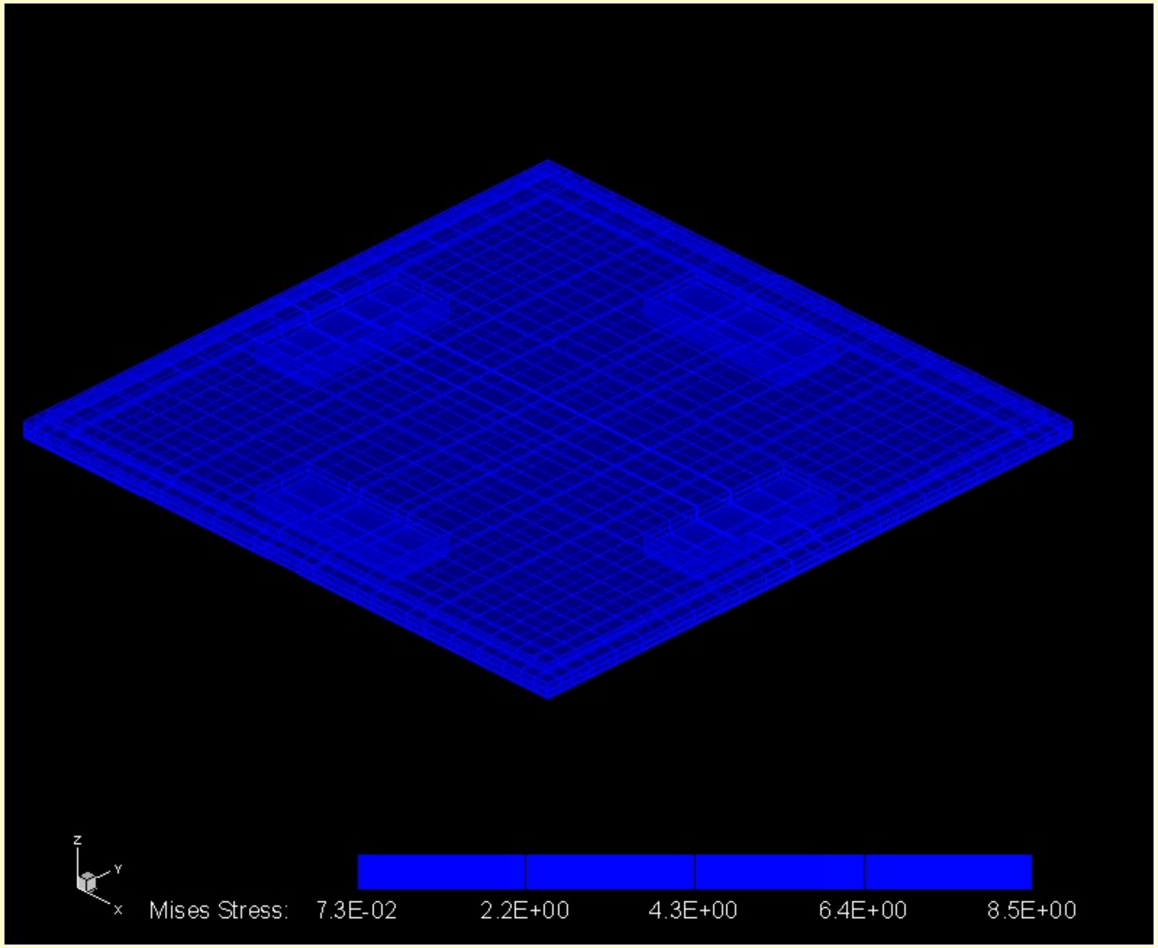
Optical Transmission Characteristics of polyimide



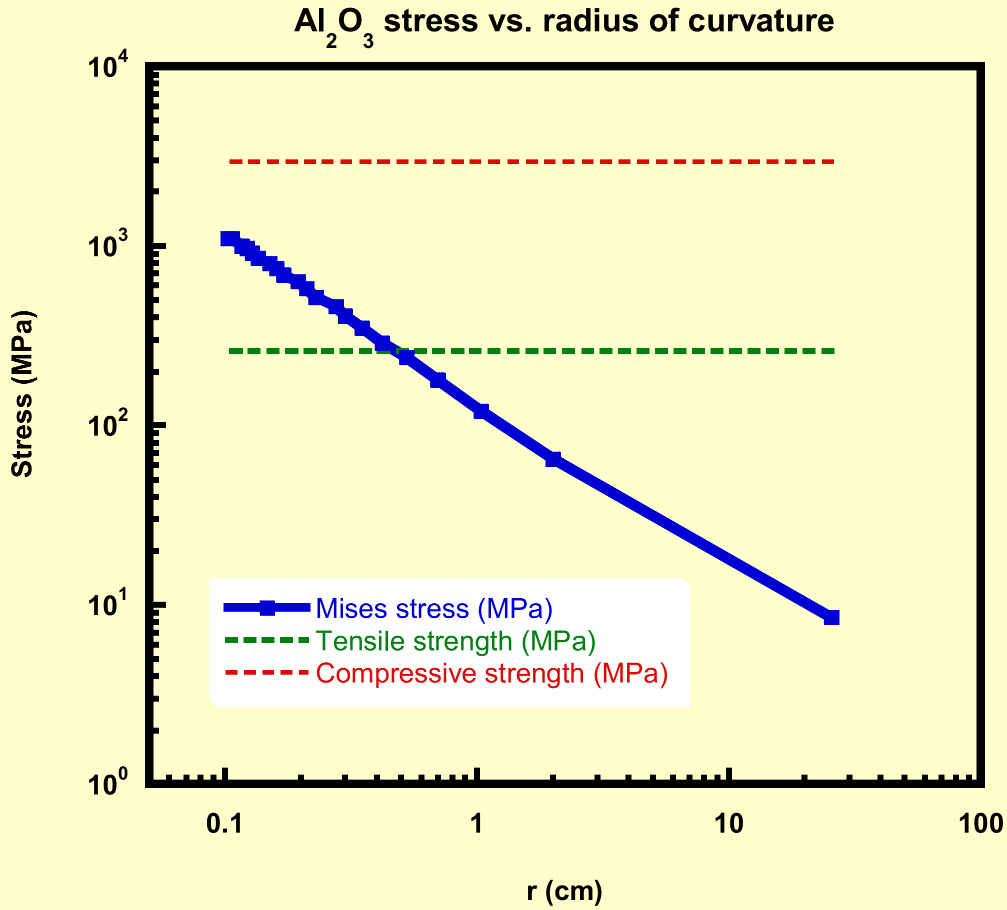
Structural analysis of vacuum element

- Mechanical Strength
  - Ceramic Al_2O_3 has a tensile strength of 260 MPa
  - ZnSe has an apparent elastic limit of 55.1 MPa

Structural integrity of vacuum element



Al_2O_3 stress analysis

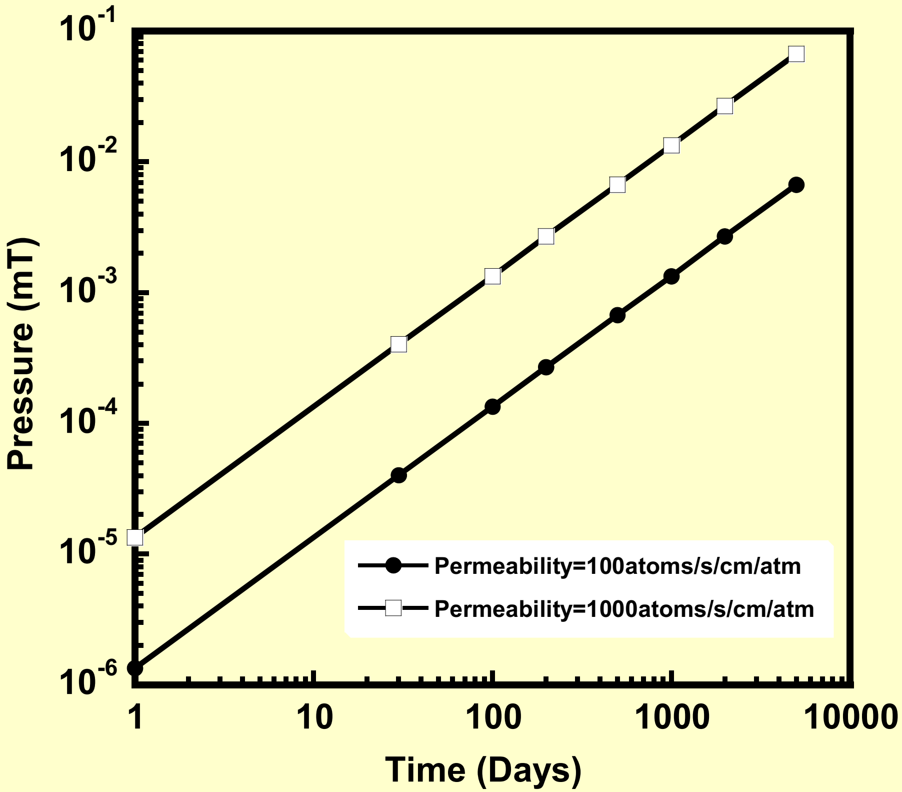


Permeability through Al_2O_3

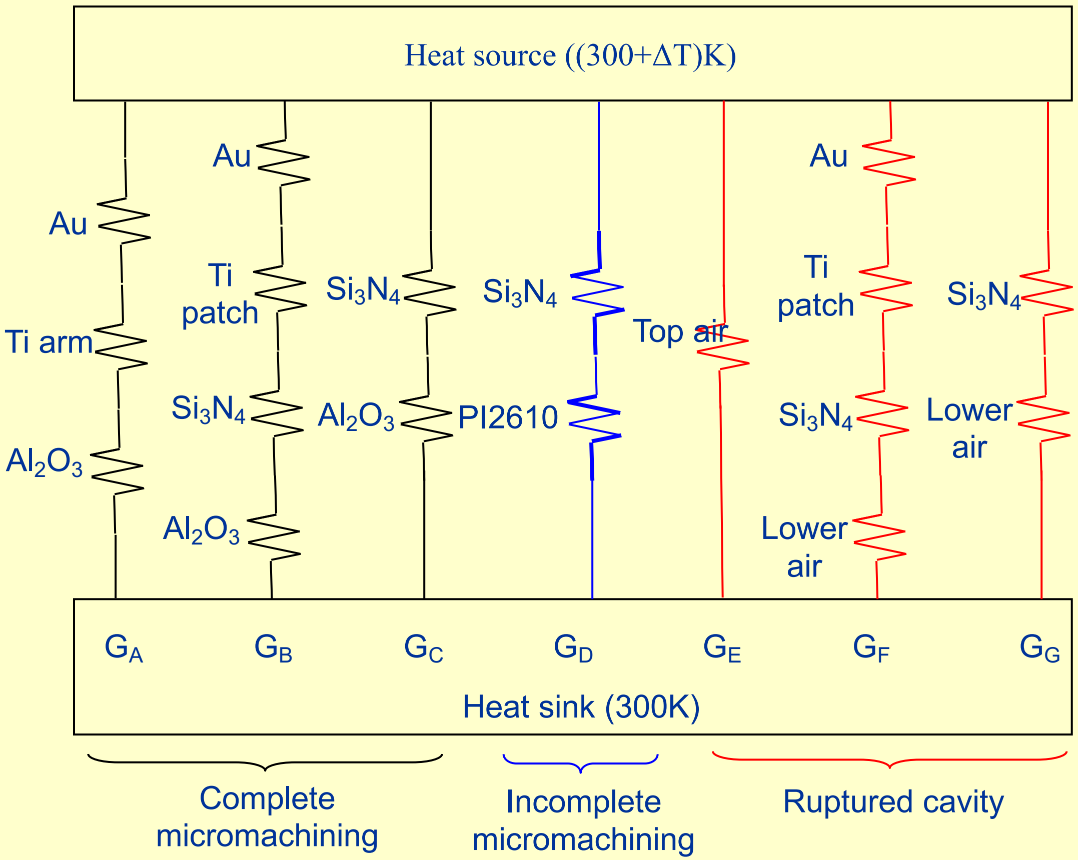
- Permeability is the flow rate through a specimen once steady state has been achieved
- He Permeability through Al_2O_3 at room temperature is ~100-1000 atoms/s/cm/atm
- $$P = \frac{nRT}{V}$$

n=number of moles

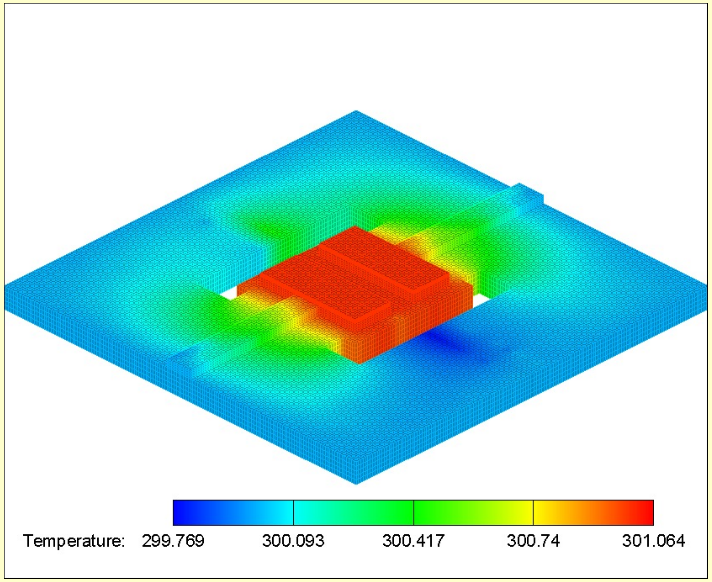
R=universal gas constant=8.314J/(mole.K)

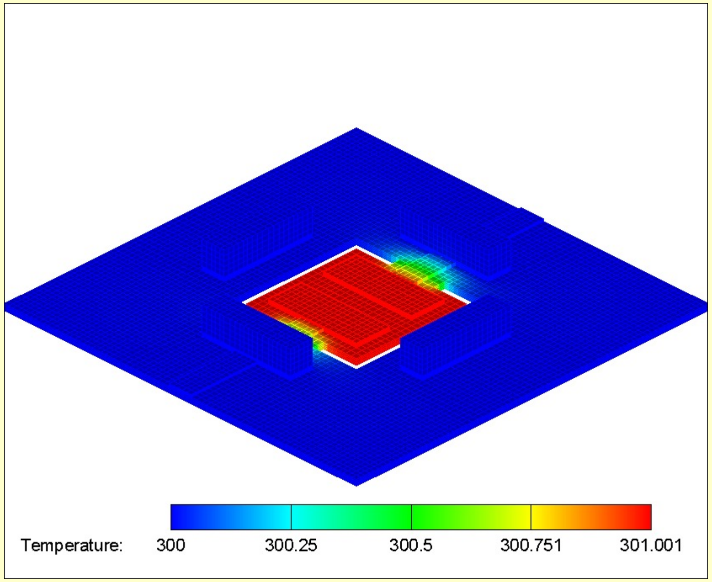


Thermal analysis (analytic)



Thermal analysis (numeric)



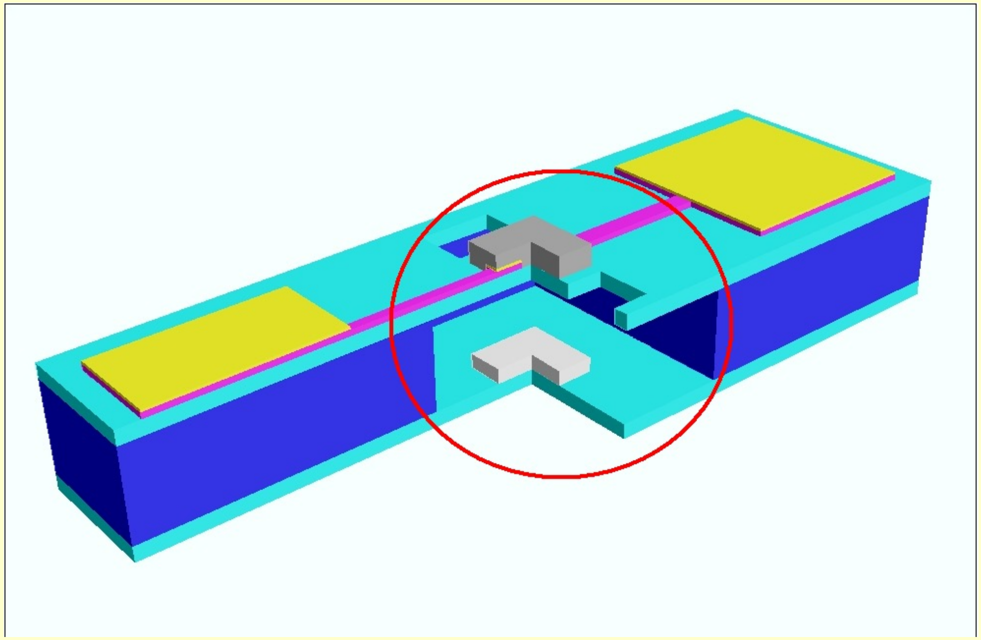


$G_{th} \approx 5 \times 10^{-6}$ W/K (Vacuum)

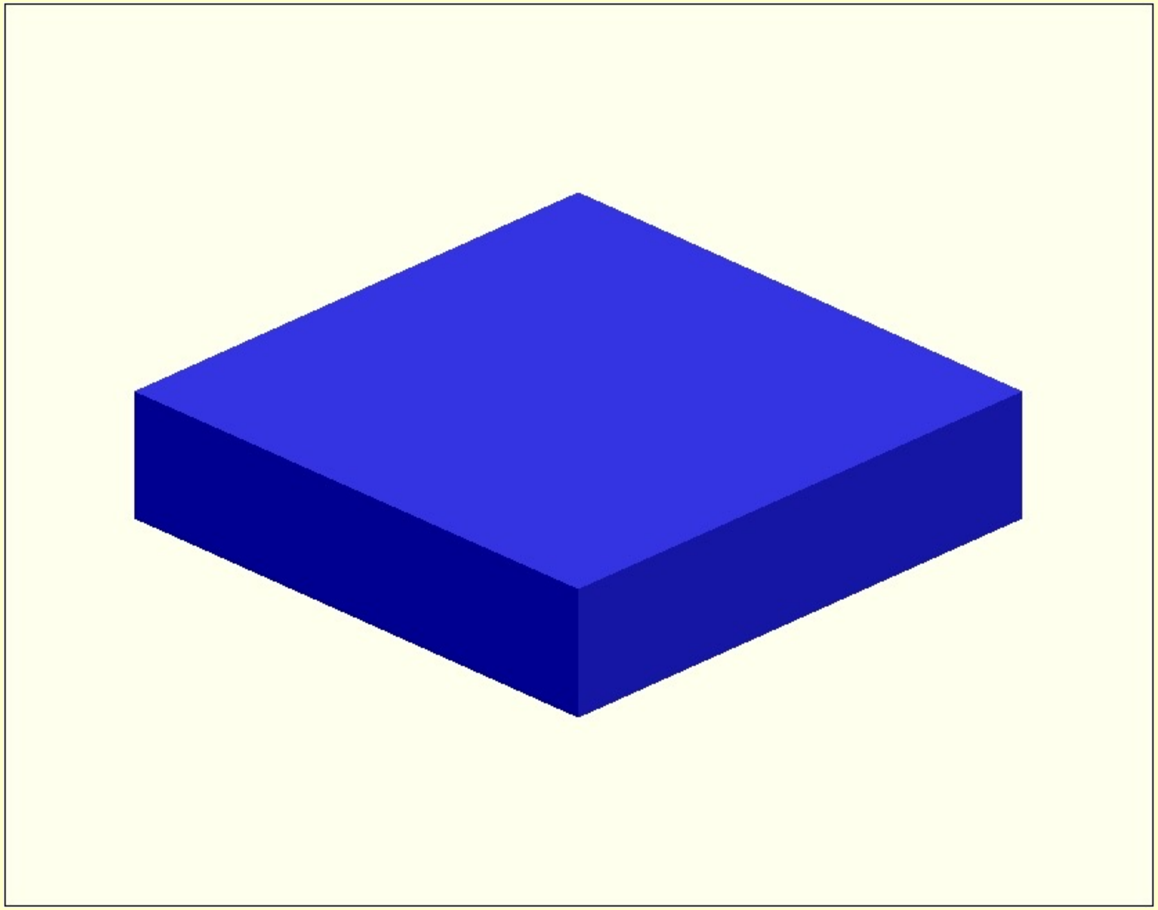
$\approx 10^{-4}$ W/K (air)

Microbolometer fabrication

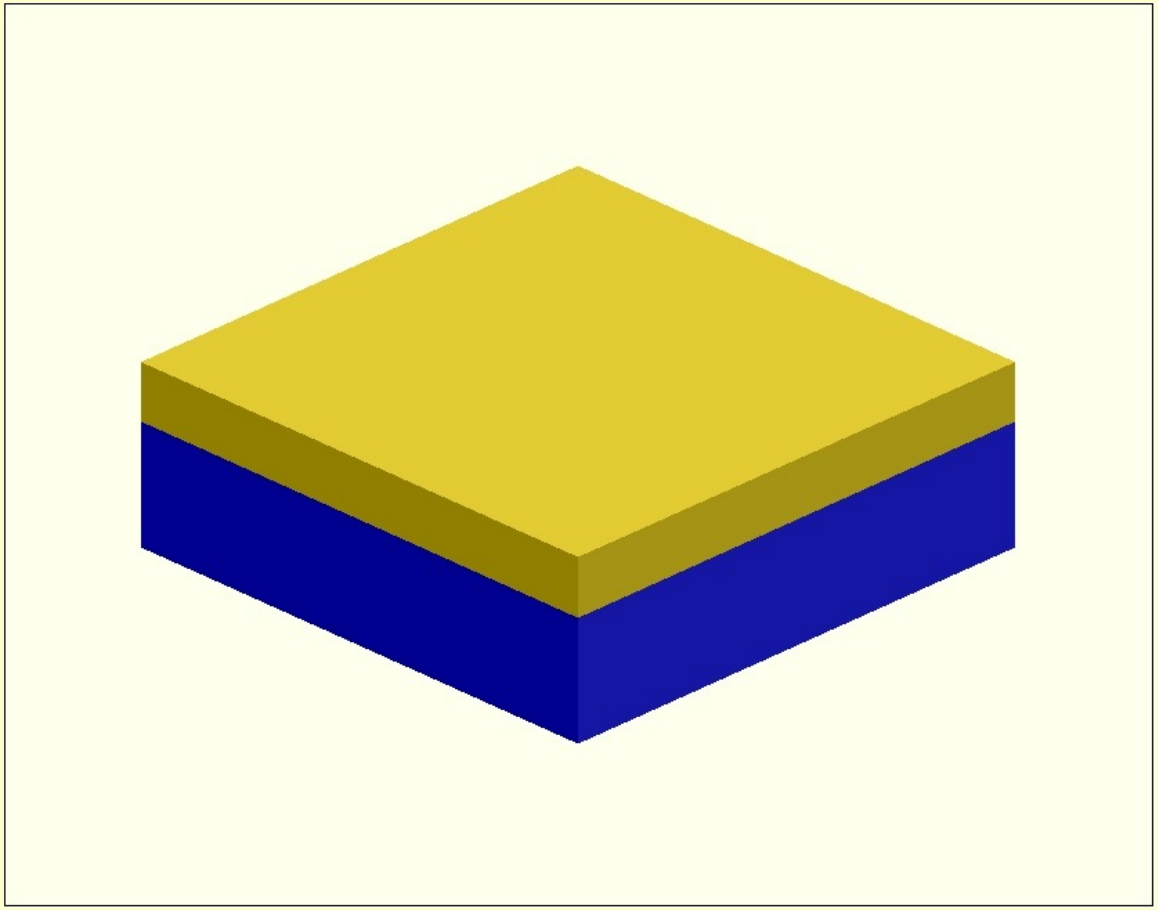
Trench Geometry
(Not to scale)



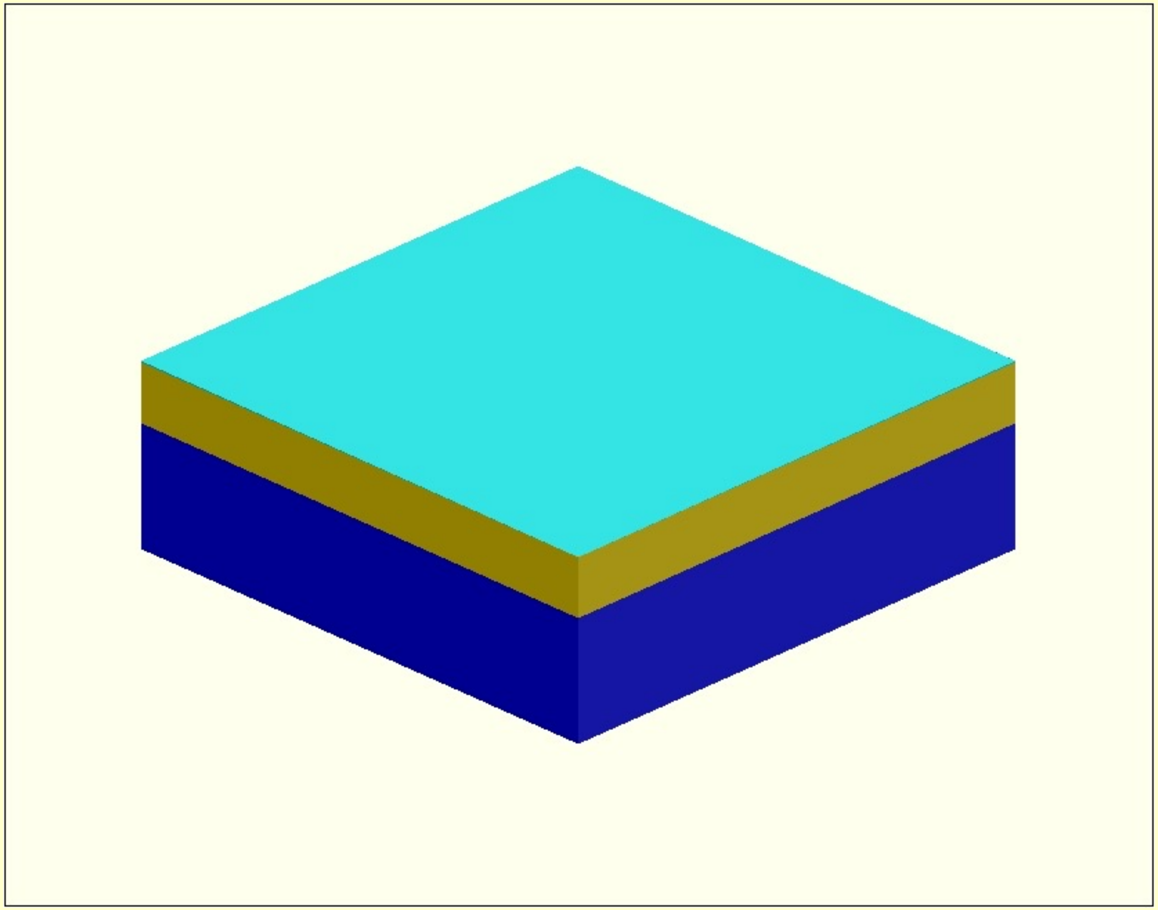
Fabrication
(Silicon wafer)



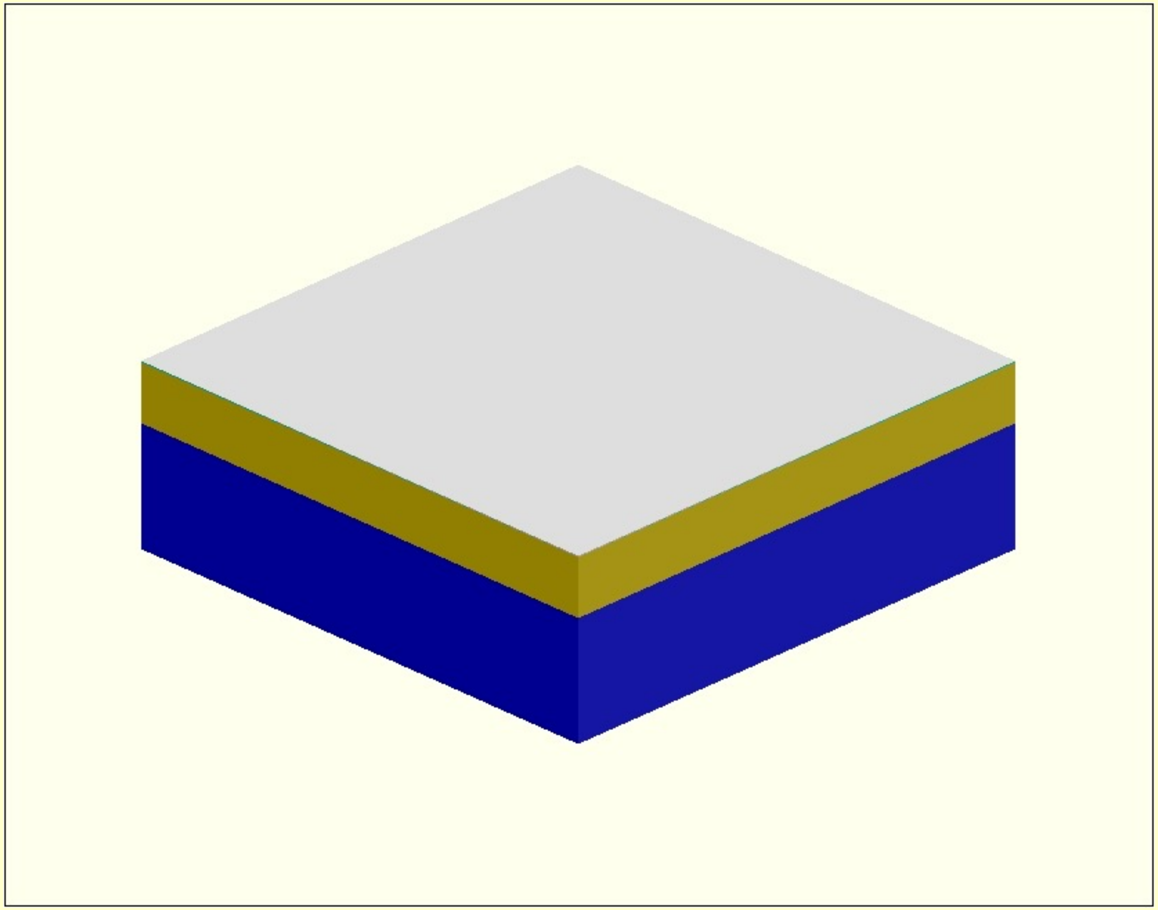
Fabrication
(PI 5878G)



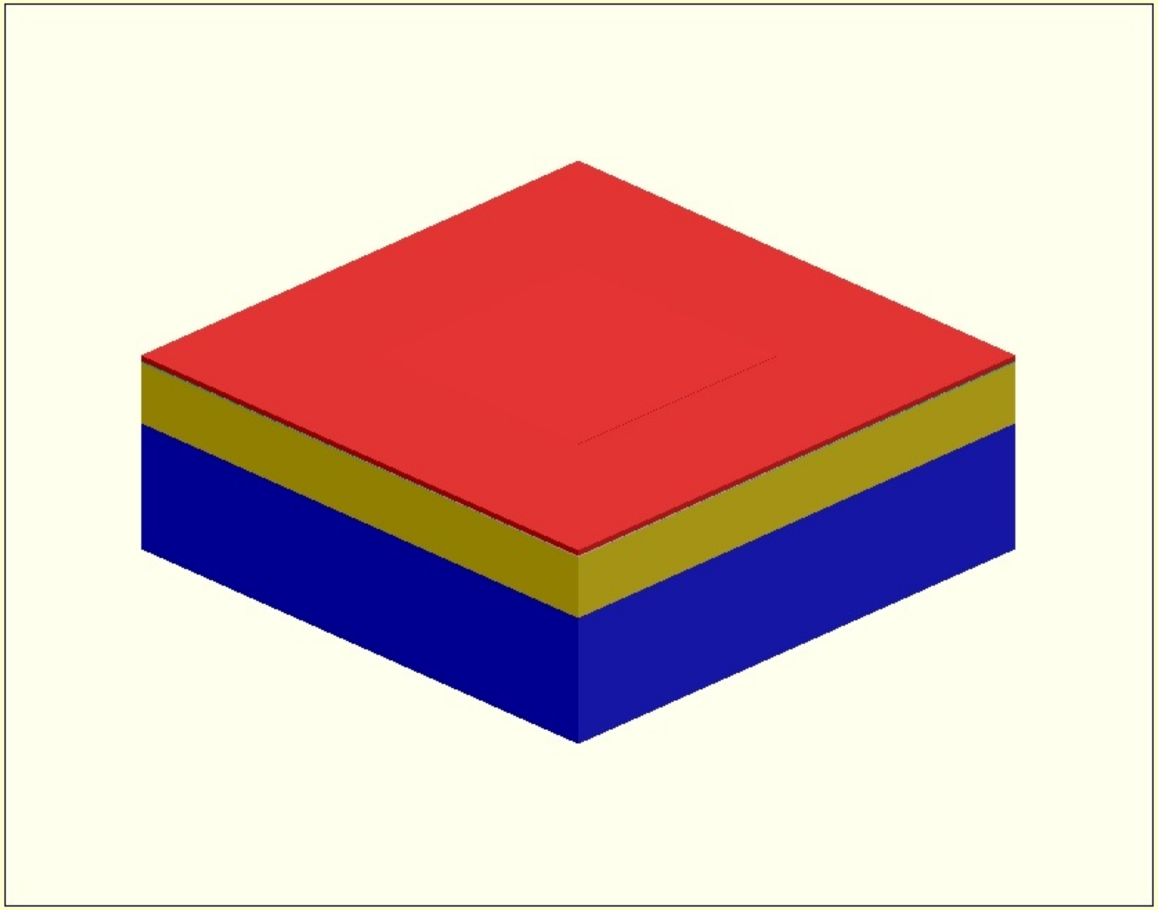
Fabrication (Nitride)



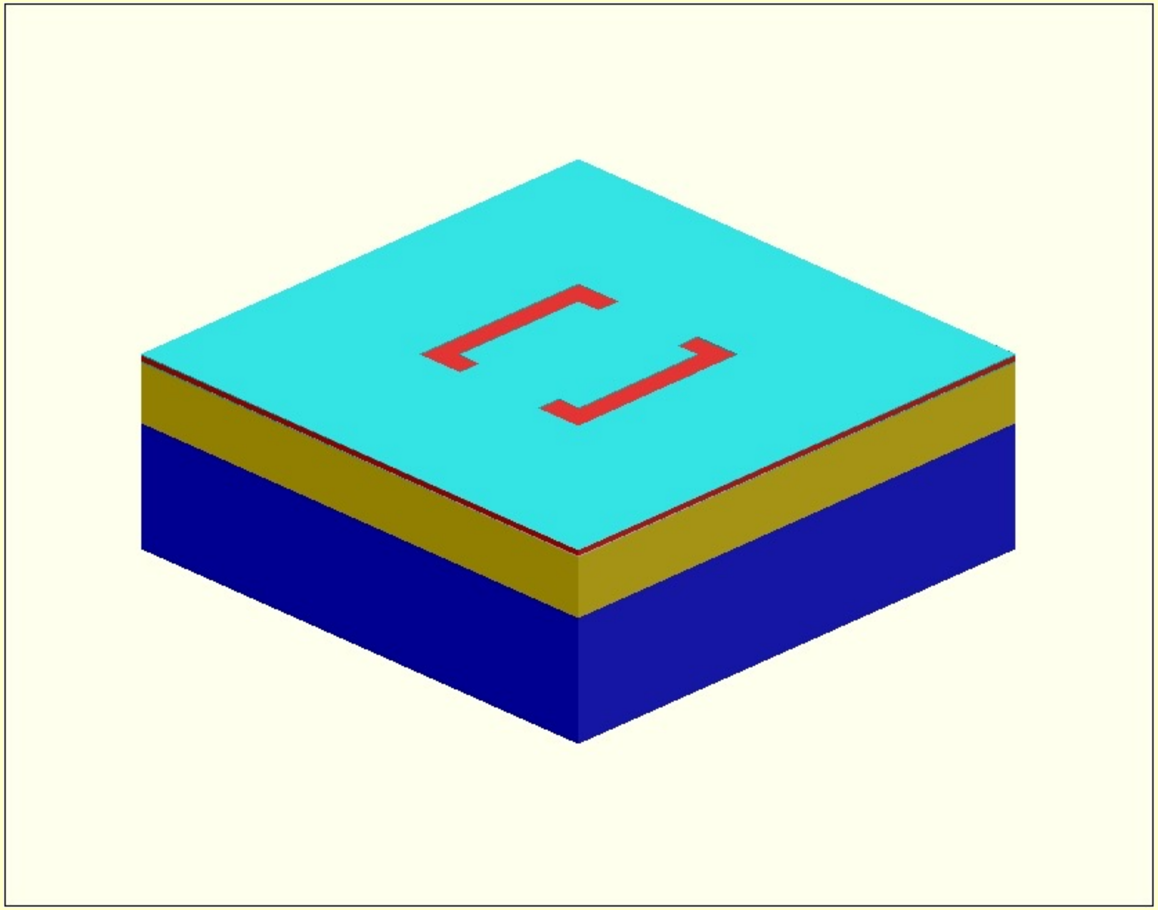
Fabrication
(Al)



Fabrication
(Sacrificial Polyimide PI 2610)



Fabrication (Support Nitride)



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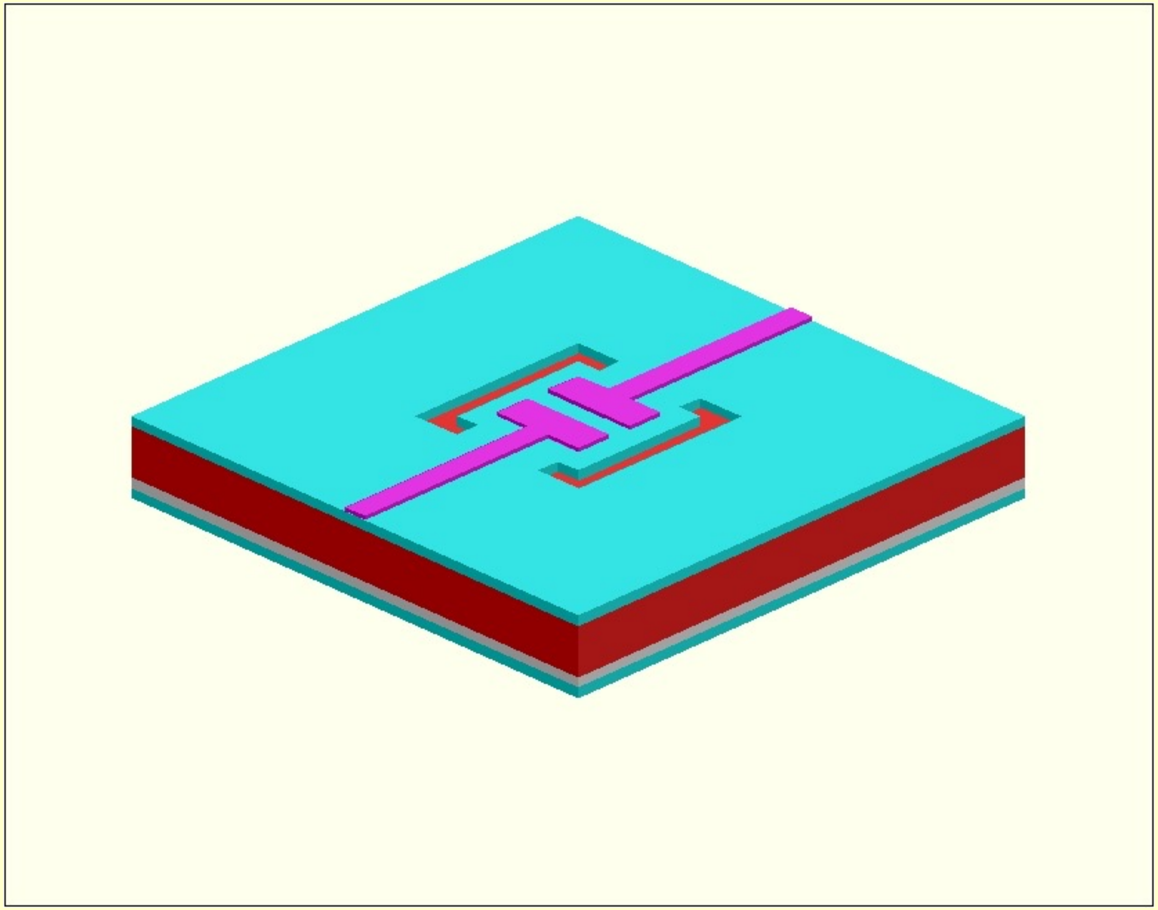
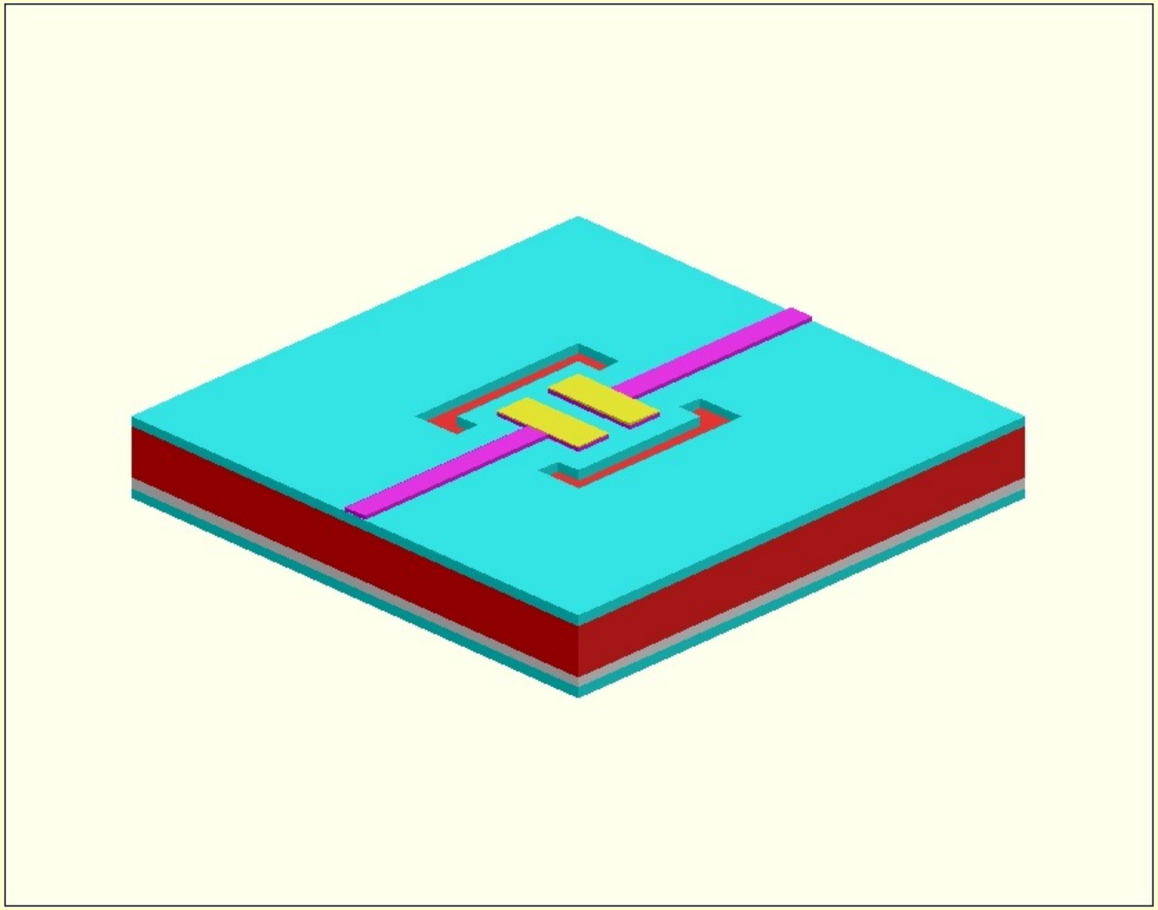
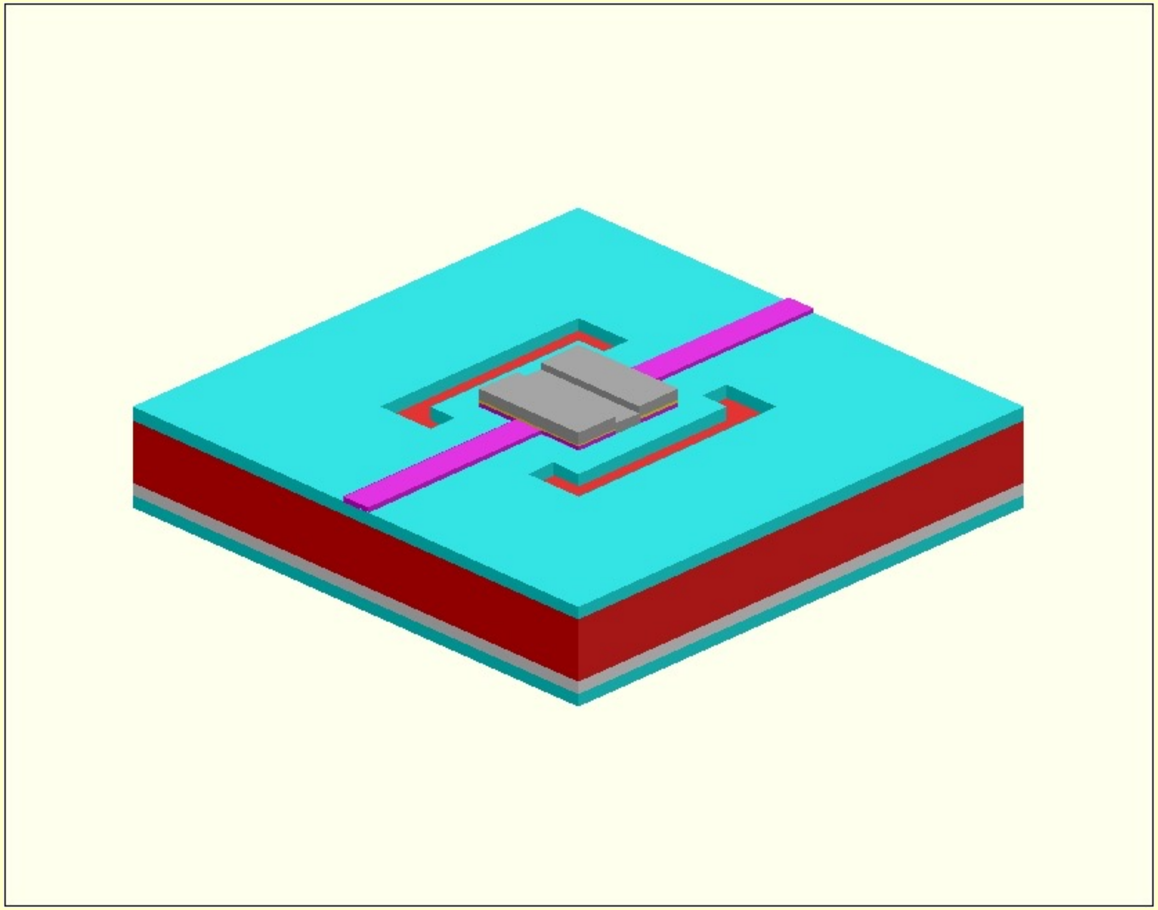
Fabrication (Ti arms)



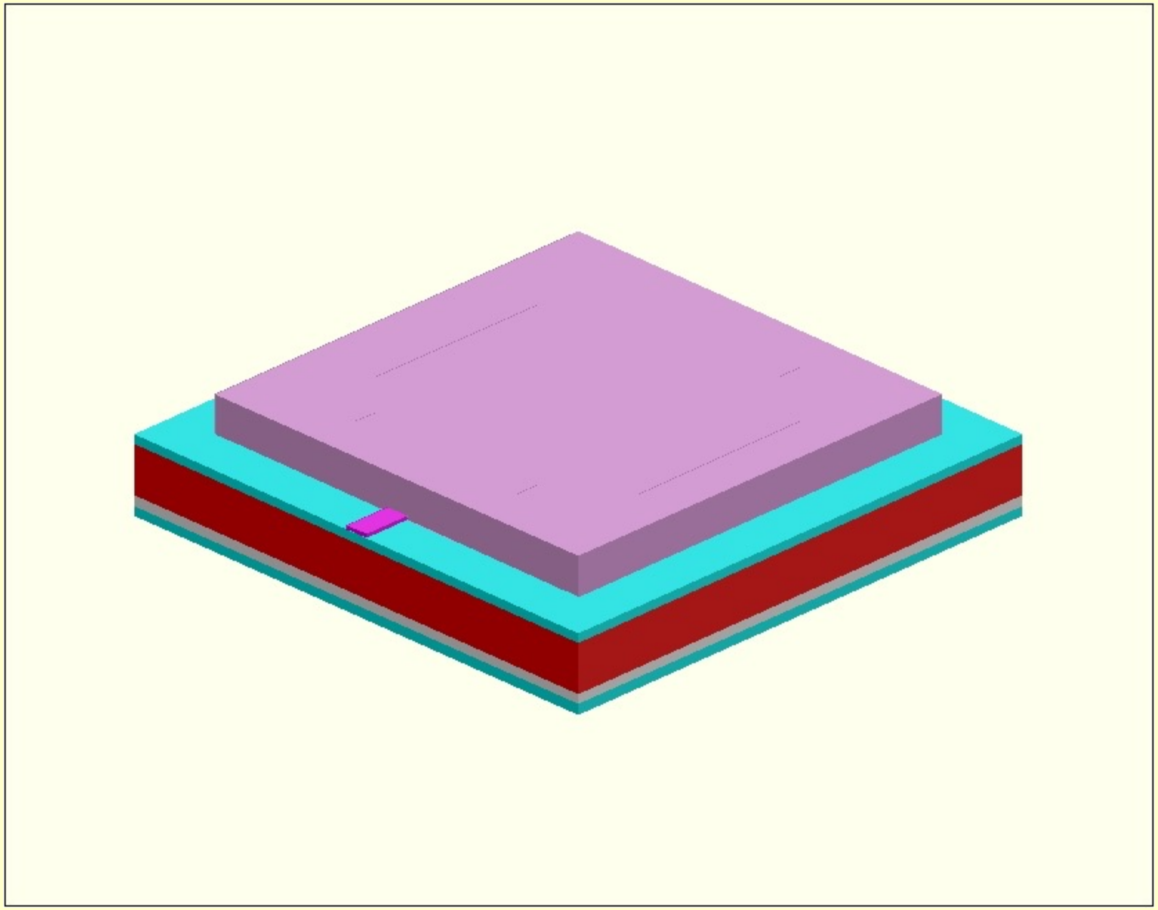
Fabrication
(Au contacts)



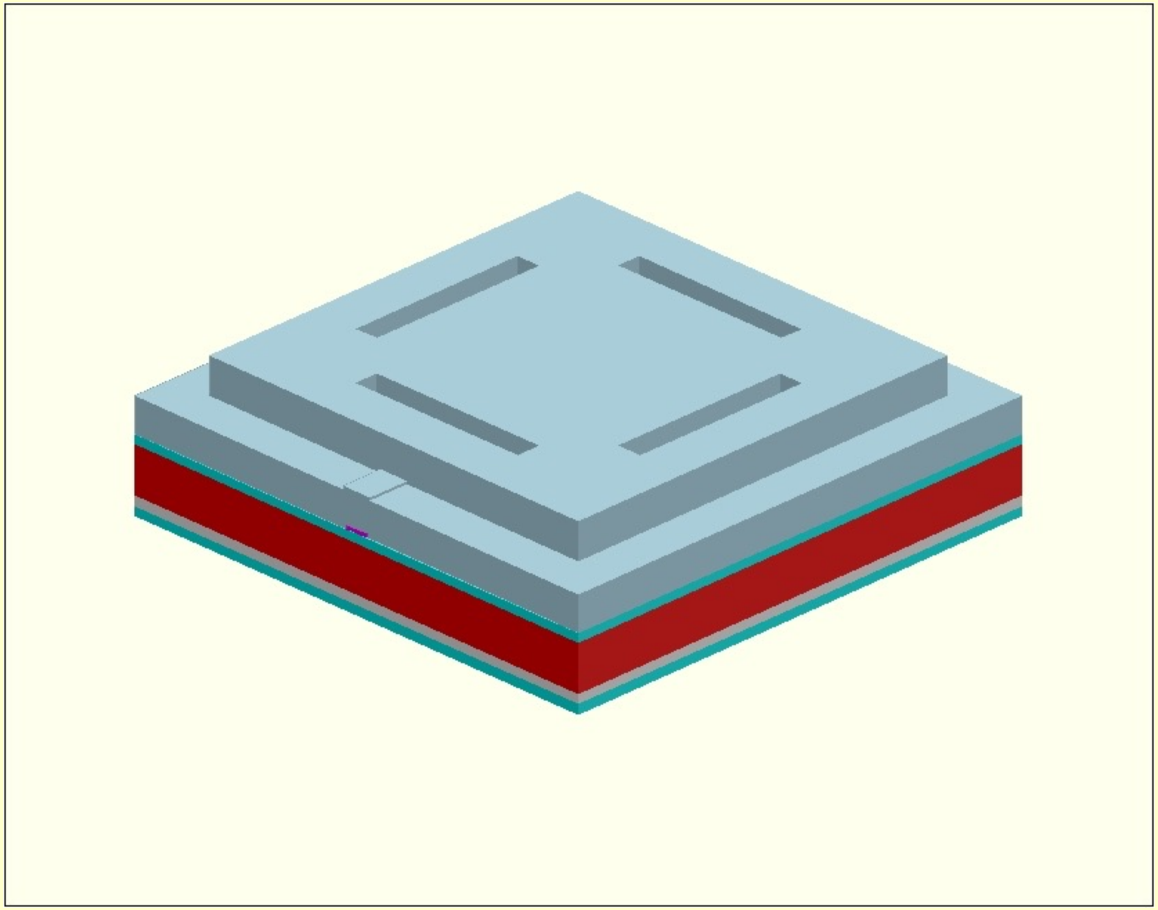
Fabrication
(YBCO detector pixel)



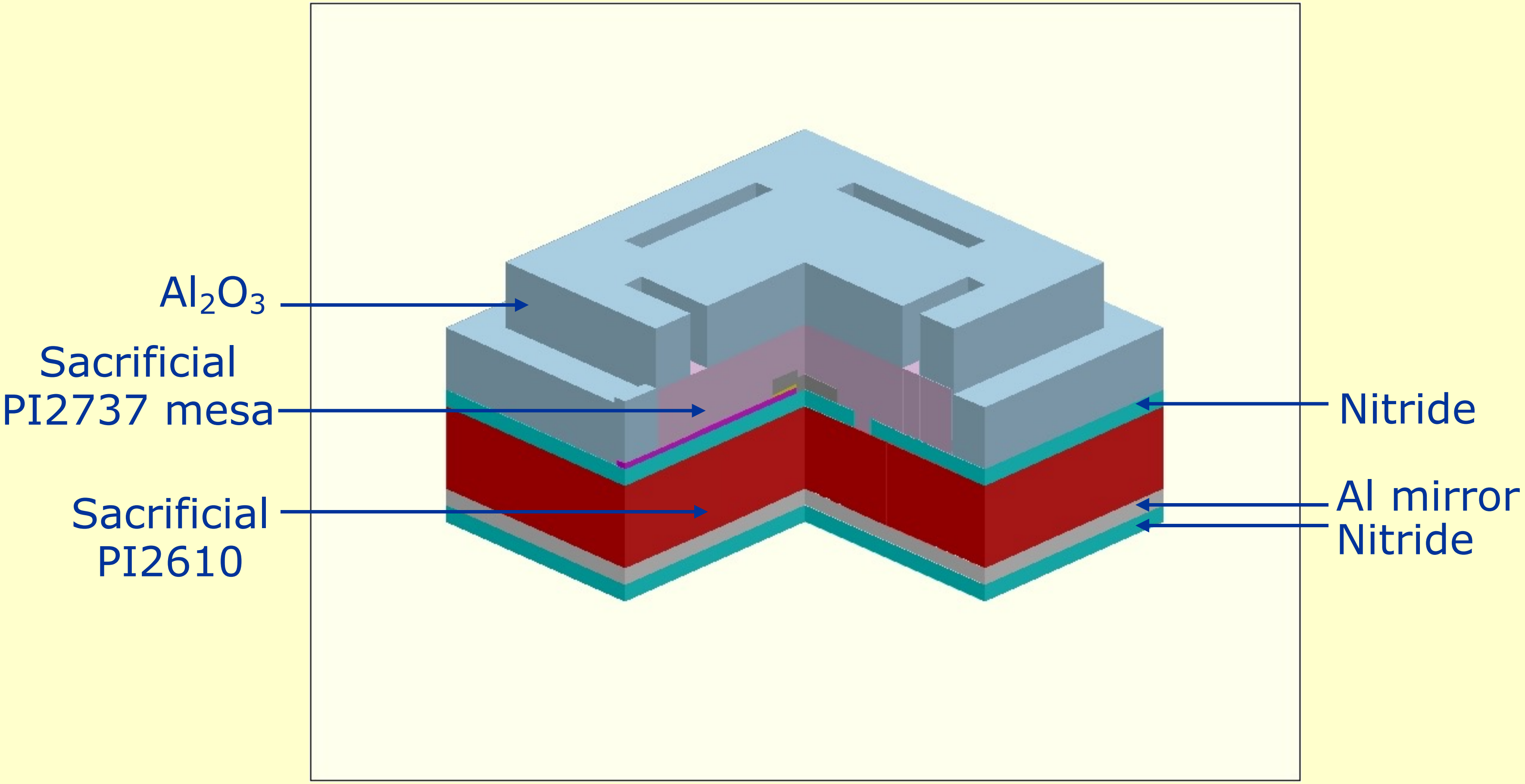
Fabrication
(Photodefinable PI2737 sacrificial mesa)



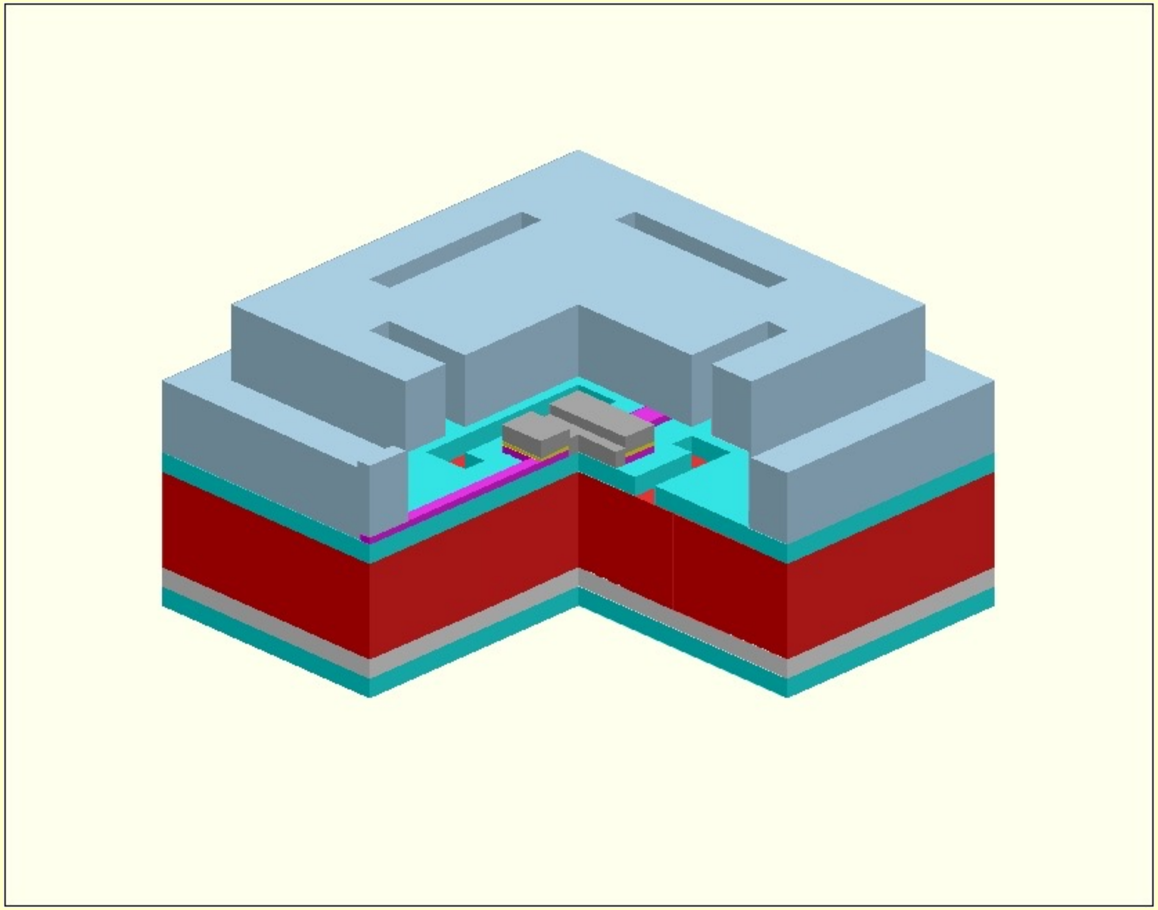
Fabrication
(Al_2O_3)



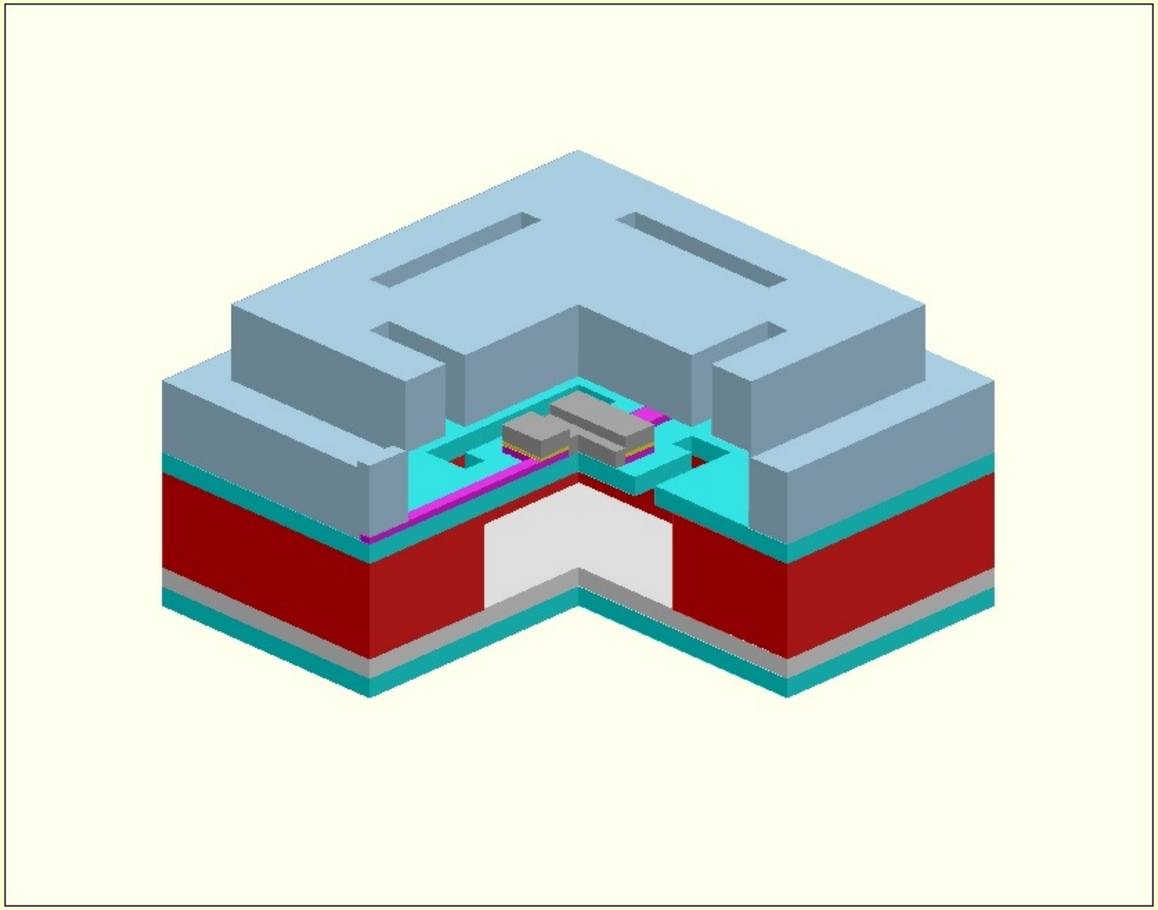
Section of vacuum cavity before micromachining



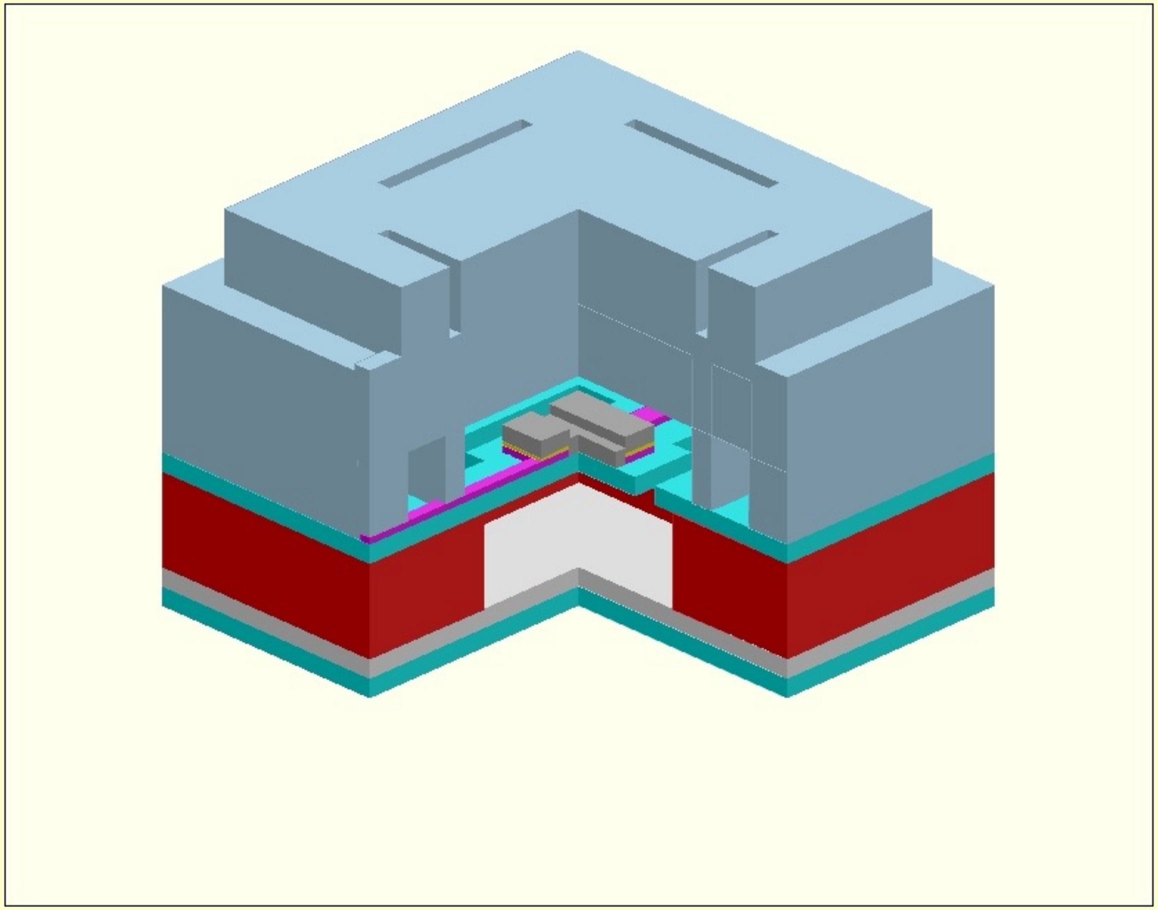
Fabrication
(Partially micromachined)



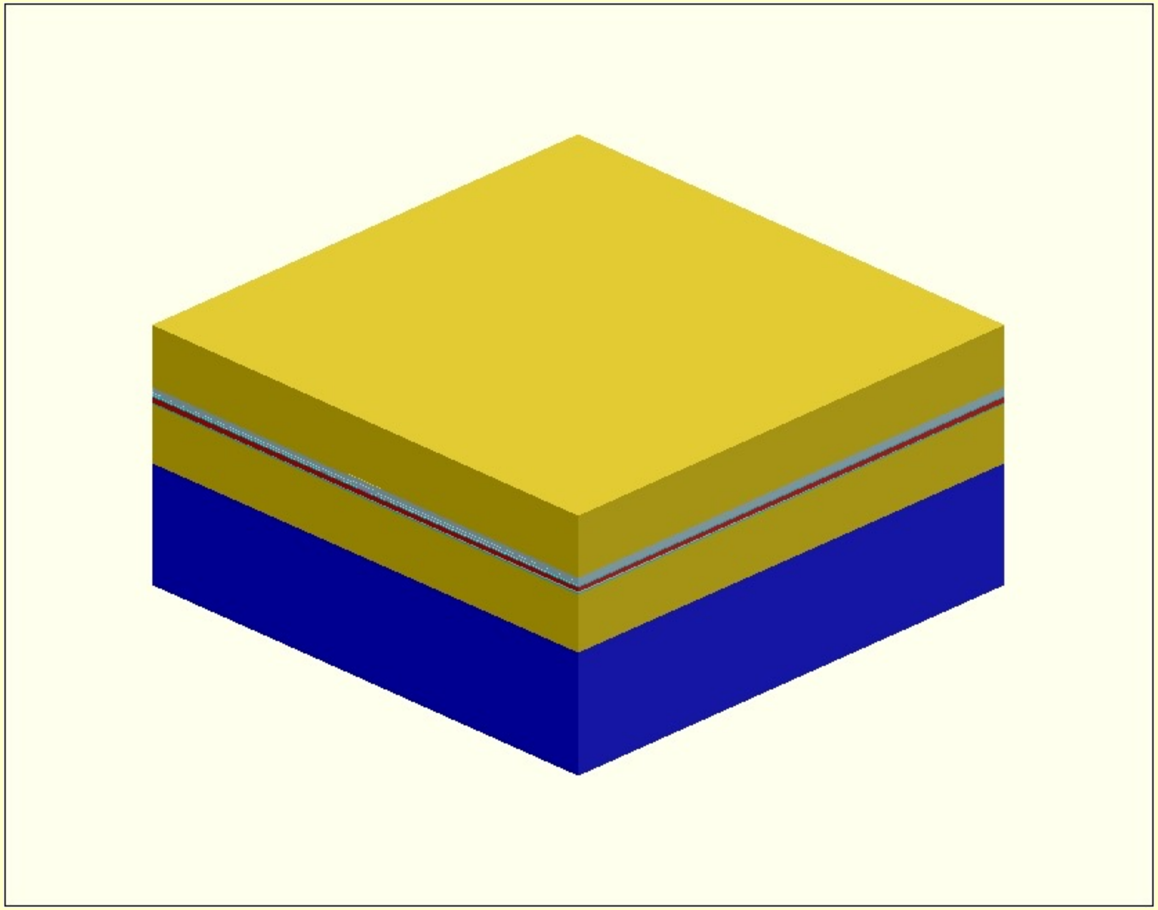
Fabrication
(Fully micromachined)



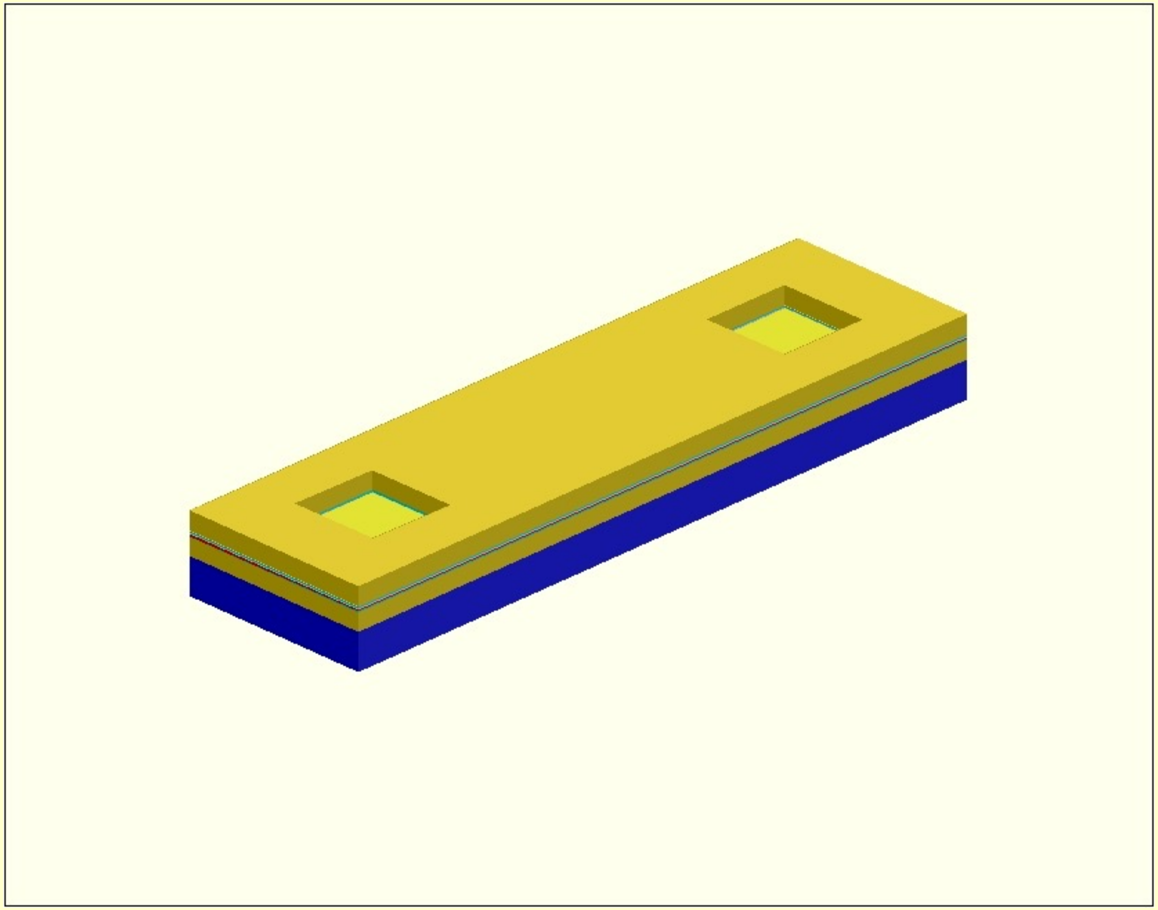
Fabrication
(Sealed vacuum cavity)



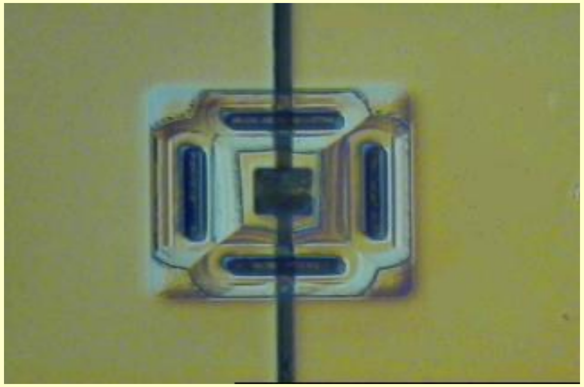
Fabrication
(Superstrate PI 5878G)



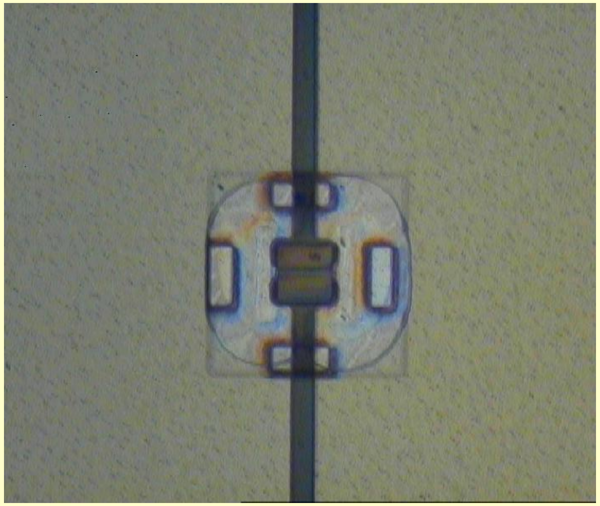
Single microbolometer



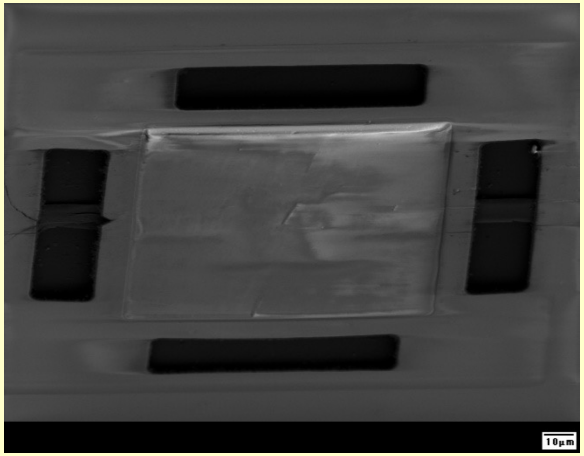
Fabrication of encapsulated devices



Partially micromachined device

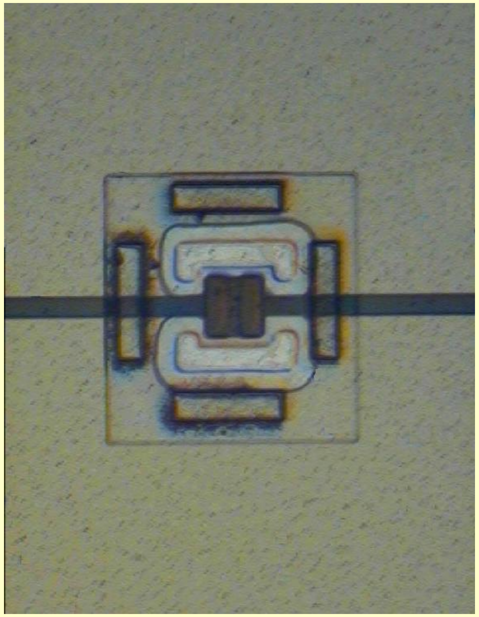


Fully micromachined device

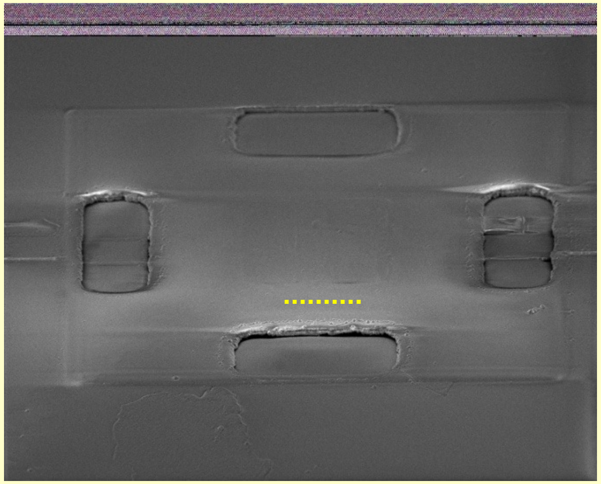


SEM graph of an unsealed micromachined device

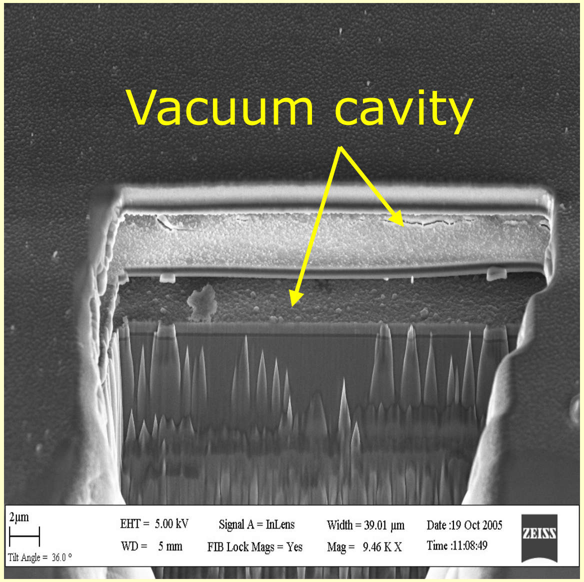
Fabrication of encapsulated devices



Sealed device

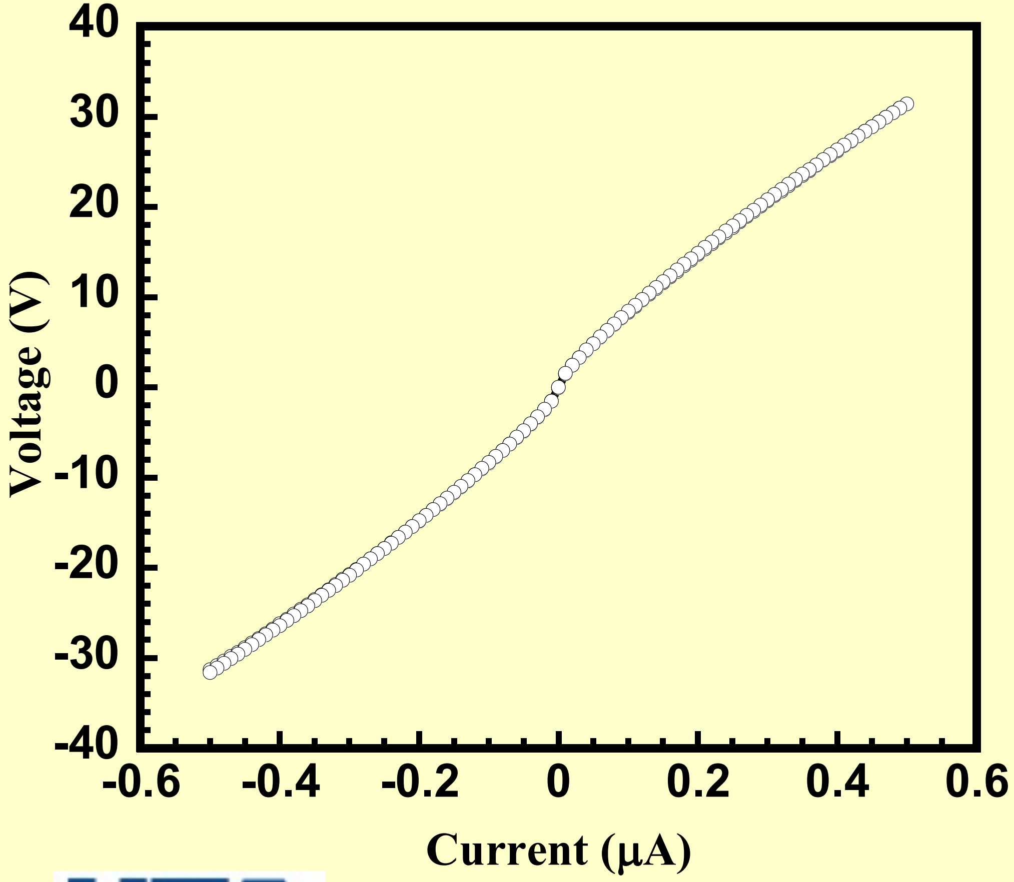


SEM graph of sealed device



SEM graph of cross section of vacuum cavity

VI curve

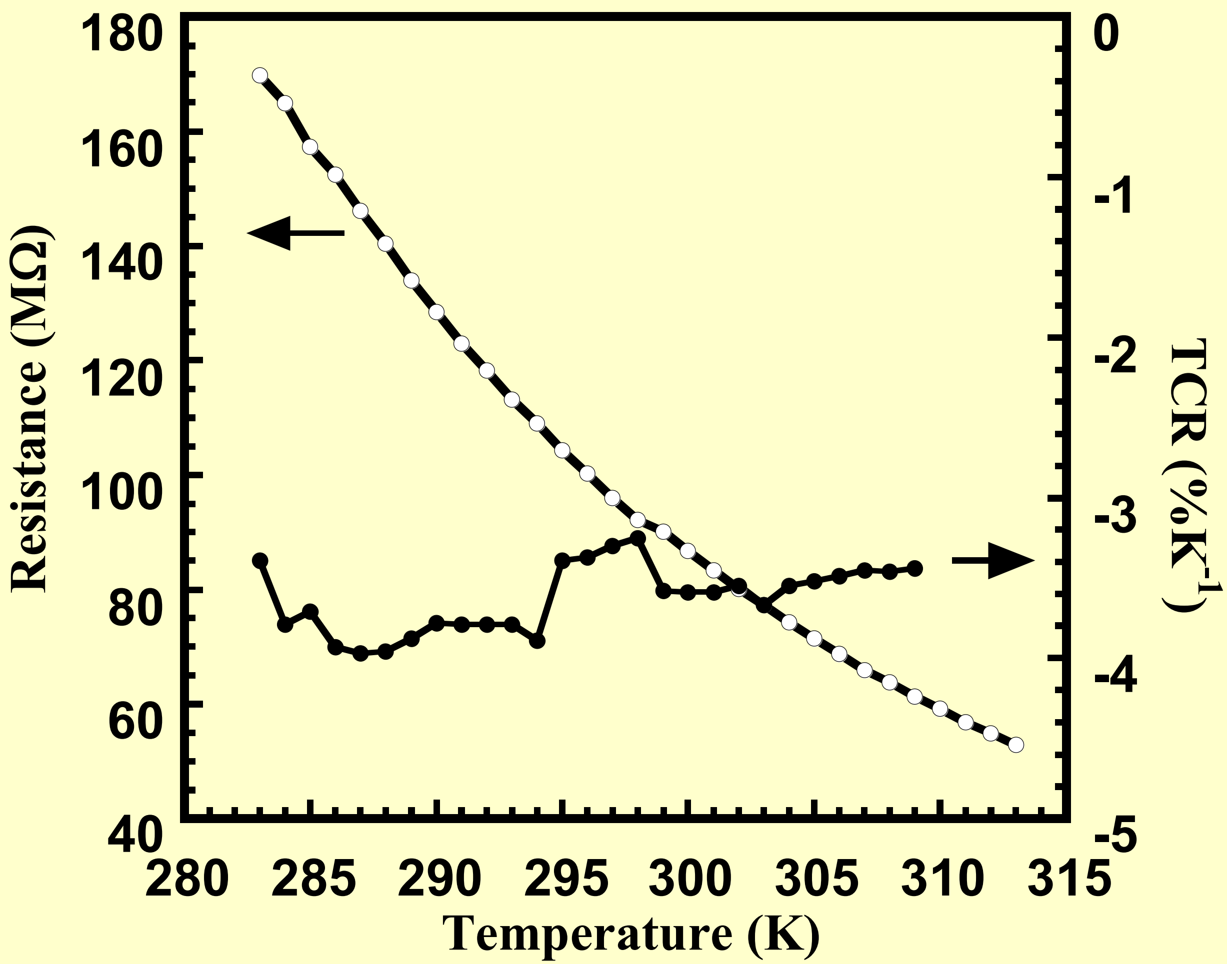


Measured G_{th}=3.73x10^{-6} W/K

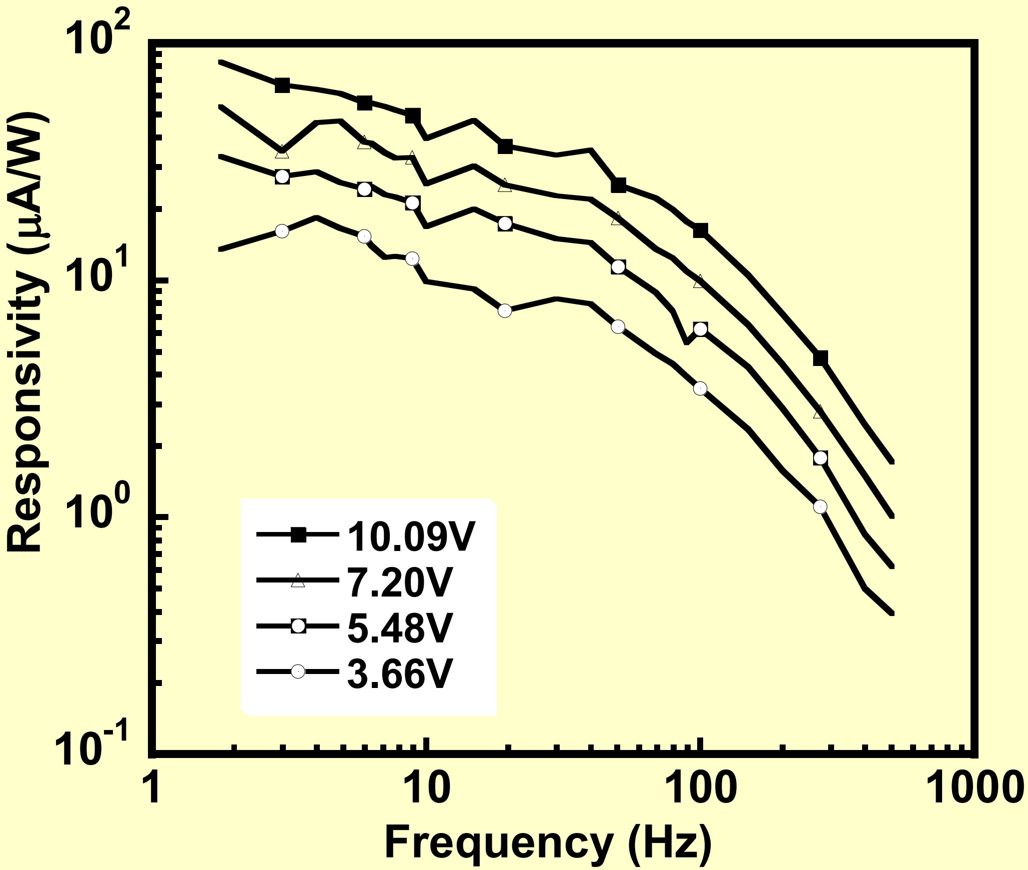
Temperature Coefficient of Resistance (TCR)

R(300K)=53.4 MΩ

TCR(300K)=-3.7%/K



Current Responsivity (R_I)



Current Responsivity (R_I)

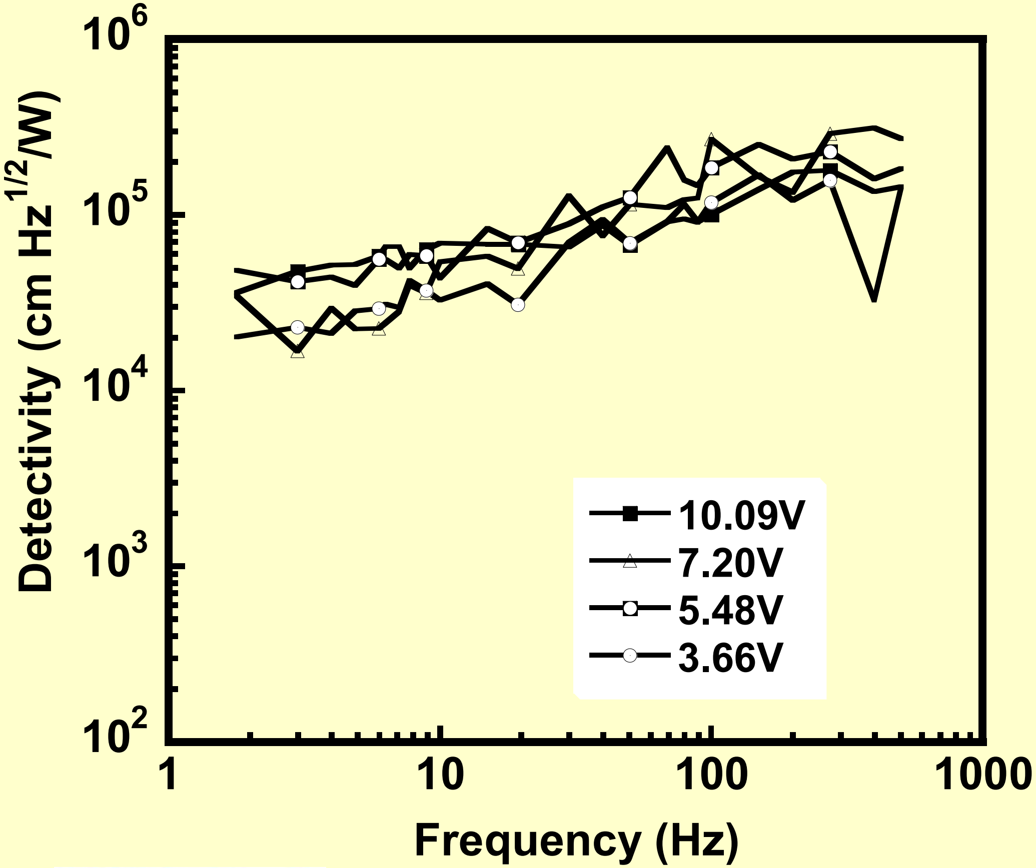
=Output current/Input power

R_I=61.3 μA/W

@ 5Hz

UTA

Detectivity (D*)



Detectivity (D*)

= Area and frequency normalized signal to noise ratio

D* = 1.76×10^5 cm-Hz$^{1/2}$/W

Conclusion

- Device level vacuum encapsulated microbolometers on flexible substrates have been fabricated

- Theoretical thermal conductance in vacuum is $5x10^{-6}$ W/K
- Measured thermal conductance is $3.73x10^{-6}$ W/K (Intact Vacuum cavity)

- Measured room temperature TCR is -3.7%/K, resistance is 53.4MΩ

- Measured R_I is 61.3 μA/W, D*=$1.76x10^5$cm-$Hz^{1/2}$/W

UTA

- This work is supported by the National Science Foundation

The End