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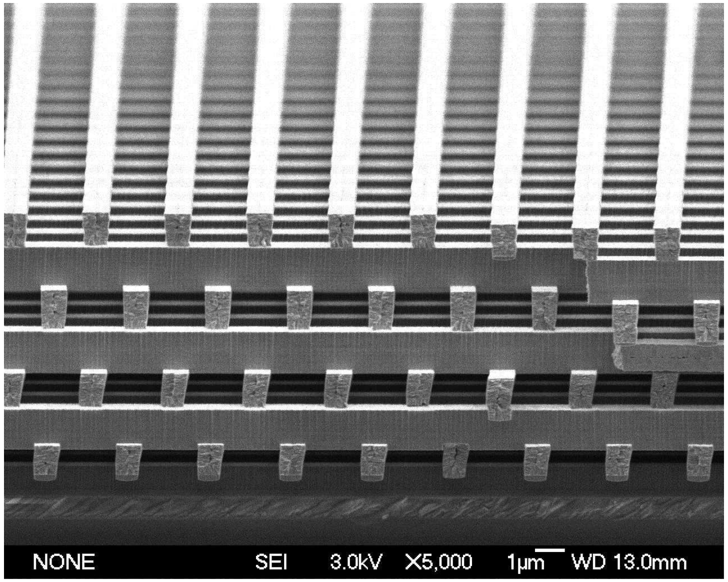
Emissivity measurements of 3D photonic crystals

Sandia National Laboratories

T.S. Luk



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Outline

- Why do we want to measure emissivity?
- Measurement methodology.
- Comparison with numerical models.
- Summary.

Why do we want to measure emissivity?

Important for :

- Thermo-photovoltaic applications: emissivity, material stability under heated environment, surface effects.
- Study the coupling behavior of photonic crystal and the substrate.
- Studying non-equilibrium behavior of photonic crystal.

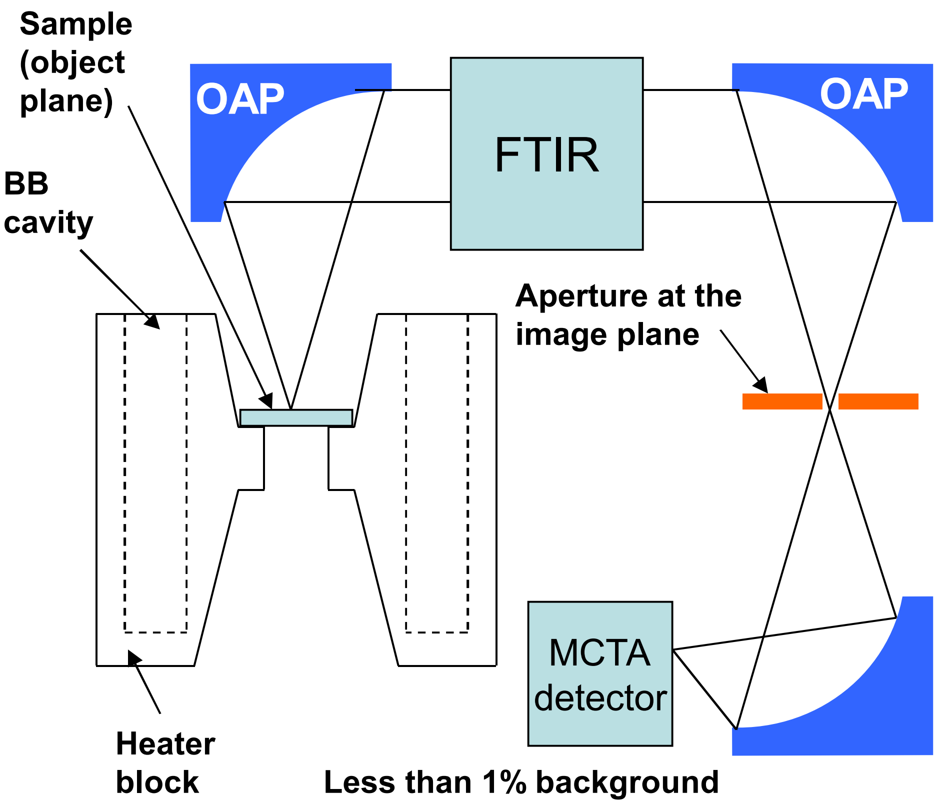
Emissivity measurement issues:

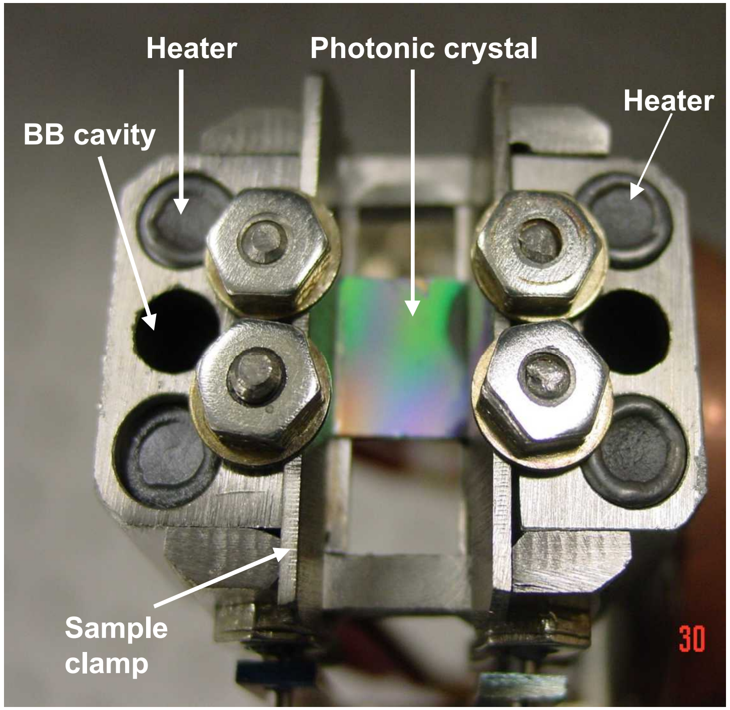
- Temperature of the emitter.
- Detector gain response.
- Detector spectral response.

Emissivity measurement methodology and setup

Methodology

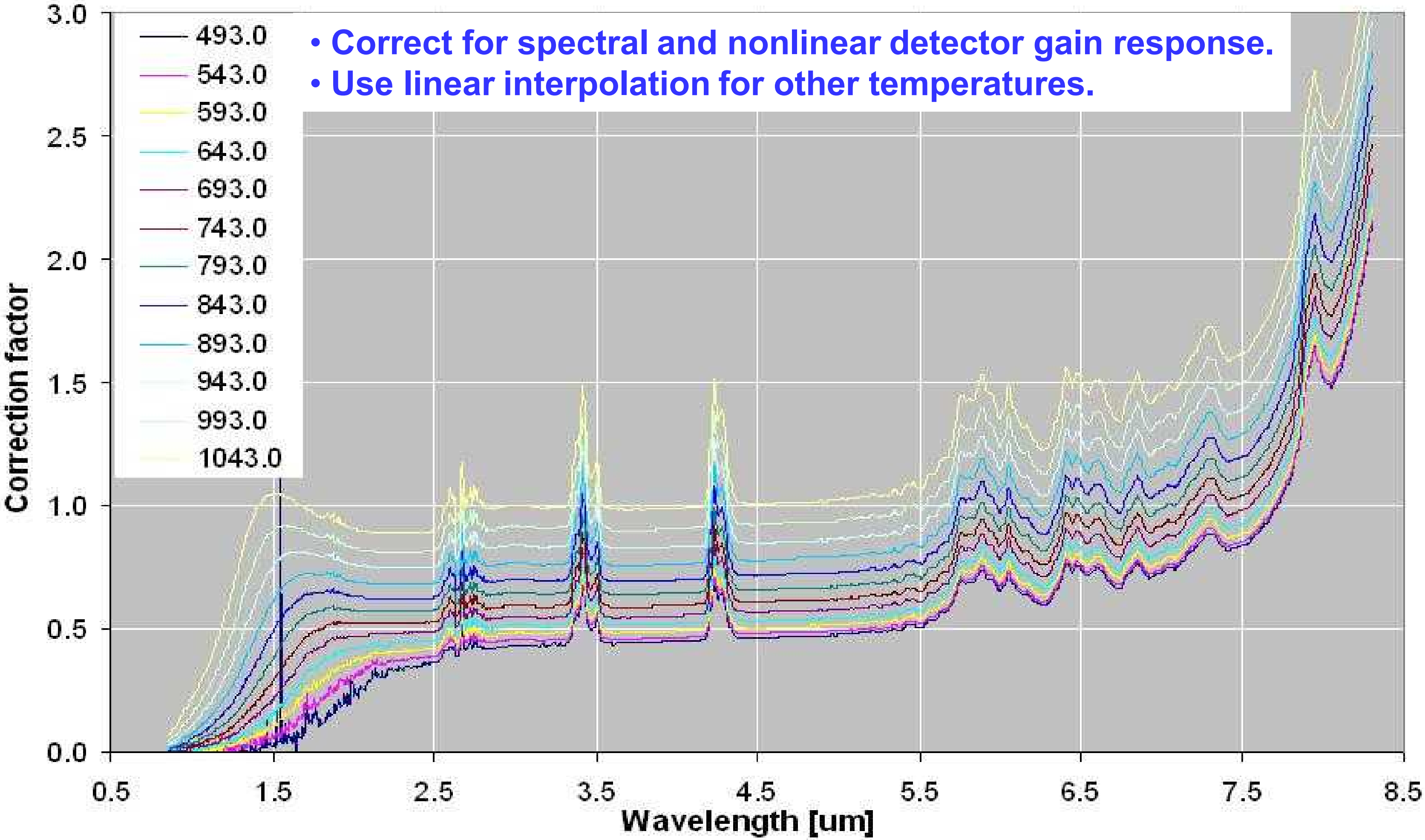
- Detector response is calibrated by a NIST traceable blackbody source.
- Temperature of the heater block is determined from the emission spectrum of the BB cavity.
- Sample surface temperature is determined by FEM thermal model.
- Emission spectra are corrected using cubic response function for each wavelength.





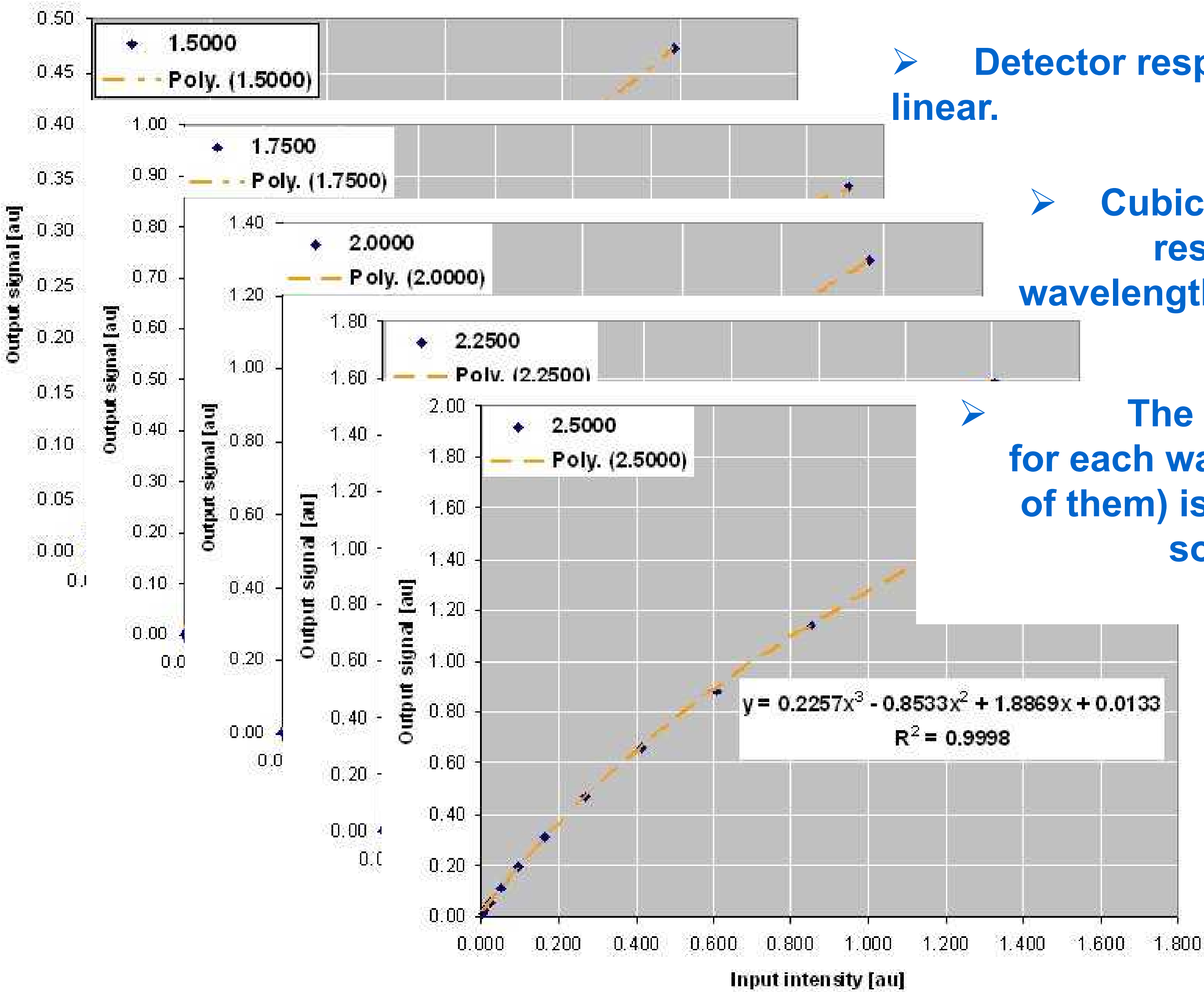
Detector calibration using NIST traceable blackbody source

Emissivity = 0.995+/-0.005
Temperature uncertainty +/- 1 deg.K



Spectral intensity correction

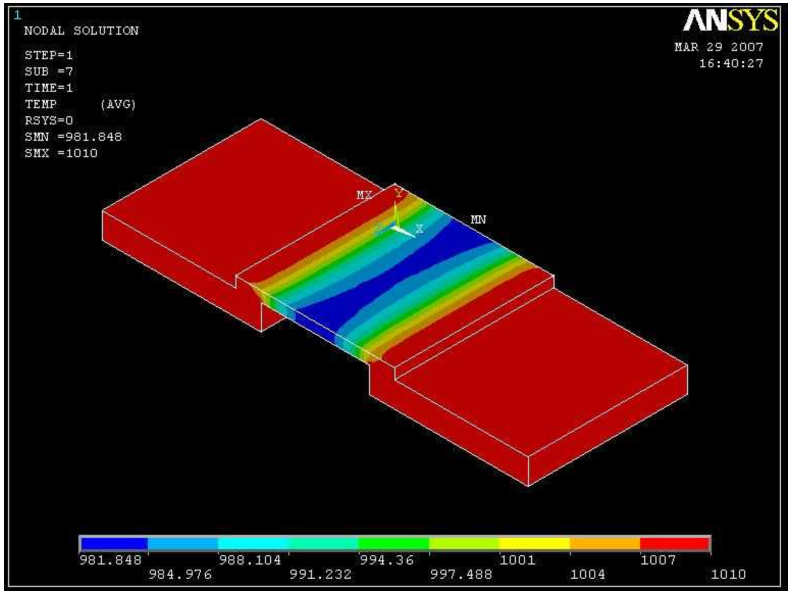
- Detector response is non-linear.
- Cubic fit the detector response for each wavelength (1490 points).
- The actual intensity for each wavelength (1490 of them) is determined by solving the cubic equation.

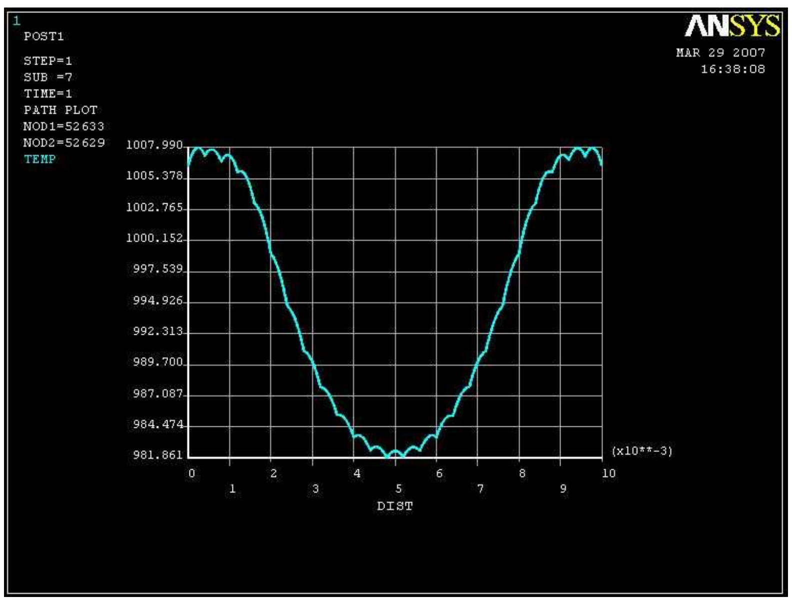


Detector signal correction, temperature determination and black paint emissivity

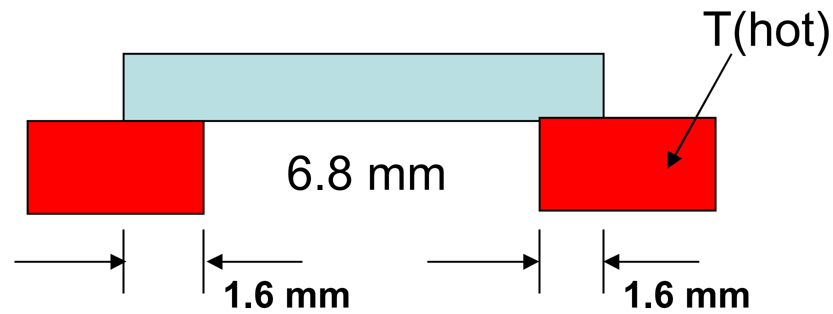
	Linear interpolation correction	Cubic fit correction scheme
Temperature of the BB cavity at 65 volt heating	1015	1013
Temperature of the BB cavity at 45 volt heating	842	841
Temperature of the paint at 65 volts heating	945	940
Temperature of the paint at 45 volts heating	808.5	809
Emissivity of HiE paint at 809K at 5um	1.00	0.994
Emissivity of HiE paint at 940K at 5 um	0.989	0.987

Thermal analysis





Silicon thickness=653 um



- ➢ **Heat loss from the silicon is by radiation with emissivity in accordance to its temperature.**
- ➢ **Use room temperature thermal conductivity.**

Heater block temp [K]	Emissivity (silicon)	Emissivity (paint)	Top center temp [K]	Top center average temp [K]	Conductivity W/(m*K)	Temp ratio
1010	0.71	1	978.098	980.08	9	0.970
1010	0.71	1	977.072	979.23	6	0.970
1010	0.71	1	976.38	978.9	3	0.969

Heater block temp [K]	Emissivity	Top center temp [K]	Top center temp averaged over 2mm [K]	T ratio
612	0.1	611.8	611.8	0.9997
737	0.425	734.8	734.9	0.9971
847	0.68	839.1	839.4	0.9910
930	0.71	914.7	915.2	0.9841
1010	0.71	981.8	982.7	0.9729

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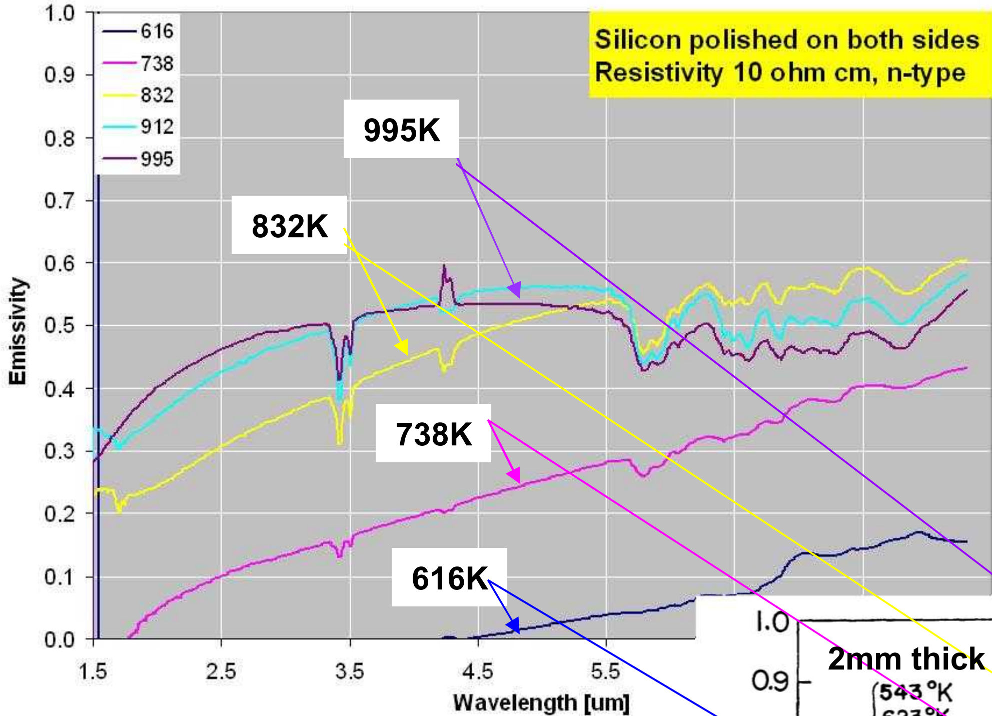
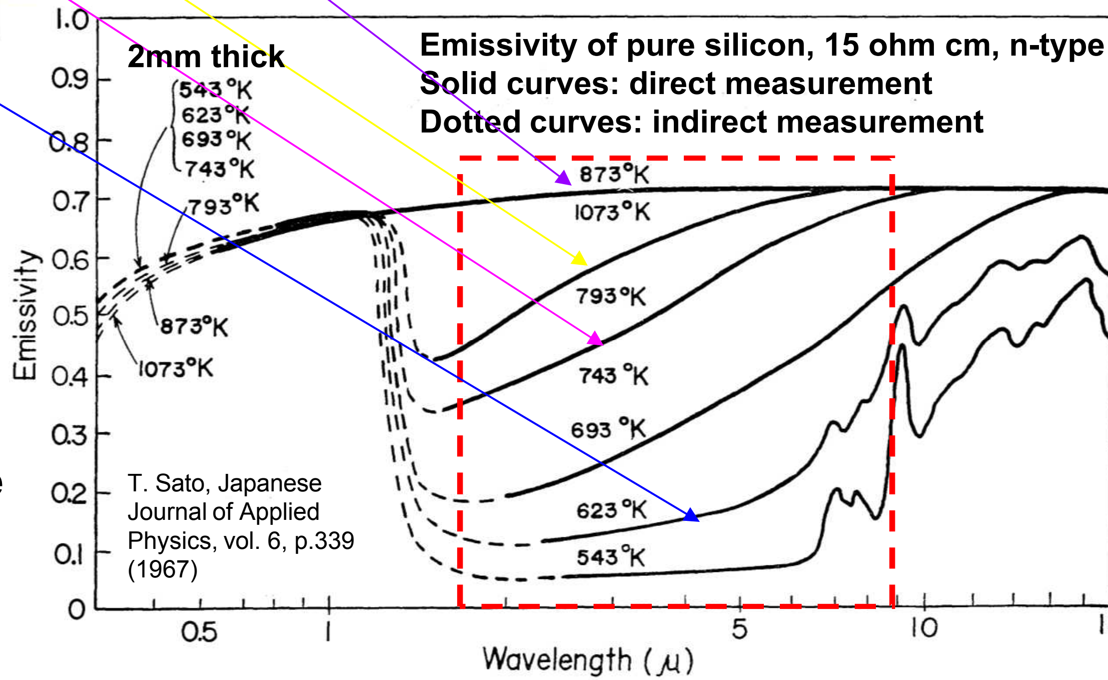
Emissivity of 10 ohm-cm n-type silicon, both side polished



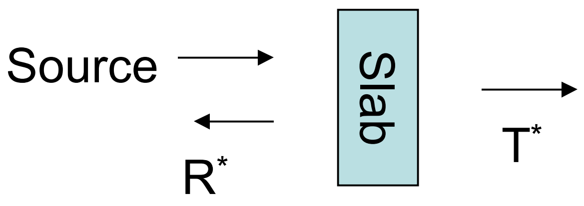
- Good qualitative agreement on temperature dependence.
- We measure 0.55 versus published value 0.71.
- Poor agreement in the short wavelength region.



Possible reasons for the discrepancy

- Actual temperature has to be 43K colder thermal model calculation which is not supported by thermal model.
- Material properties difference such as thickness of the sample, oxide thickness and resistivity.

Emissivity model: plane parallel



Conservation of Energy

R+A+T=1

For Transmissivity T=0,
then we have

Kirchoff's Law

emissivity E = 1-R

For transmissivity T not equals to 0, then we have, where

R is the reflectivity of an interface, and R^* is the reflectivity of the slab (apparent reflectivity),

T is the transmissivity of an interface, and T^* is the transmissivity of the slab (apparent transmissivity).

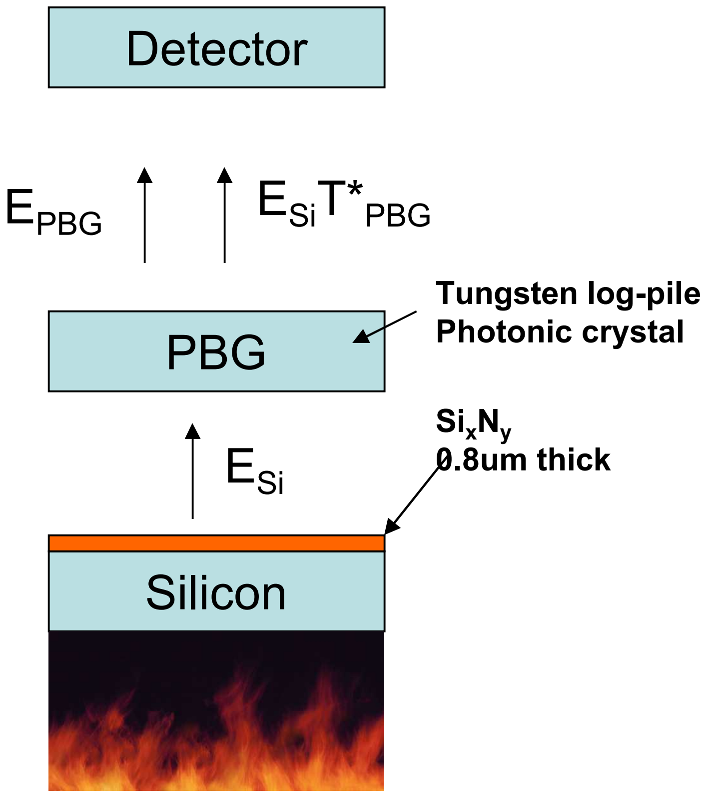
$$E(\lambda, t) = \frac{\{1-R(\lambda, t)\}\{1-T(\lambda, t)\}}{\{1-R(\lambda, t)\cdot T(\lambda, t)\}}$$

$$R^*(\lambda, t) = R(\lambda, t)\left\{1+\frac{T^2(\lambda, t)\{1-R(\lambda, t)\}^2}{1-R^2(\lambda, t)\cdot T^2(\lambda, t)}\right\}$$

$$T^*(\lambda, t) = T(\lambda, t)\frac{\{1-R(\lambda, t)\}^2}{\{1-R^2(\lambda, t)\cdot T^2(\lambda, t)\}}.$$

Since T and R may not be determined for PBG materials, only T^* and R^* can be measured.
Therefore, this model <u>cannot</u> be used for PBG materials.

Emissivity model: uncoupled system



Questions:
How does the Silicon and Si_xN_y film affect the emission properties?

How big is the etalon effect of photonic crystal?

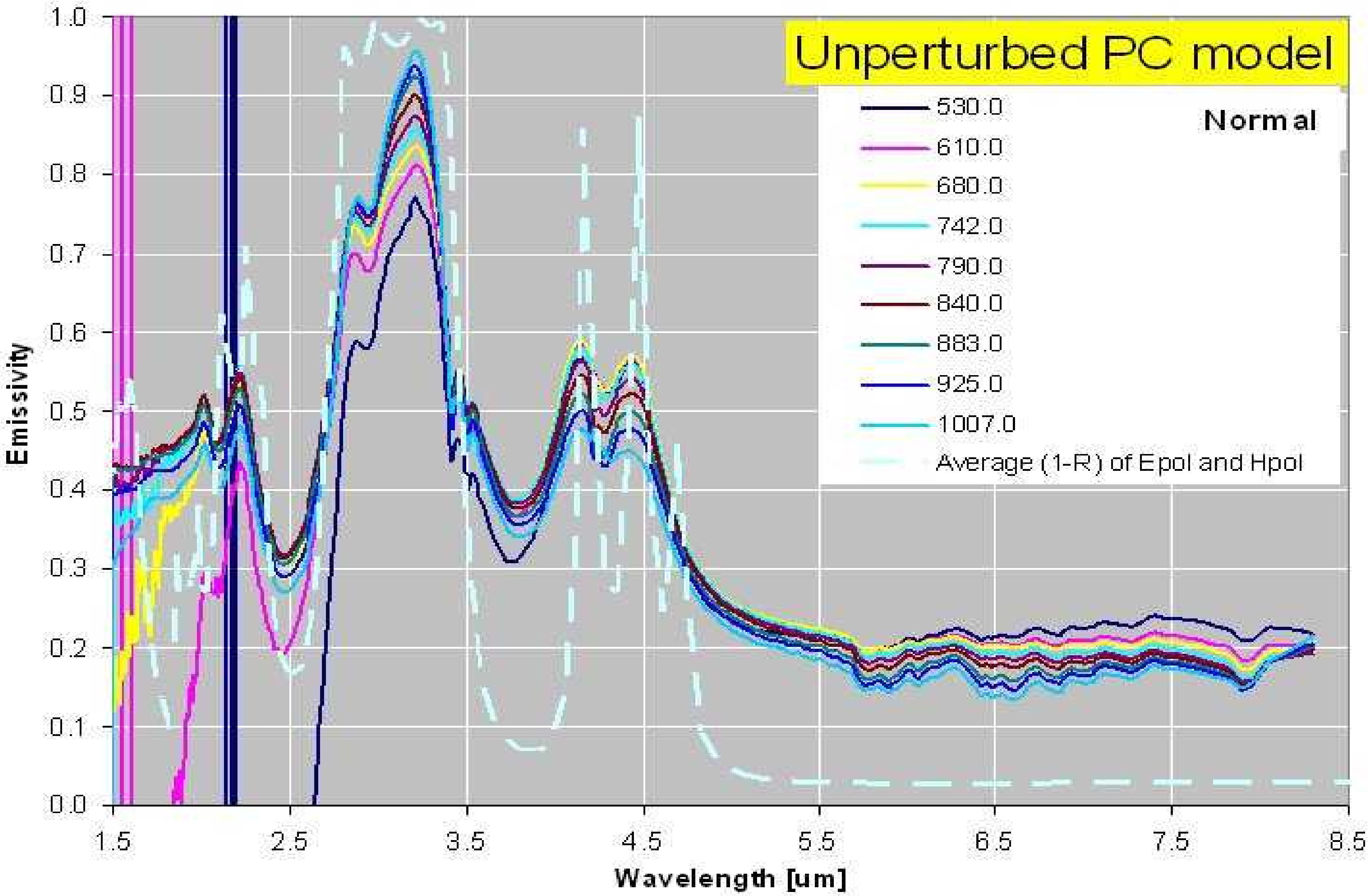
Measured emission
$= E_{PBG} + E_{SixNy\text{-}Si} T^*_{PBG}$

$= (1 - R^*_{PBG}) + (E_{SixNy\text{-}Si} - 1) T^*_{PBG}$

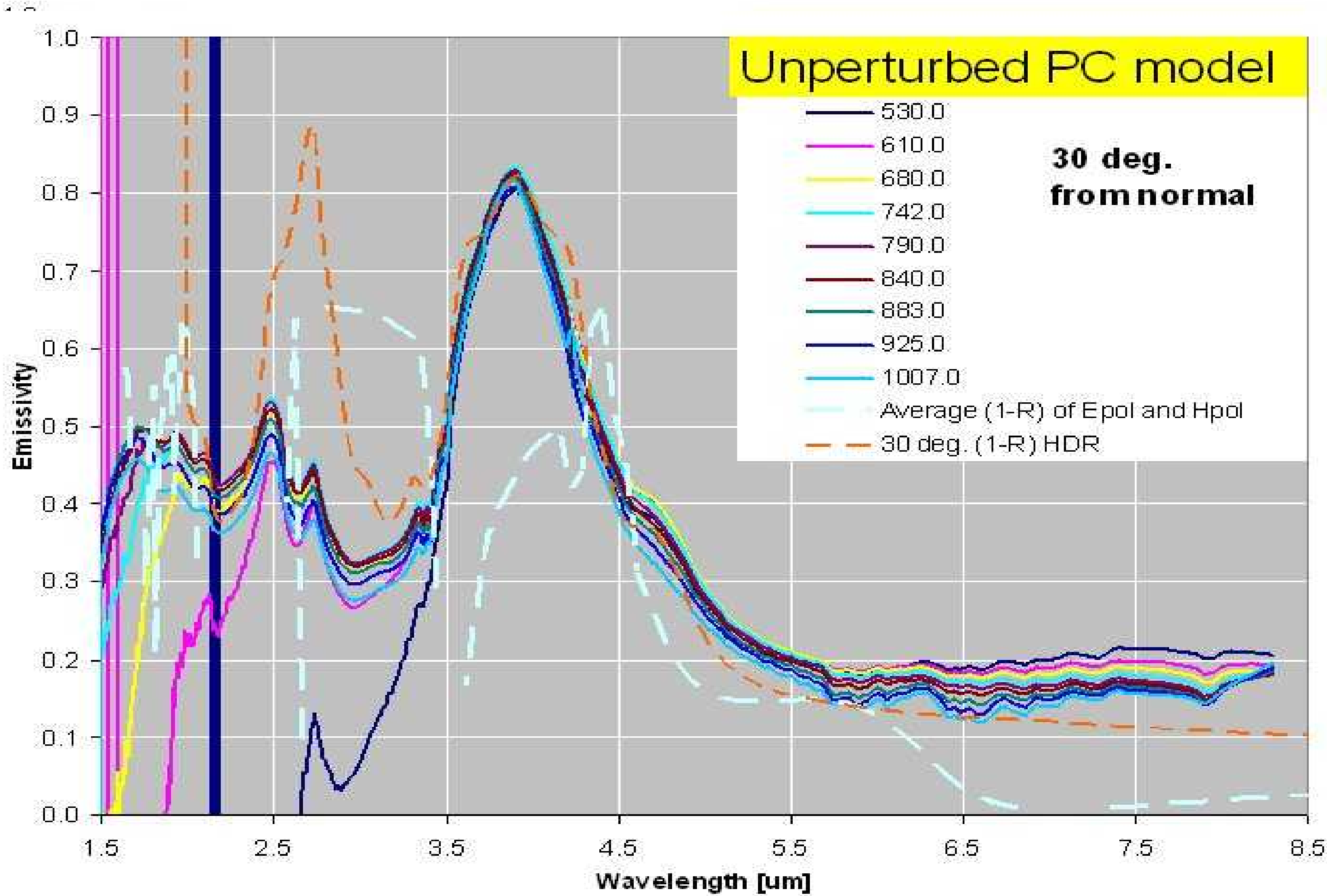
If $E_{SixNy\text{-}Si} = 1$

Measured emission
$= (1 - R^*_{PBG})$

Emissivity of photonic crystal



Angular dependence emissivity



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Error estimate

Temperatures

- Temperature error of the BB cavity +/- 2K.
- The error in the sample surface temperature needs further investigation. However, the observed temperature using black paint is colder than the model predicts which is the wrong direction.
- Thermal model provides guidance but not sufficient to accurately determine the sample temperature.
- Need to use NIST traceable emissivity material for temperature determination.

Bench method

- Black paint emissivity, no published data (manufactured data better than 0.9).
- We measure 1.0 to 0.98
- Silicon emissivity (published as 0.71).
- We measure 0.58, below published value by 0.16.

Summary

- PC emissivity agrees with (1-R) calculation, which implies that it is not perturbed by the supporting silicon substrate.
- Also good agreement with the HDR (1-R) measurement.
- Emissivities of off-normal directions have only qualitative agreement with theory.
- More work need to be done to determine the sample temperature more accurately. Perhaps NIST traceable standard emissivity will help.