Thermal Vacuum Testing and Feasibility Investigations for VO_2-Based Variable Emittance Coatings

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Presented By
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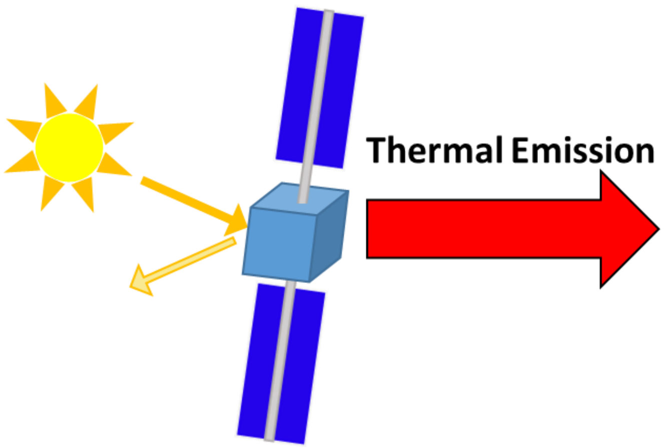
Outline

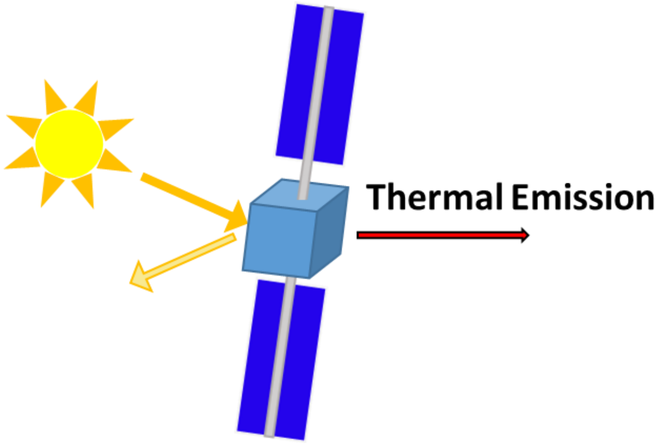
- Background and Motivation
  - Thermochromic variable emissivity passive thermal control
  - Characteristics of vanadium dioxide (VO_2)
- FP Emitter Design and Fabrication
- Thermal Vacuum Experiment
  - Samples Tested
  - Experimental Set-up
  - Heat Transfer Model
- Cryogenic and High Temperature Stability
- Effect of Partial Heating and Cooling

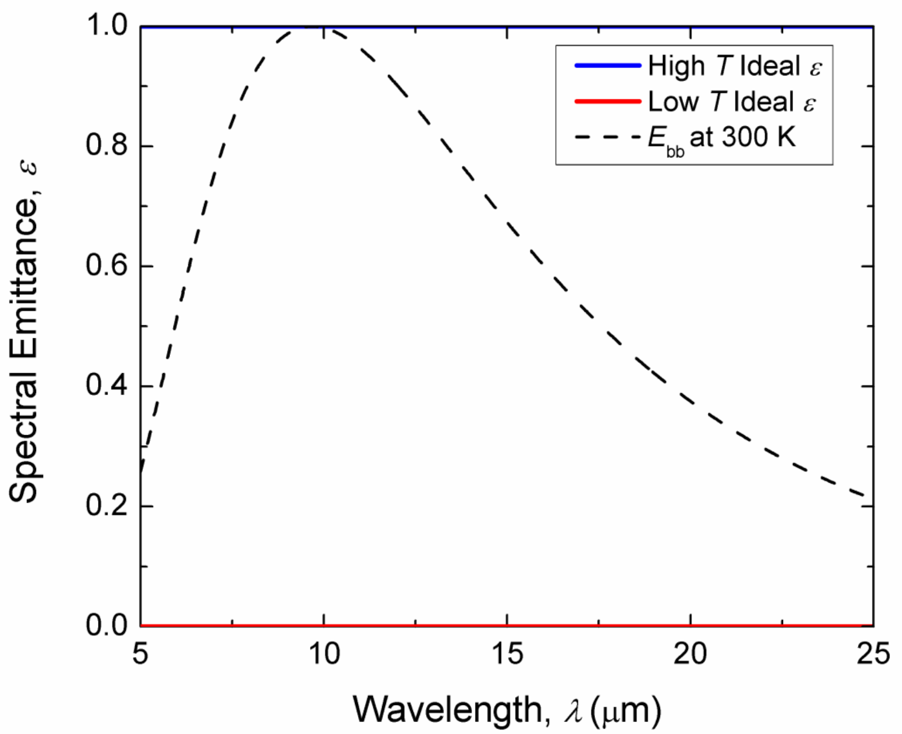
Background and Motivation

High Temperature (Cooling)



Low Temperature (Heating)





Ideal Broadband Emittance

- **High Temp: ε ≈ 1**
- **Low Temp: ε ≈ 0**

Characteristics of VO_2

- At low temperatures, VO_2 is an **insulator** whose behavior can be described by the Lorentz oscillator model:

$$\varepsilon_d(\omega) = \varepsilon_\infty + \sum_{j=1}^{N} S_j \frac{\omega_j{}^2}{\omega_j^2 - i\gamma_j\omega - \omega^2}$$

- At high temperatures, VO_2 is a **metal** whose behavior can be described by the dispersion model:

$$\varepsilon_m(\omega) = \varepsilon_\infty + \frac{-\omega_p^2\varepsilon_\infty}{\omega^2 - i\omega\omega_c} + \sum_{j=1}^{N} S_j \frac{\omega_j{}^2}{\omega_j^2 - i\gamma_j\omega - \omega^2}$$

*Taylor et al., Thin Solid Films, **682**, 29-36 (2019)*

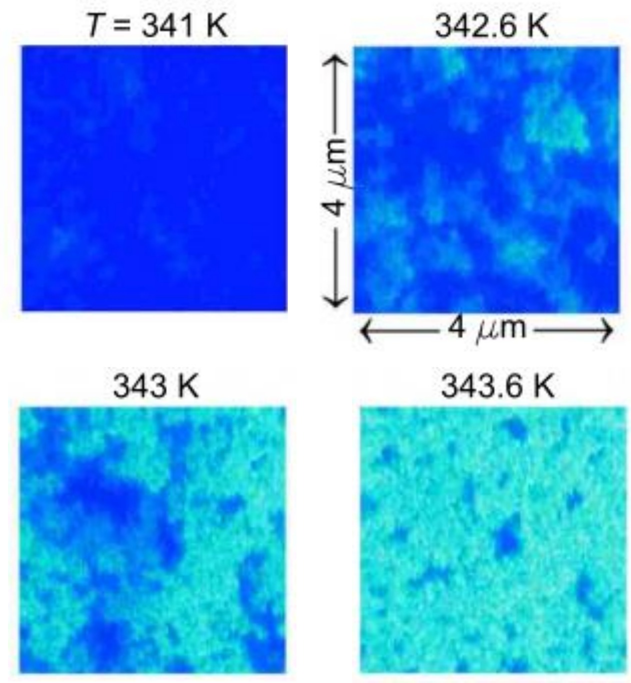
During its transition, VO_2 is considered as an **effective medium**

Bruggeman EMT

$$f\frac{\varepsilon_m - \varepsilon_{eff}}{\varepsilon_{eff} + q(\varepsilon_m - \varepsilon_{eff})} + (1 - f)\frac{\varepsilon_d - \varepsilon_{eff}}{\varepsilon_{eff} + q(\varepsilon_d - \varepsilon_{eff})} = 0$$

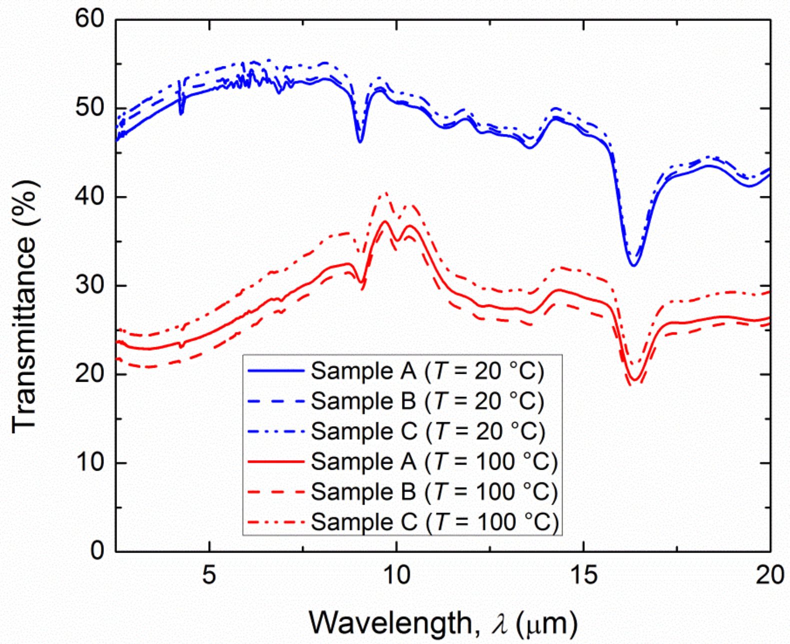
where:

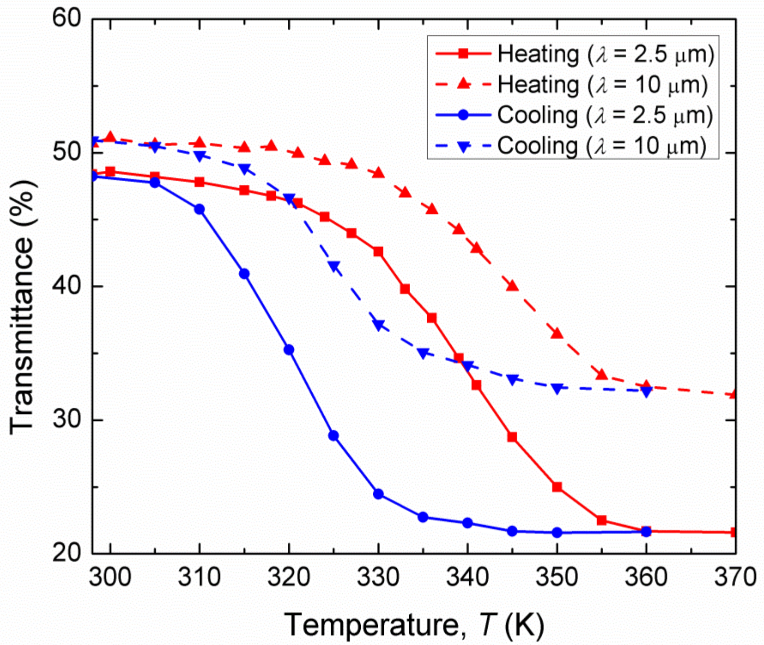
- ε_{eff} effective dielectric constant of composites
- ε_d dielectric function for insulating constituent
- ε_m dielectric function for metallic constituent
- f filling factor
- q depolarization factor, q_o from table, q_E from Qazilbash et al.



*Qazilbash et al., Phys. Rev. B, **79**, 075107 (2013)*

Characteristics of VO_2





- Films prepared via furnace oxidation
- Phase transition at 68 ºC upon heating and 48 ºC upon cooling
- Hysteresis of 20 ºC between heating and cooling

*Taylor et al., Thin Solid Films, **682**, 29-36 (2019)*

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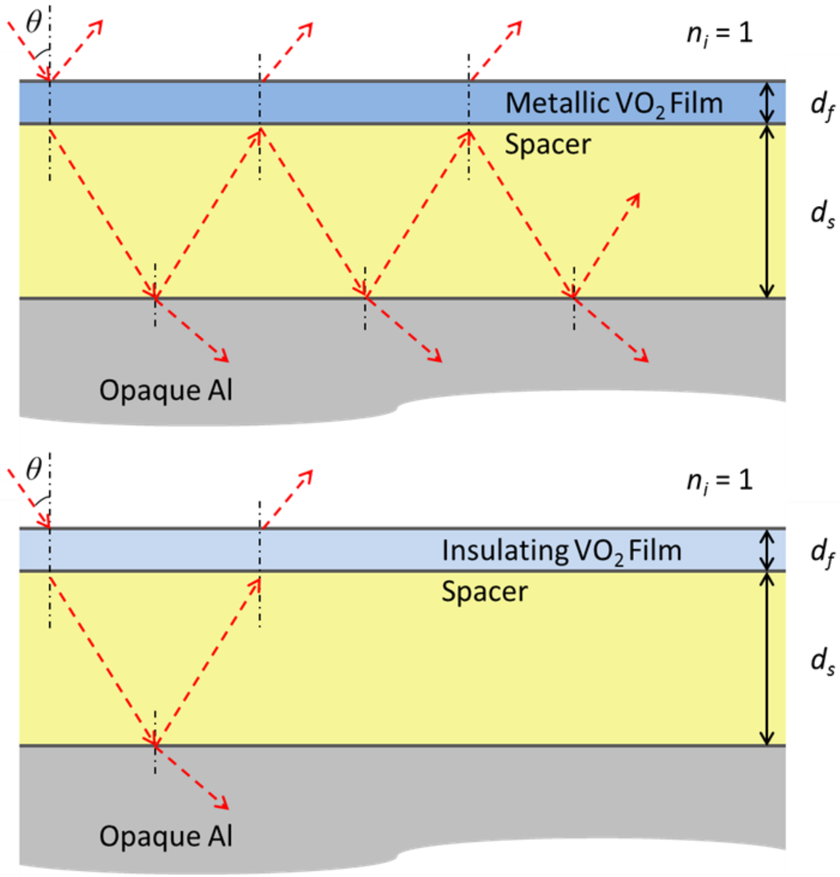
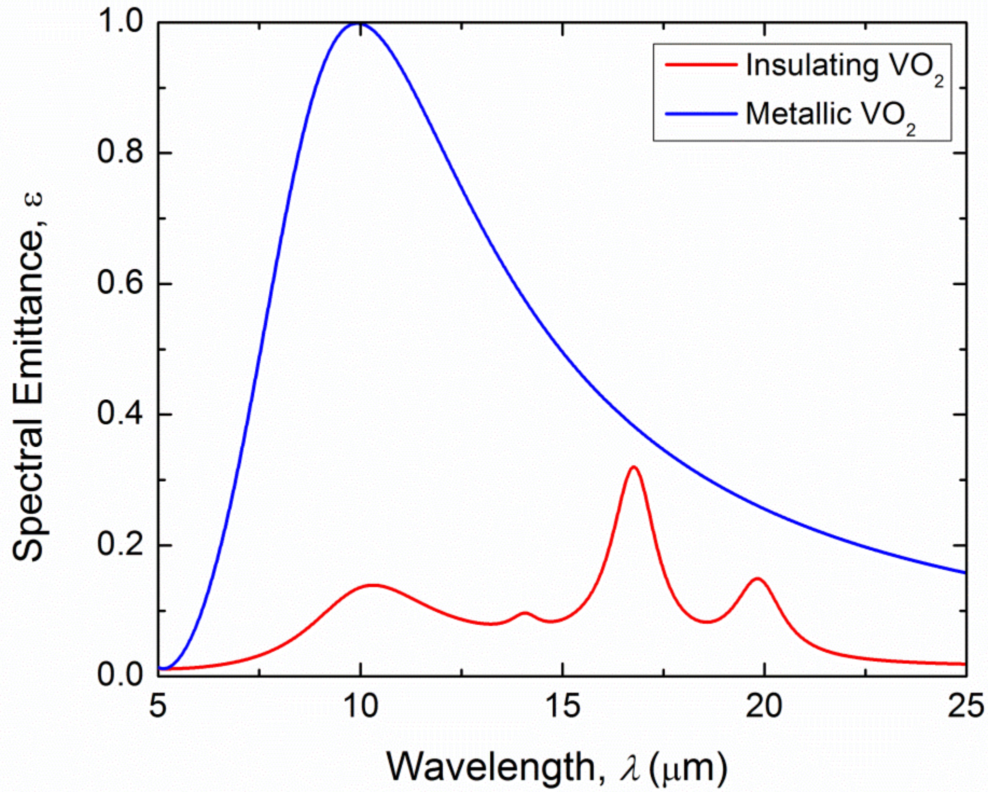
FP Emitter Design and Fabrication

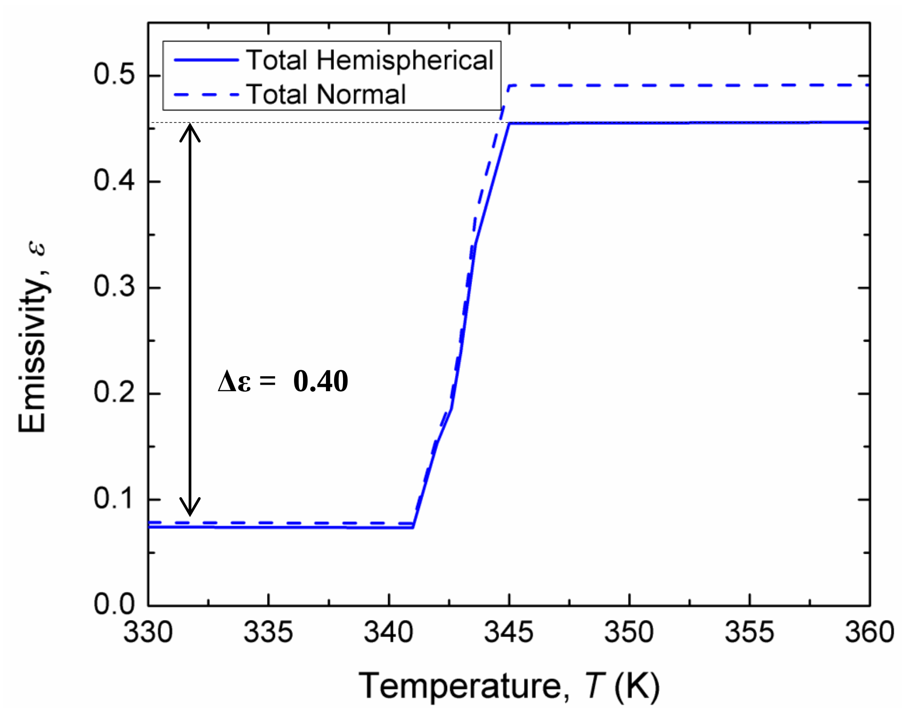


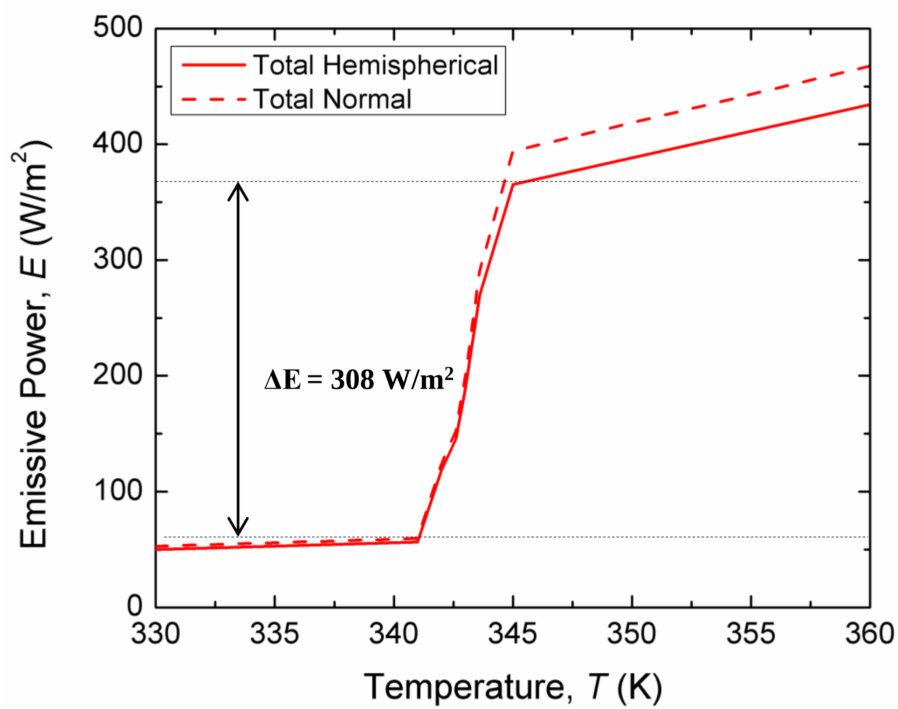


d_f = 25 nm
d_s = 730 nm

*Taylor et al., J. Quant. Spectrosc. Radiat. Transfer, **197**, 76-83 (2017)*

FP Emitter Design and Fabrication





Total Hemispherical Emissivity:

$$\varepsilon = \frac{2\int_{0.3\mu m}^{40\mu m} E_{bb} \int_{0}^{\pi/2} \varepsilon_{\lambda}^{'}(T,\lambda,\theta)\cos\theta\sin\theta d\theta d\lambda}{\sigma T^4}$$

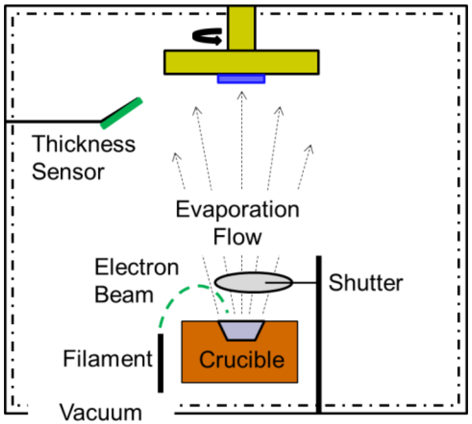
Total Hemispherical Emissive Power:

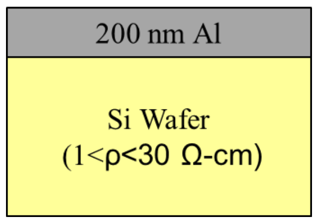
$$E_{\text{hem}} = \varepsilon\sigma T^4$$

Taylor et al., J. Quant. Spectrosc. Radiat. Transfer, 197, 76-83 (2017)

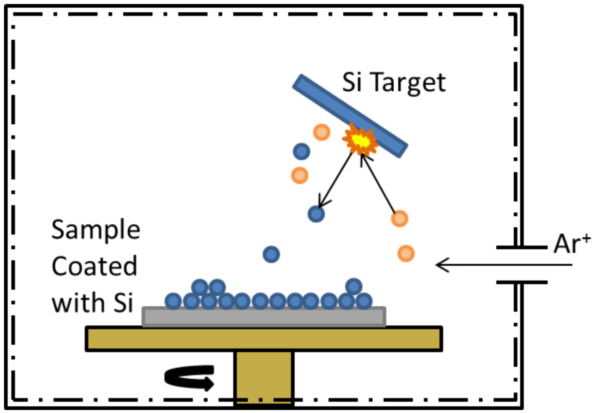
FP Emitter Design and Fabrication

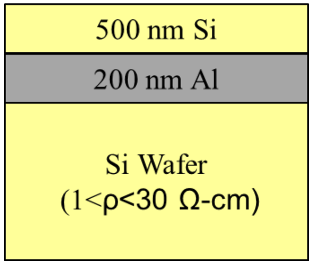
1 200 nm of Al with Electron Beam Evaporation (EBE)



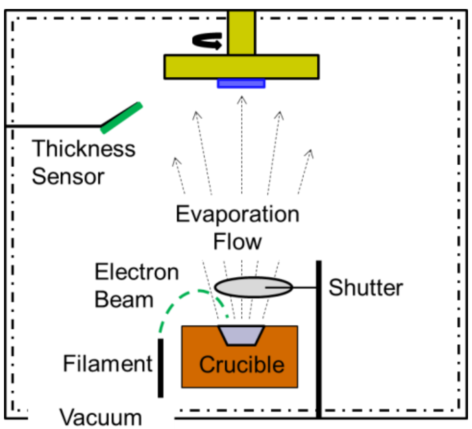


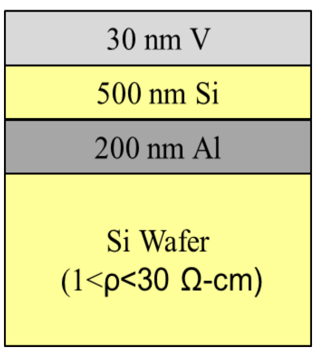
2 500 nm of Si with RF Magnetron Sputtering



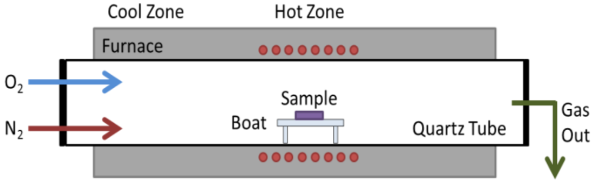


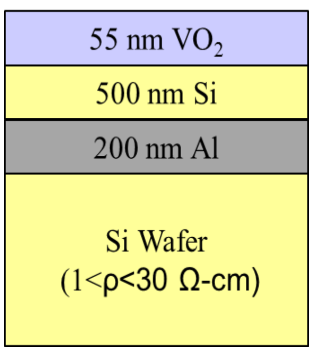
3 30 nm of V with EBE





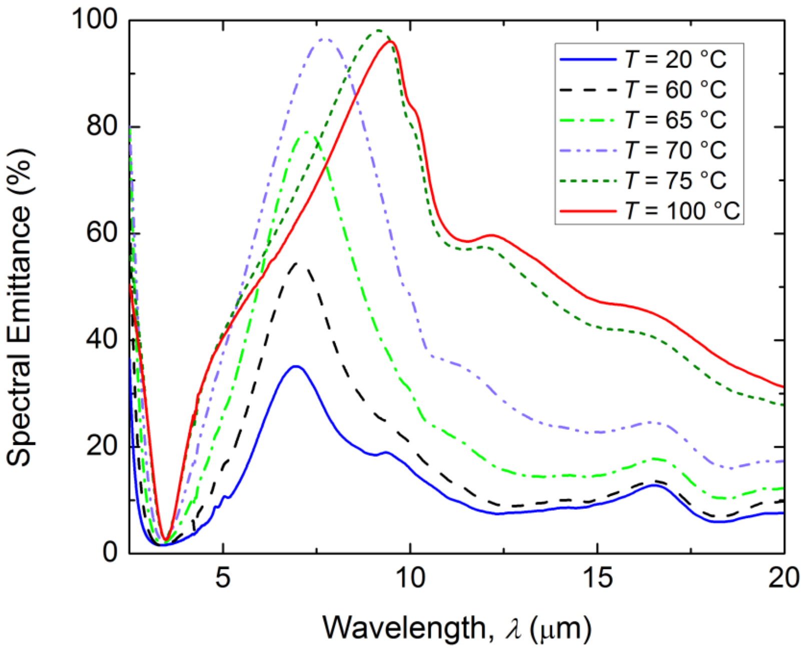
4 Oxidize in Tube Furnace



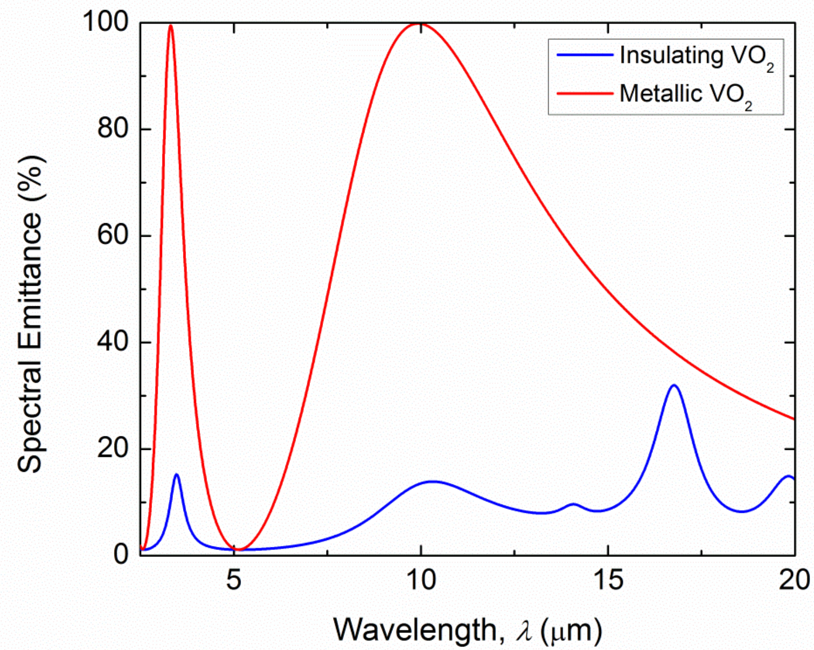


FP Emitter Design and Fabrication

Fabricated FP Emitter



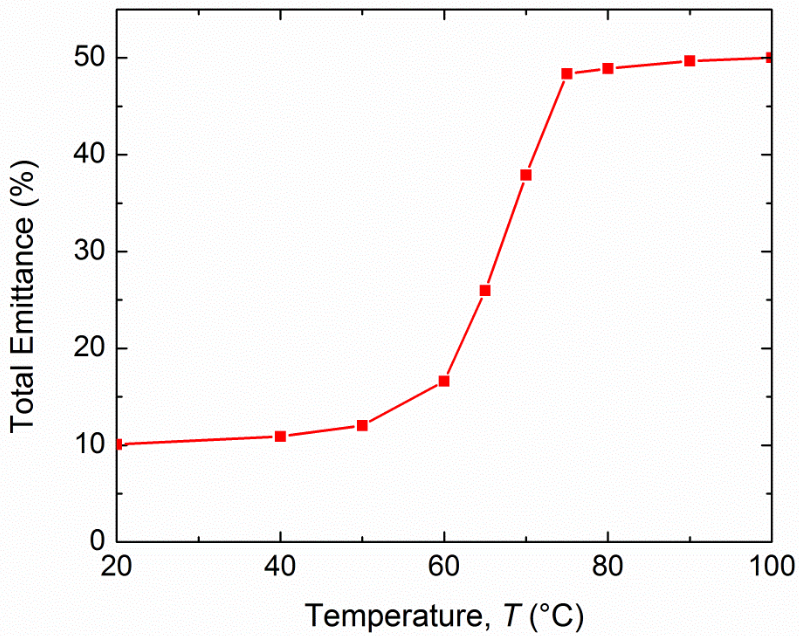
Theoretical FP Emitter



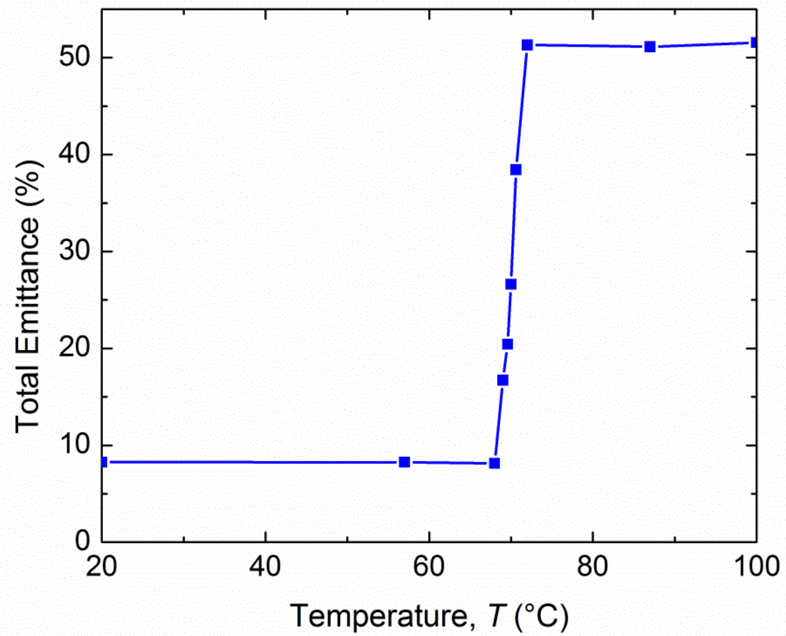
- Fabricated two FP emitter samples with similar spectral emittance
- Fabricated samples exhibit the expected behavior:
  - High emittance at high temperature (metallic VO_2)
  - Low emittance at low temperature (insulating VO_2)
  - Emittance peak around 10 μm

FP Emitter Design and Fabrication

Fabricated FP Emitter



Theoretical FP Emitter



- Fabricated emitter achieves a total emittance difference of 40%
- Transition regime for fabricated emitter is wider than the designed emitter due to the crystal orientation of our fabricated VO_2 (polycrystalline versus monocrystalline)

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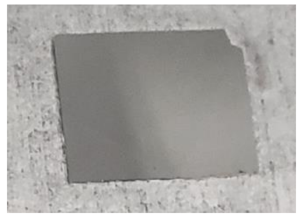
Samples Tested

Black (Acktar)*

$\varepsilon_{IR} \approx 100\%$

Aluminum (200 nm on Si)



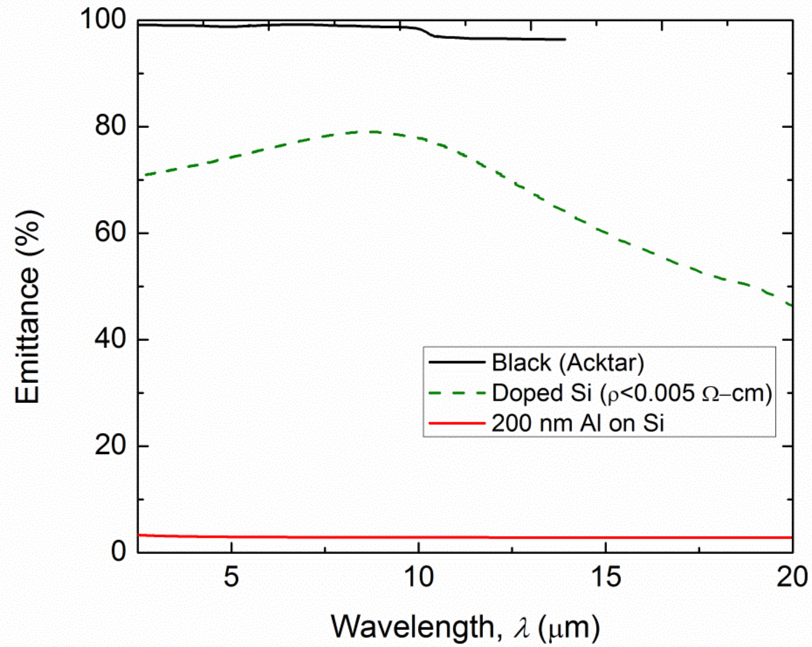
$\varepsilon_{IR} = 3\%$

Heavily Doped Silicon

$\varepsilon_{IR} \approx 70\%$

VO_2 FP Emitter

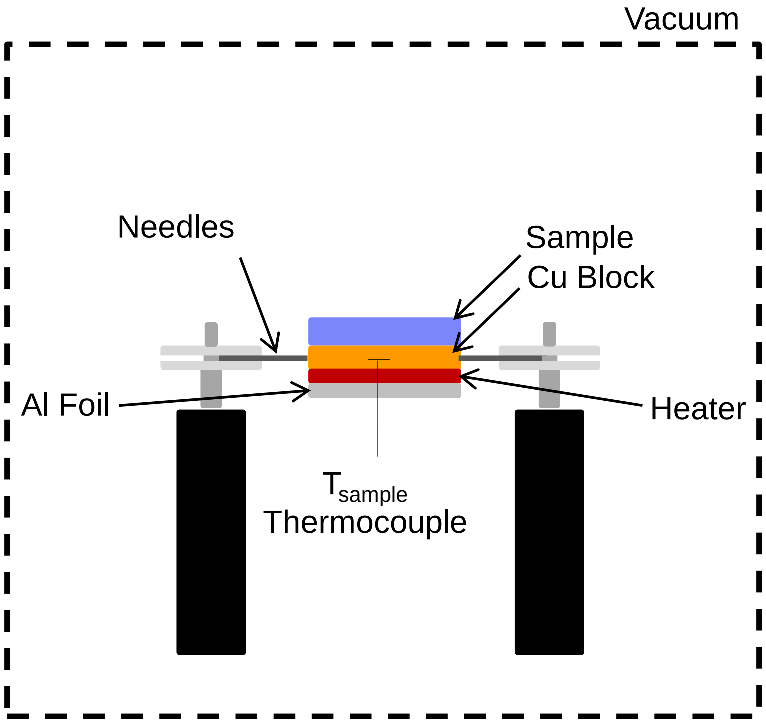
ε_{IR} = Varies with T



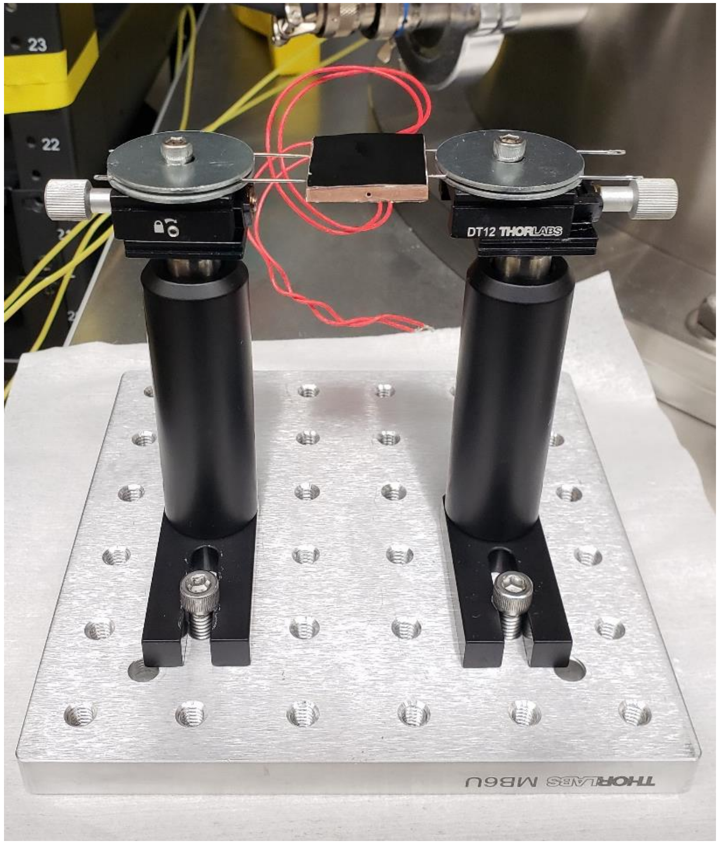
***Acktar properties from:**
https://www.acktar.com/product/metal-velvet-2/

Thermal Vacuum Experiment

Schematic



Experimental Set-up



Four Samples:

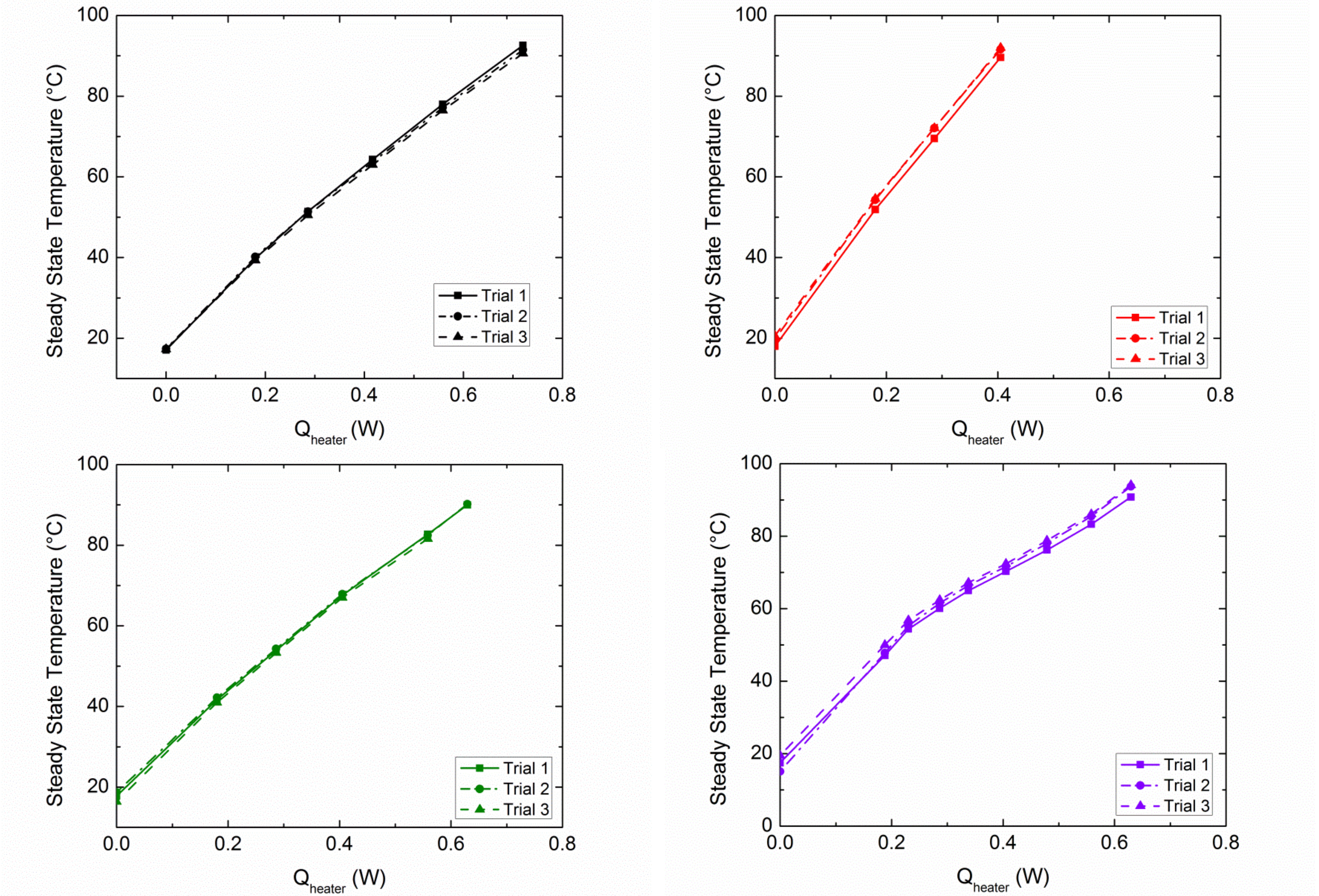
Black (Acktar), ε ≈ 100%

Aluminum, ε = 3%

Heavily Doped Silicon, ε ≈ 70%

FP Emitter, ε = Varies with T

Thermal Vacuum Experiment



For all 4 samples, the results from all 3 trials are close

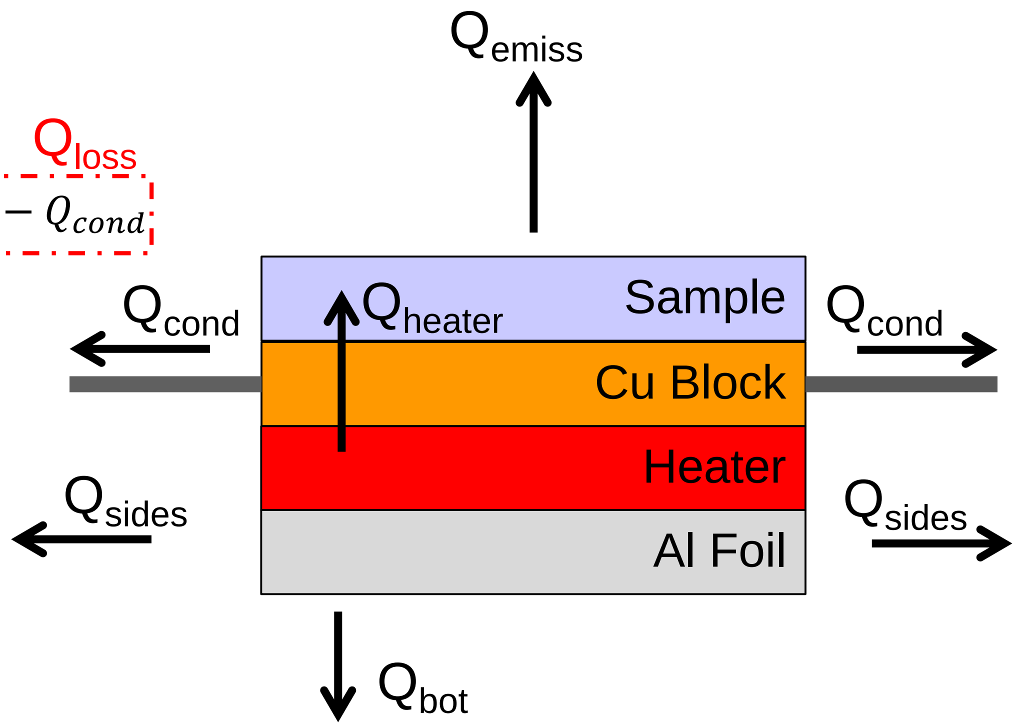
Theoretical Modeling

$$\sum Q = 0 = Q_{heater} - Q_{emiss} - \underbrace{Q_{sides} - Q_{bot} - Q_{cond}}_{Q_{loss}}$$

$$Q_{heater} = Q_{emiss} + Q_{sides} + Q_{bot} + Q_{cond}$$

$$Q_{heater} = P_{heater} = I^2 R$$

$$Q_{emiss} = \varepsilon\sigma(T^4_{sample} - T^4_{wall})$$

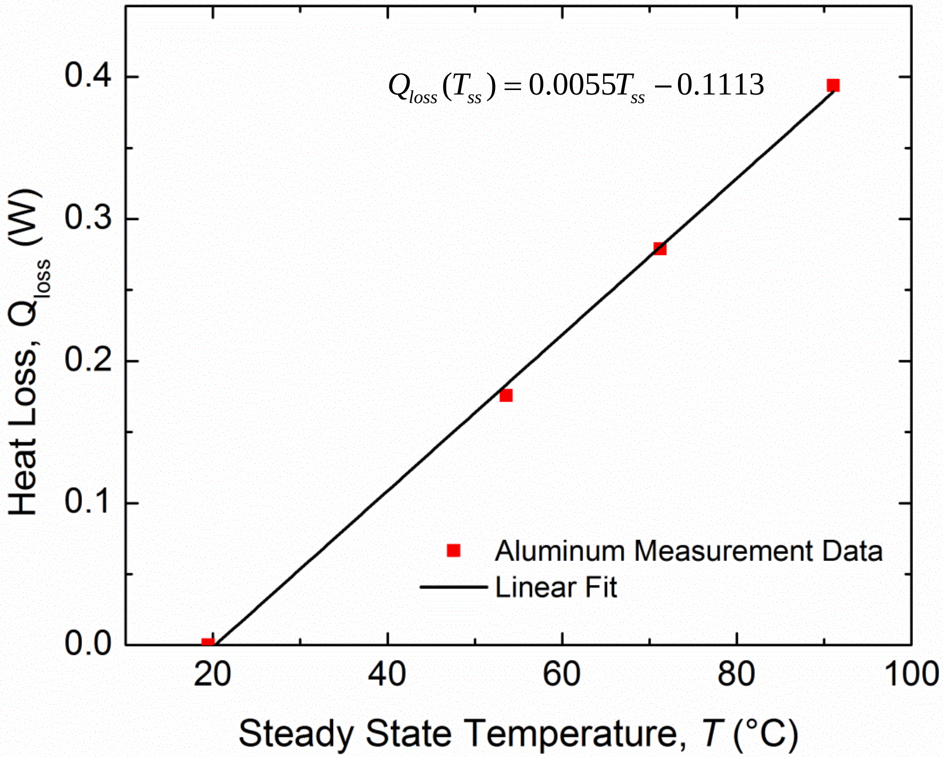


→$Q_{loss}(T)$ is determined from the aluminum measurements:

ε_{Al} = 3%

$$Q_{loss}(T) = Q_{heater} - Q_{emiss}$$

Thermal Vacuum Experiment



$$Q_{heater} = P_{heater} = I^2 R$$

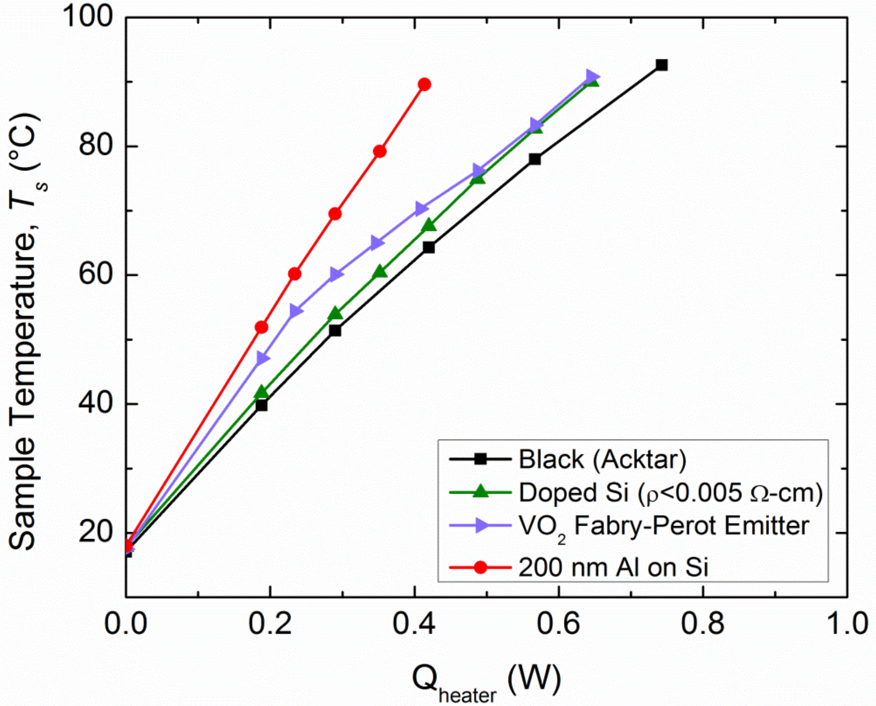
$$Q_{emiss} = \varepsilon\sigma(T^4_{sample} - T^4_{wall})$$

$$Q_{loss}(T) = Q_{heater} - Q_{emiss}$$

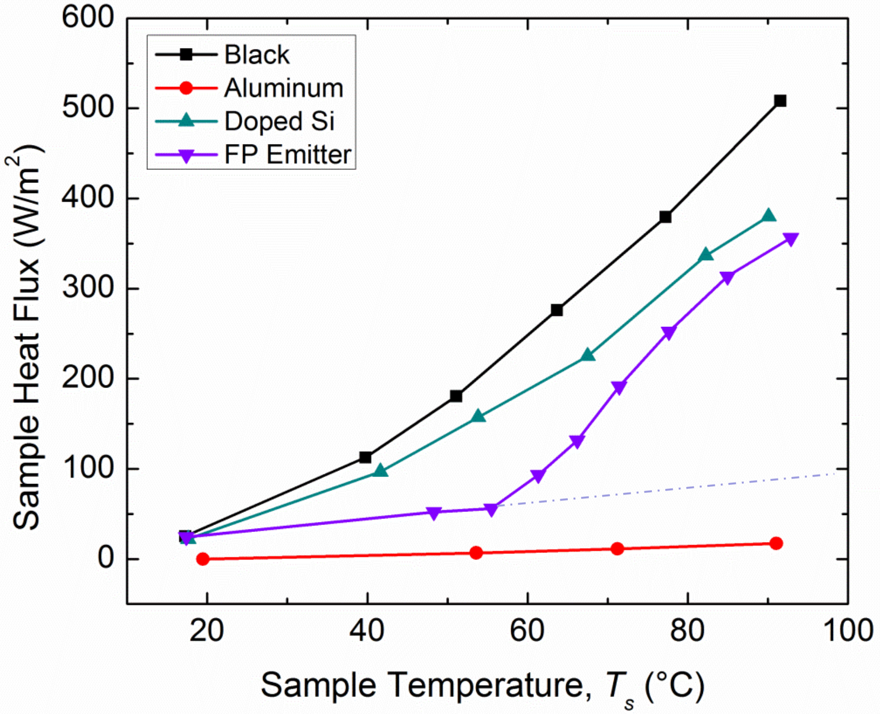
- Determined the heat loss as a function of steady state temperature
- Losses fit to aluminum since majority of Q_{heater} would be lost through conduction and back/side radiation losses due to aluminum's low ε_{IR}

Thermal Vacuum Experiment

Collected Data



Post-Processed Data



Clear change in emitted heat flux upon VO_2 phase transition

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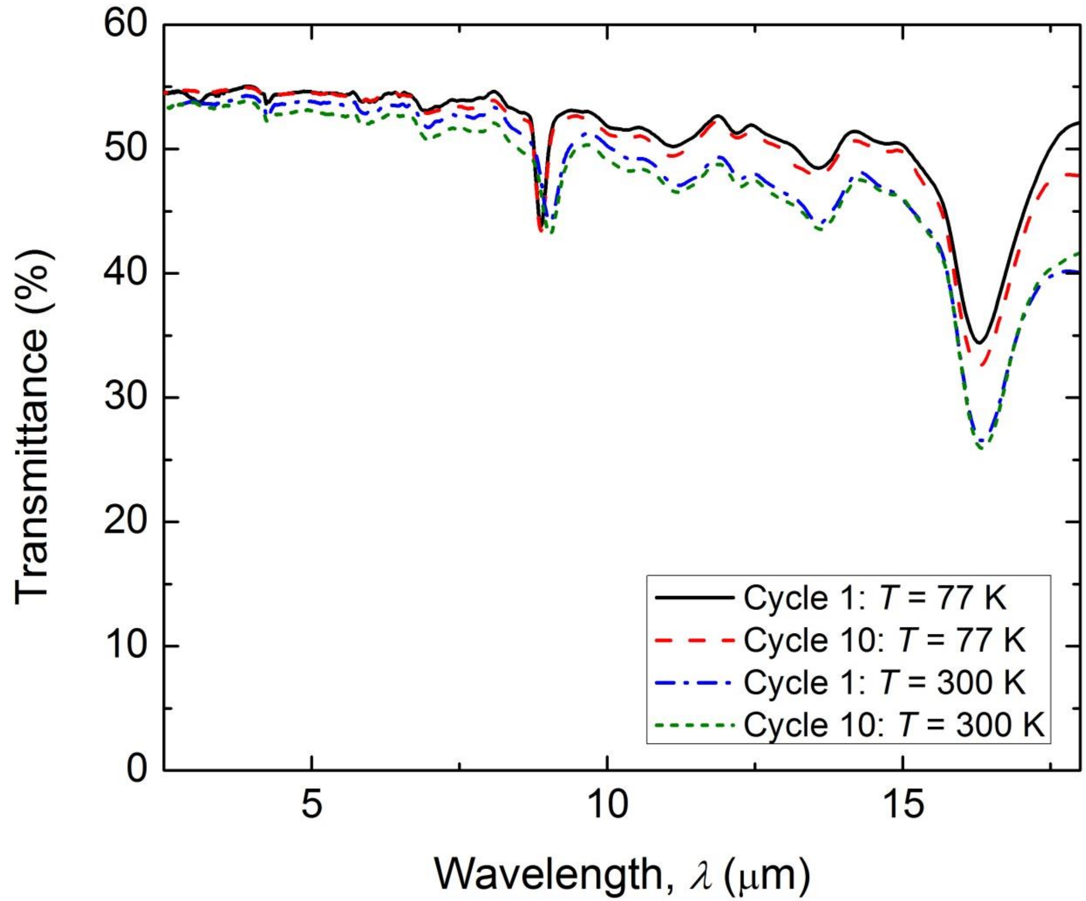
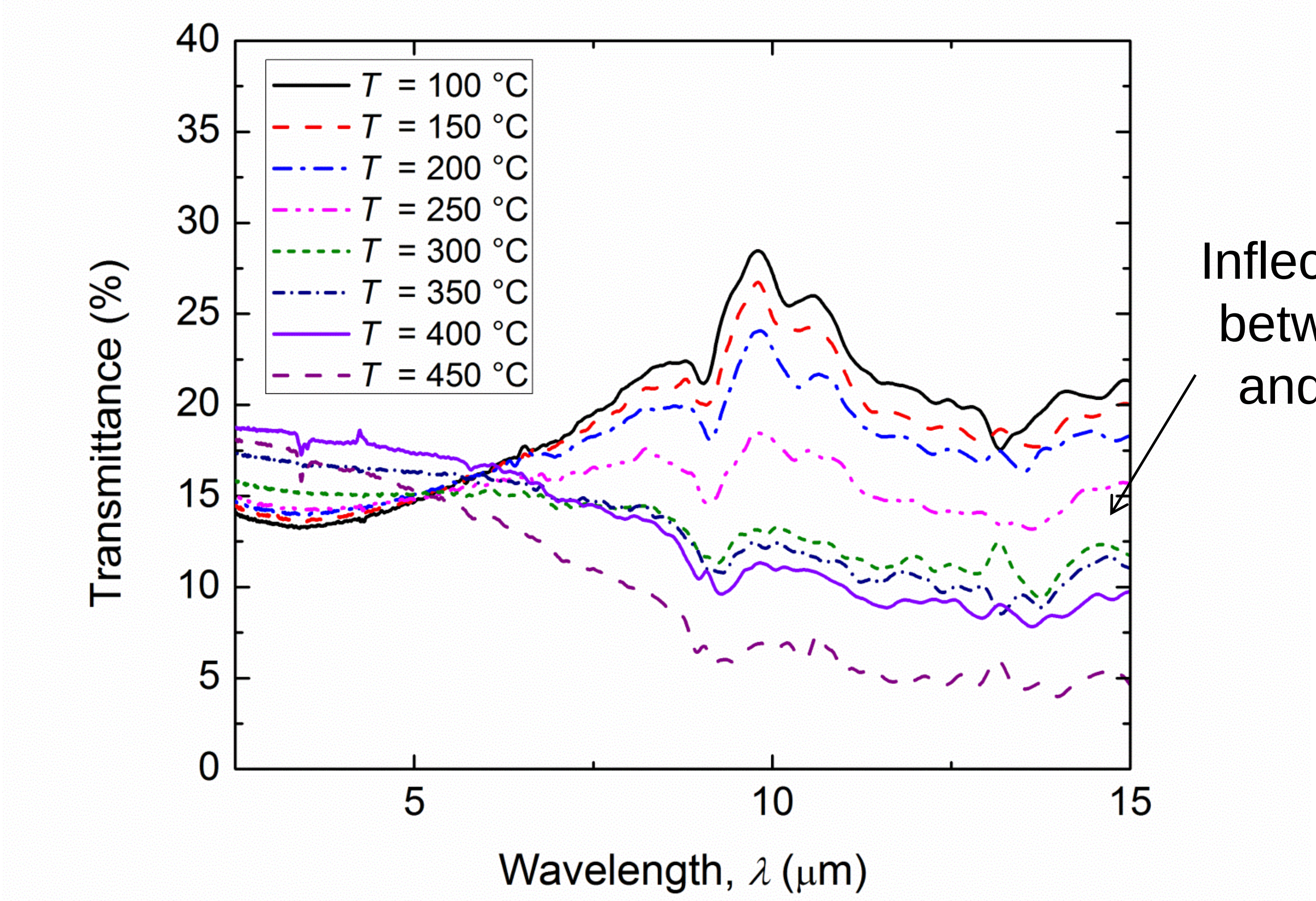
Cryogenic Stability



- Sample does not appear to be susceptible to cryogenic temperatures
- Small increase in IR transmittance at cryo temperatures may be related to trace amount of VO_2(B) in sample → observable with Raman

High Temperature Stability



Inflection point between 250 and 300 ºC

- Sample can withstand temperatures up to 250 ºC (tentatively)
- Above 300 ºC, spectra is similar to metallic vanadium
- Follow-up cycling experiment required

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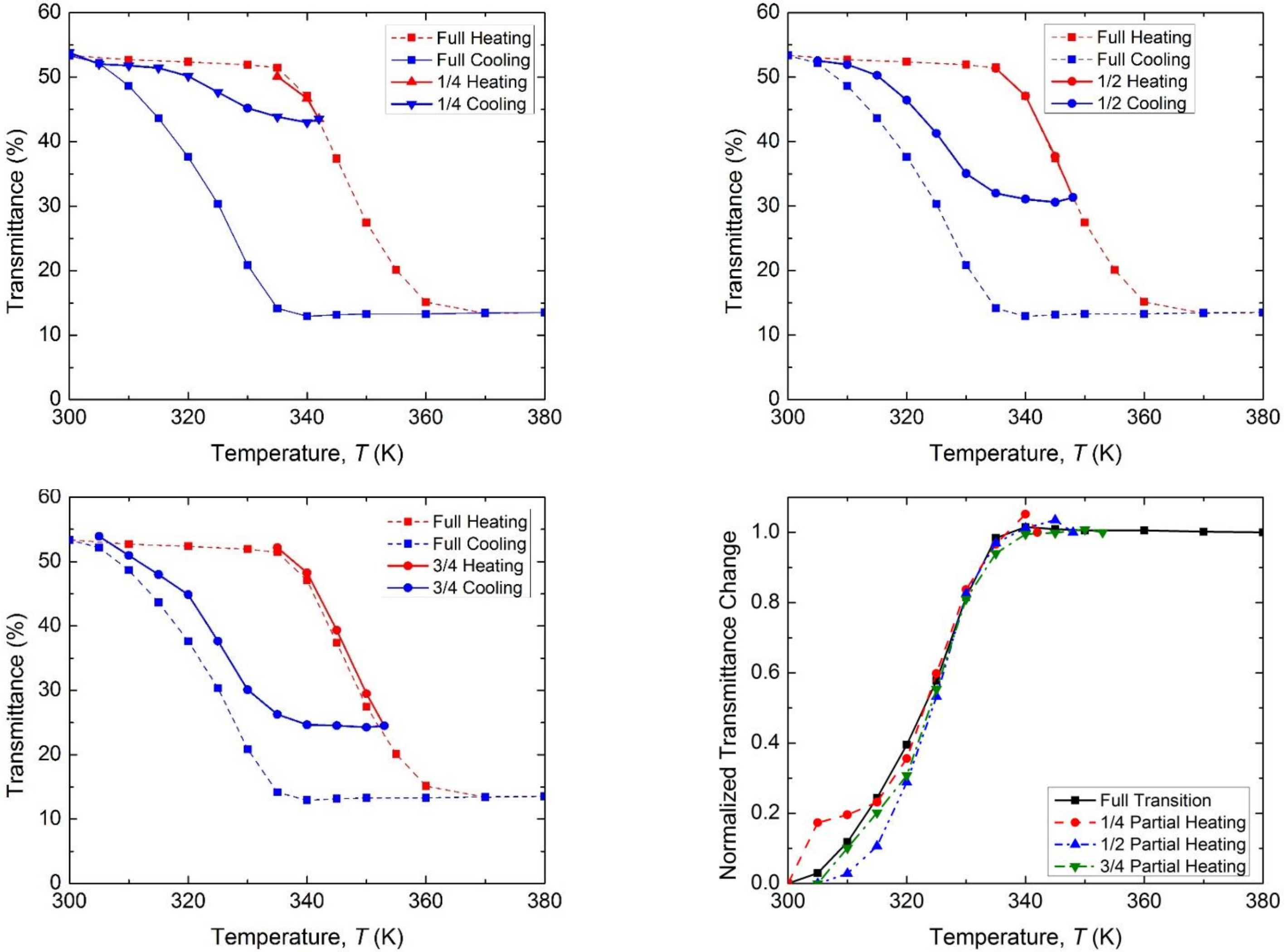
- **Effect of Partial Heating and Cooling**

Effect of Partial Heating



What happens if VO_2 is only heated partway in its transition and then cooled?

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- Conclusion

Conclusions

- Several FP emitter samples are fabricated via physical vapor deposition techniques and furnace oxidation
- The temperature-dependent optical properties of two fabricated FP emitter samples are measured
- The variable heat flux of one FP emitter is experimentally demonstrated via a thermal vacuum experiment
- The fabricated VO_2 thin films are shown to be insensitive to cryogenic temperatures and cryogenic thermal cycling
- The tentative maximum temperature for VO_2 films fabricated via our furnace oxidation method is 250 ºC
- When partially heated and then cooled, the VO_2 transitions along an intermediate path which can be described by an effective medium theory

Acknowledgments

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