TFAWS Passive Thermal Paper Session

Thermochromic Variable Emittance Radiation Coatings for Spacecraft Thermal Management

Arizona State University

Presented By
Sydney Taylor

Thermal & Fluids Analysis Workshop
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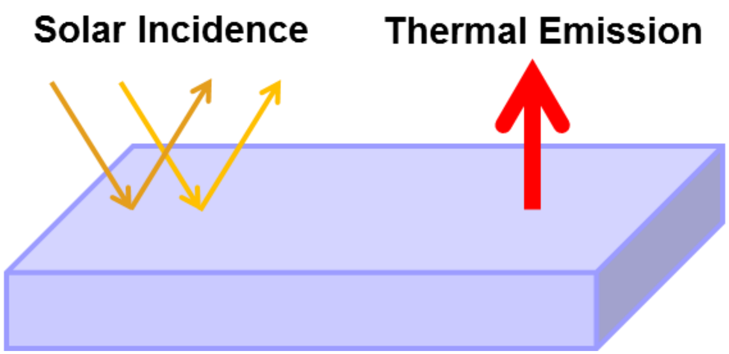
NASA Marshall Space Flight Center
Huntsville, AL

Outline

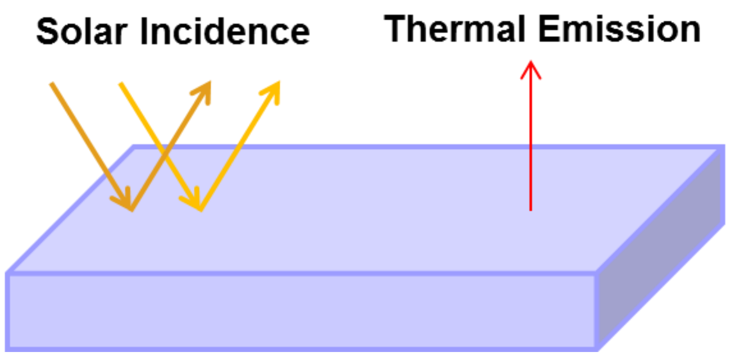
- Introduction
  - Motivation and background
  - Characteristics of vanadium dioxide (VO_2)
- Sample Fabrication and Measurement Techniques
  - Sample to be fabricated
  - VO_2 fabrication process
  - Test facilities
- Experimental Results
  - Fabrication parametric study
  - VO_2 thin film properties
- Variable Emitter
  - Fabrication process
  - Preliminary results
- Future Work and Summary

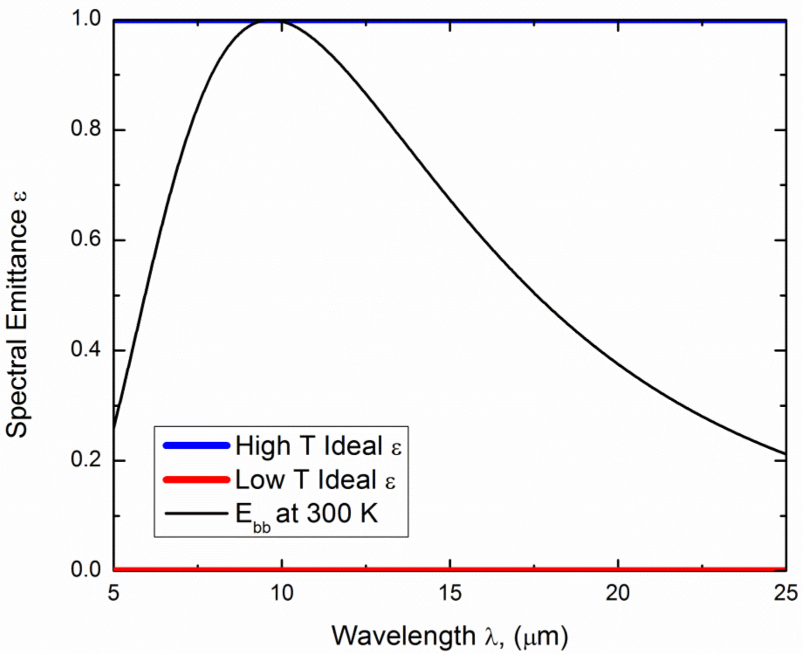
Motivation and Background

High Temperature



Low Temperature

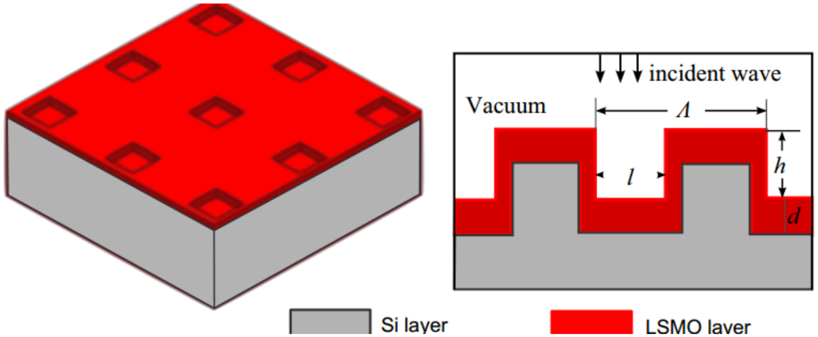


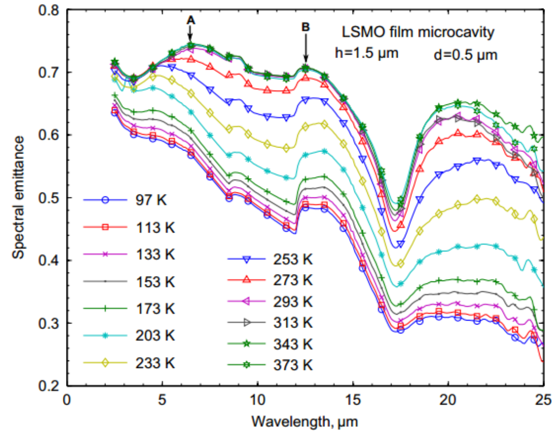


Spectral Selectivity for Variable Emitters:

1. High Temp - $\alpha \approx 0, \varepsilon \approx 1$
2. Low Temp – $\alpha \approx 0, \varepsilon \approx 0$

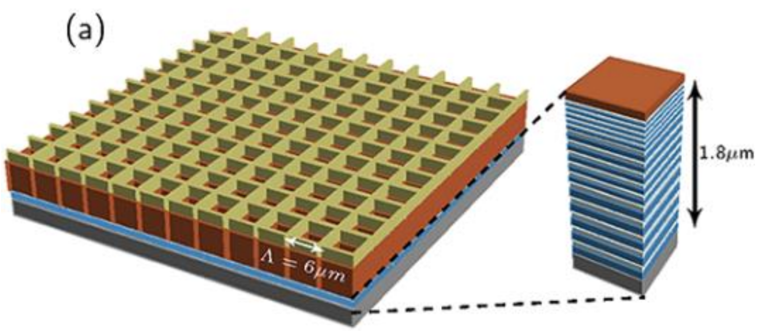
Motivation and Background

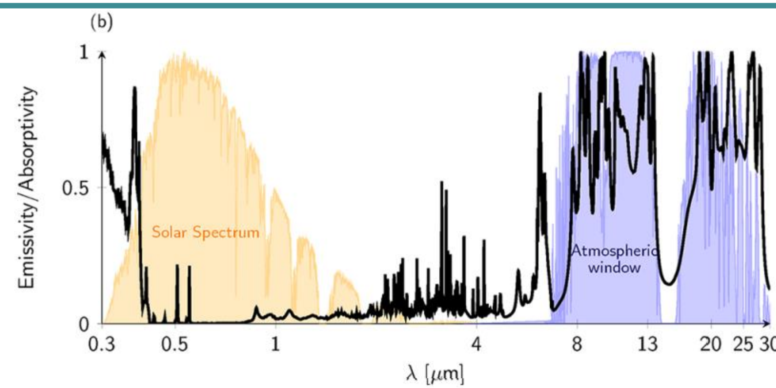




Variable Emittance w/ LSMO

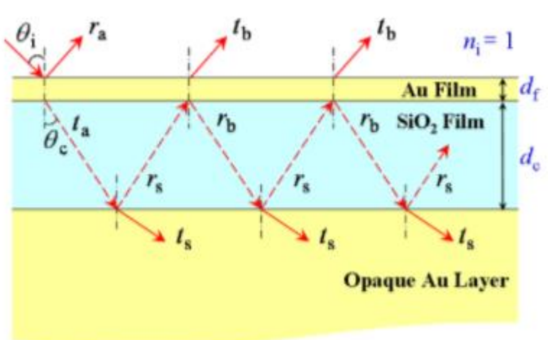
*Fan et al., Sol. Energ. Mat. Sol. Cells., **3**, 1047-1051 (2015)*

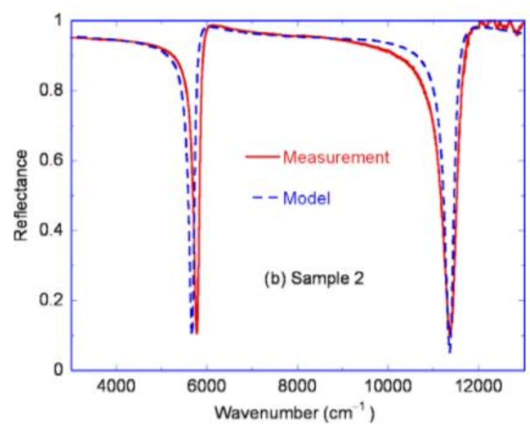




1D Photonic Crystals

*Raman et al., Nano Lett., **515**, 540-544 (2014)*





Fabry-Perot Cavity

*Wang et al., Int. J. Heat. Mass. Trans., **52**, 3024-31 (2009)*

Characteristics of VO_2

- At low temperatures (T < 341 K), 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 (T > 345 K), VO_2 is a **metal** whose behavior can be described by the Drude model:

$$\varepsilon_m = \frac{-\omega_p^2 \varepsilon_\infty}{\omega^2 - i\omega\omega_c}$$

Barker et al., Phys. Rev. Lett., 17, 1286 (1966)

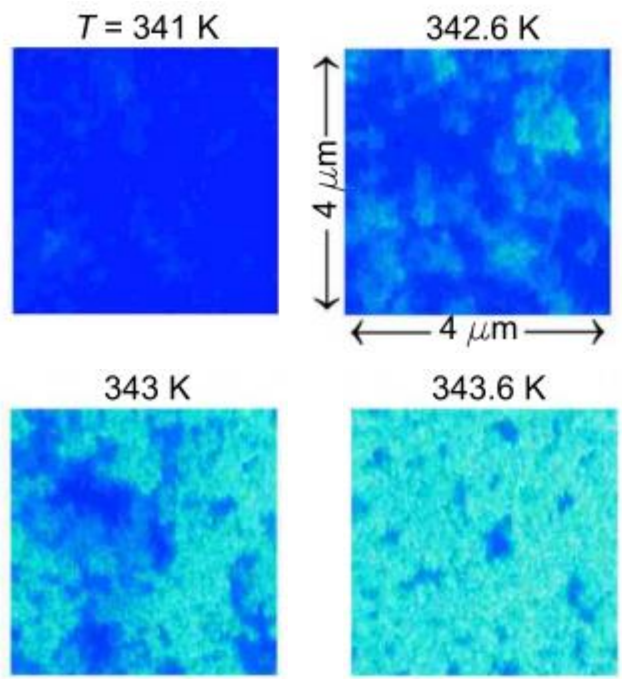
During its transition (341 K < T < 345 K), VO_2 is considered as an **effective medium**

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)*

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  - **VO_2 fabrication process**
  - **Test facilities**
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  - VO_2 thin film properties
- Variable Emitter
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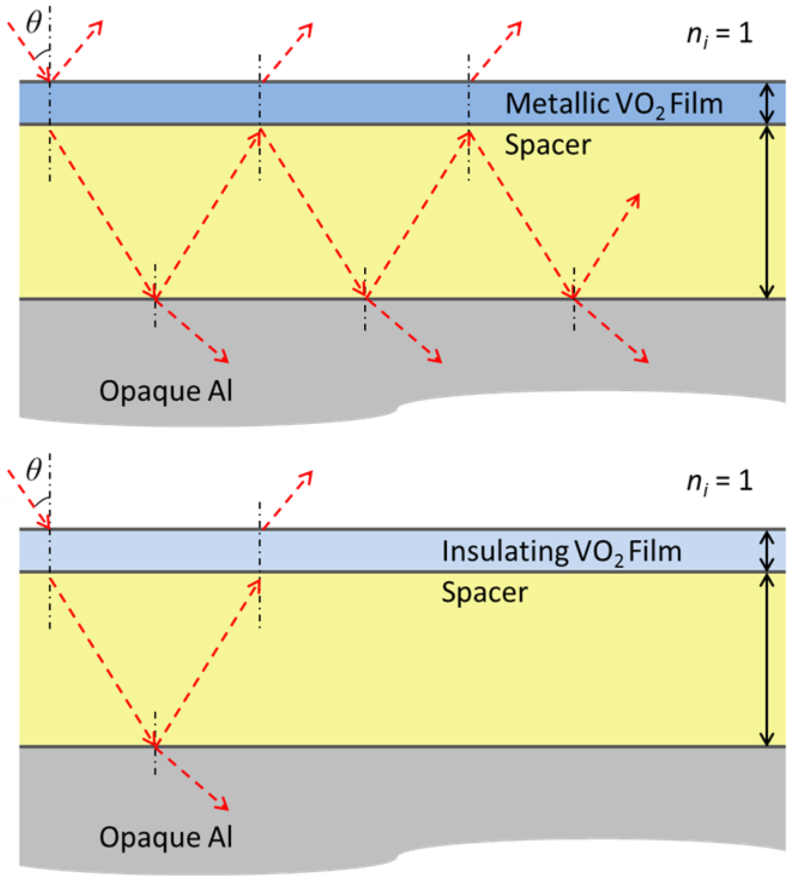
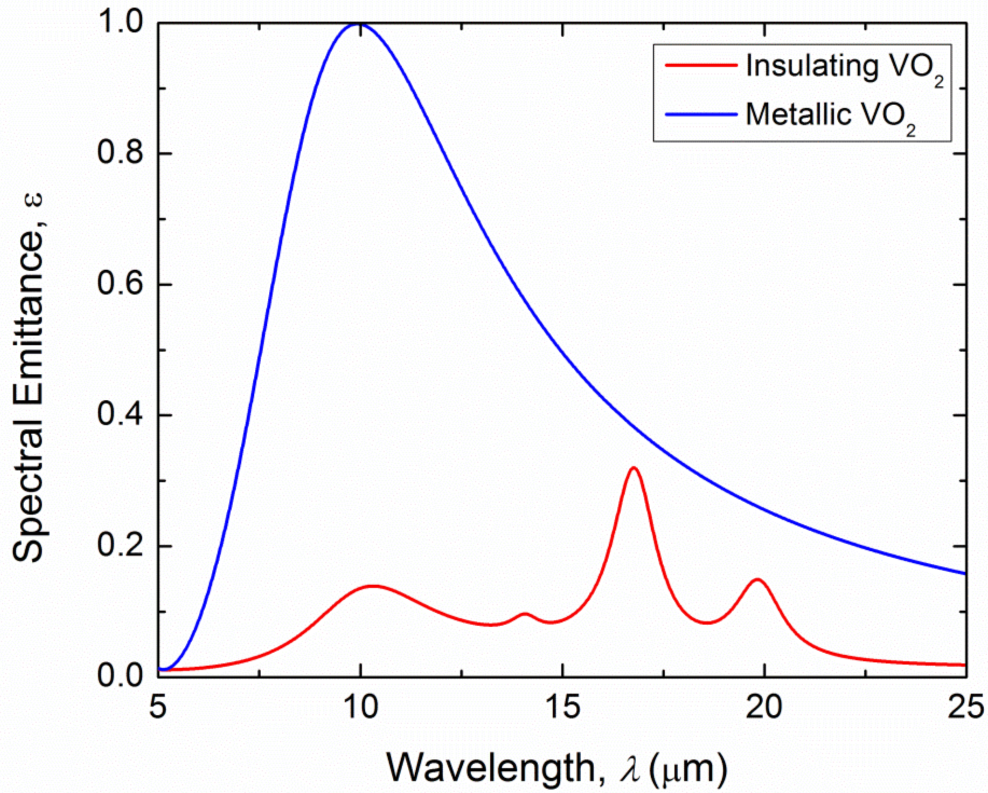
Sample to Be Fabricated

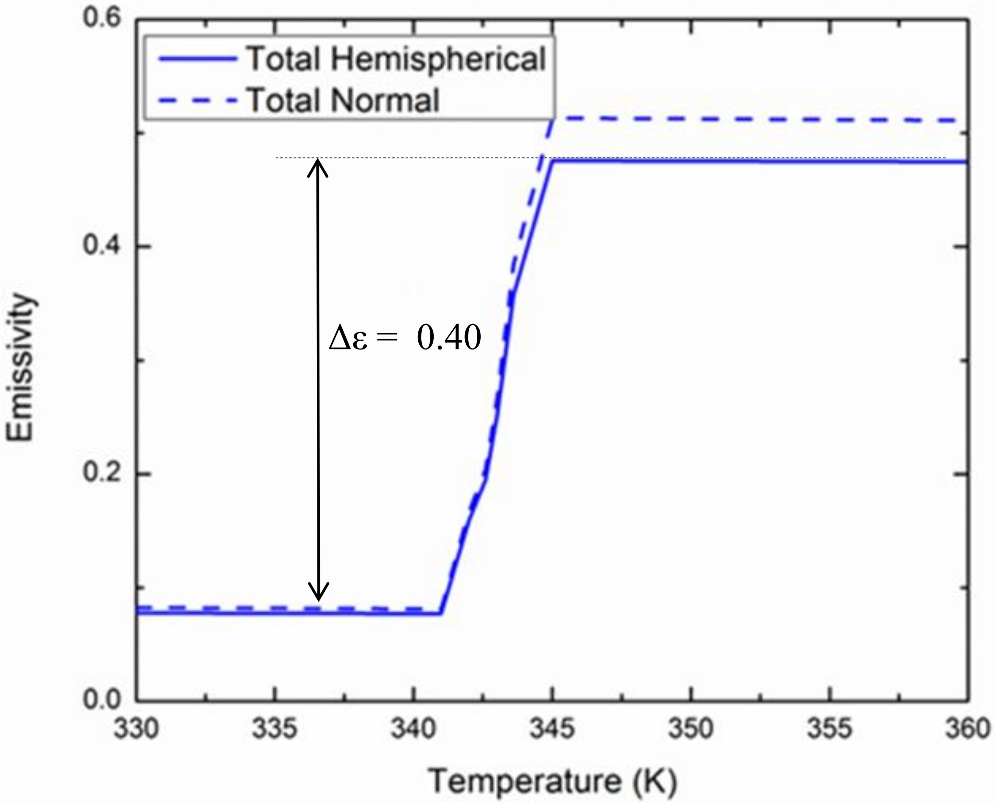




$d_f = 25$ nm
$d_s = 730$ nm

Taylor et al., J. Quant. Spectrosc Radiat. Trans., accepted (2017)

Sample to Be Fabricated



Total Hemispherical Emittance

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

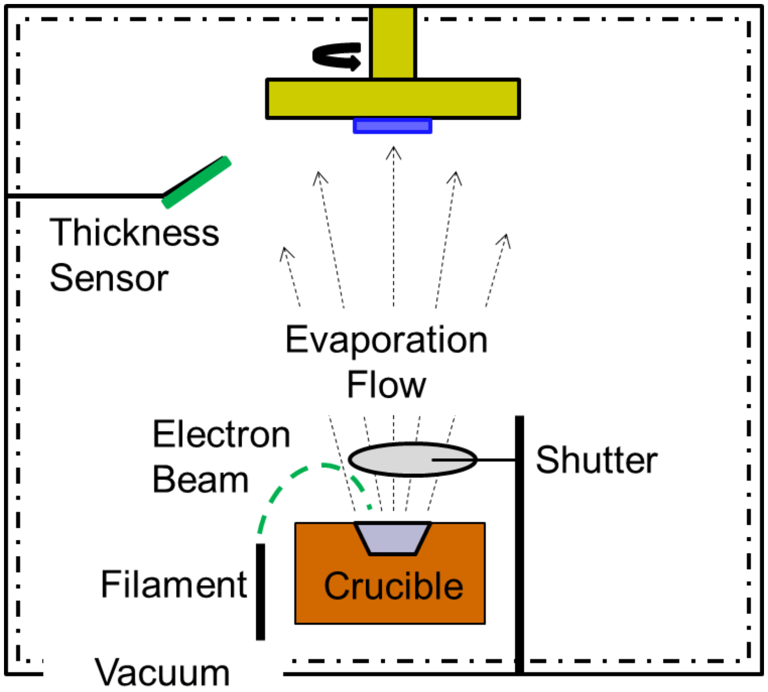
- 0.40 change in total emittance ε expected
- Behavior is independent of direction for θ < 60°

Taylor et al., J. Quant. Spectrosc Radiat. Trans., accepted (2017)

VO_2 Fabrication Process

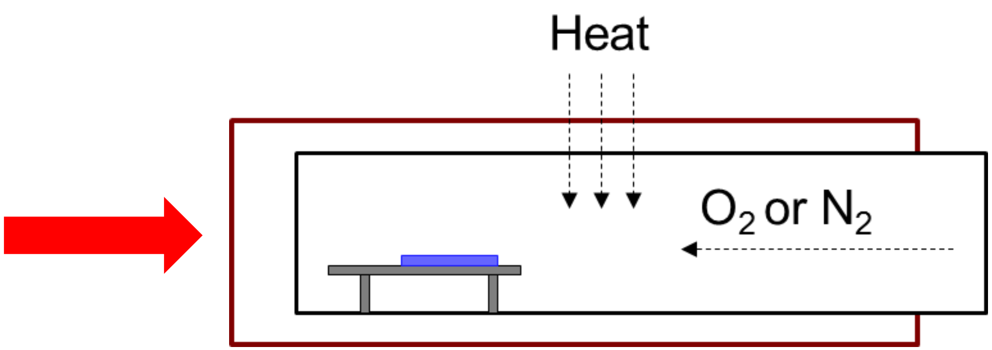
Electron Beam Evaporation:

- Deposit V thin film



Tube Furnace Oxidation:

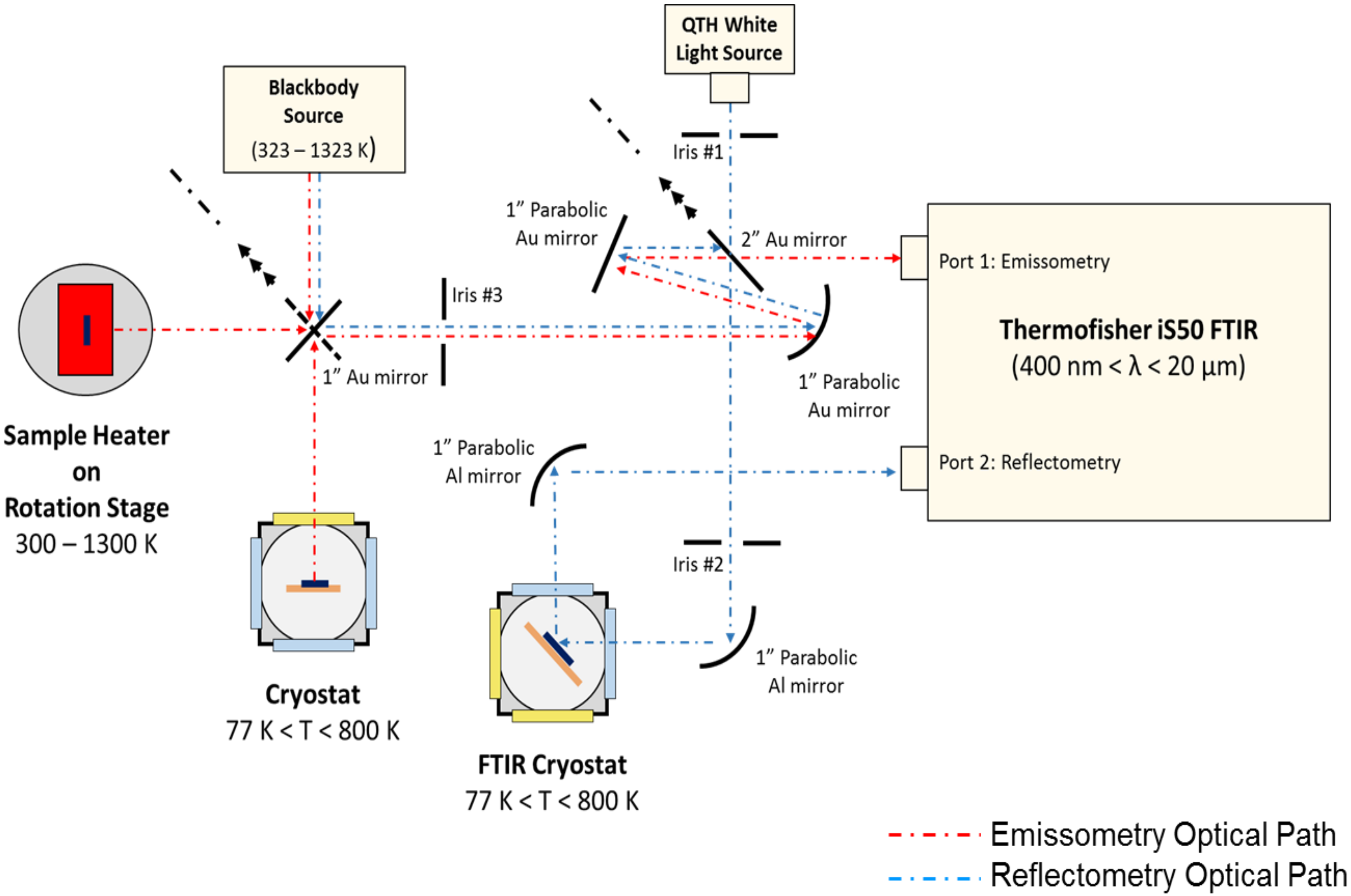
- Oxidize V thin film to VO_2



What furnace conditions do we need?

- **Temperature**
- **Furnace Time**
- **O_2 flow rate**
- **N_2 flow rate**

Test Facilities



Taylor et al., Rev. Sci. Instru., to be submitted (2017)

Test Facilities

Temp-Dependent Transmittance

Temp-Dependent Reflectance

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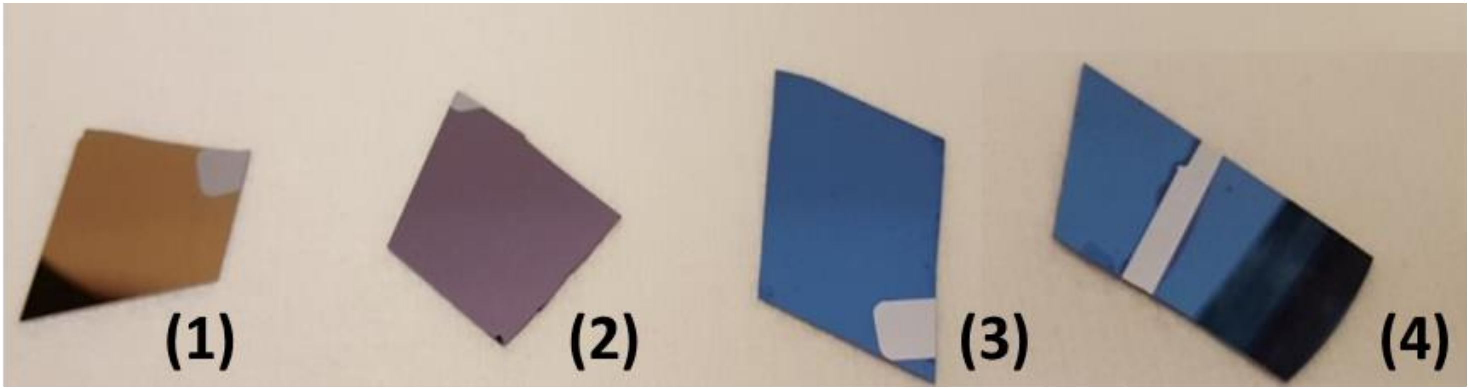
Fabrication Parametric Study

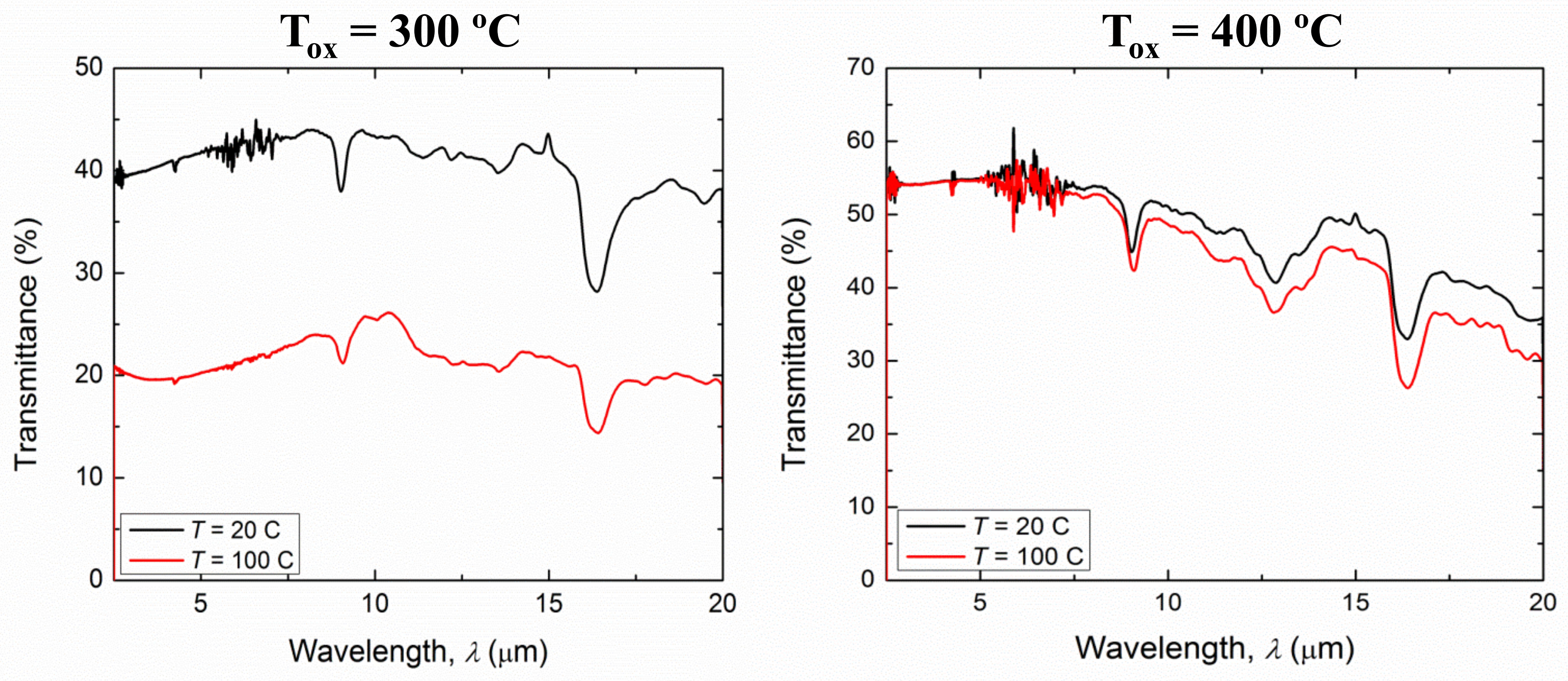
Initial Screening Test



	Time (min.)	O_2 flow (SLPM)	Temperature, T_{ox} (°C)	ΔTransmittance (%)
Sample 1	20	1.5	297	9
Sample 2	60	0.5	303	18
Sample 3	15	1.5	399	~0
Sample 4	60	0.5	403	~0

Fabrication Parametric Study

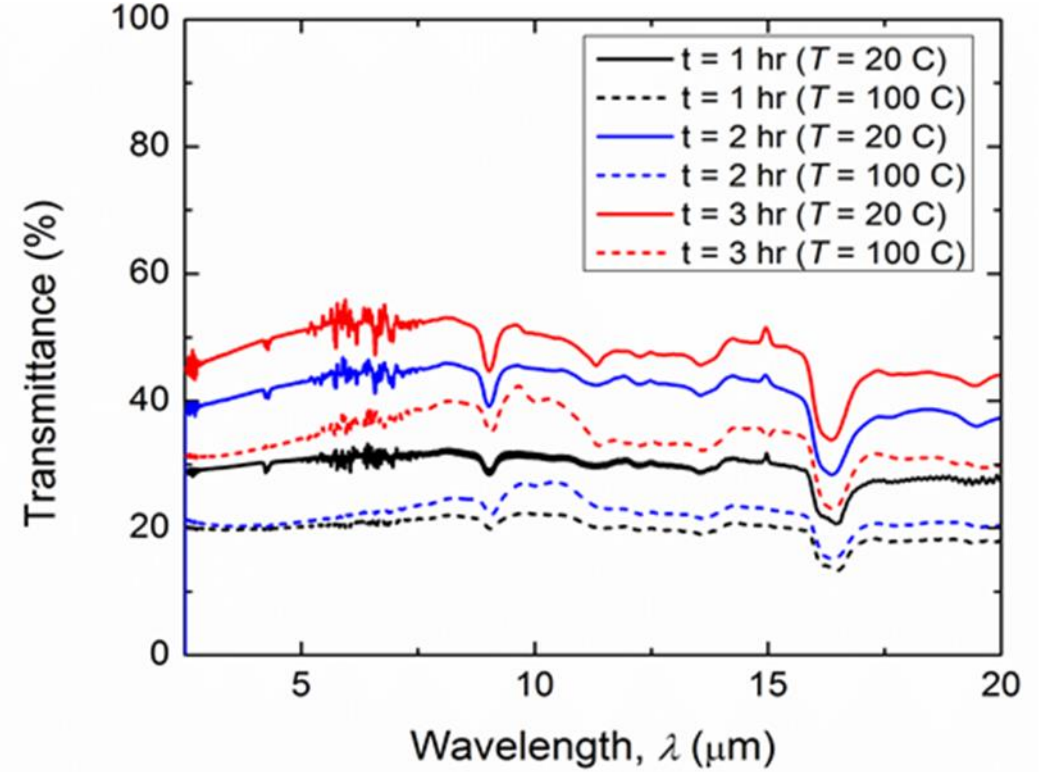
Initial Screening Test



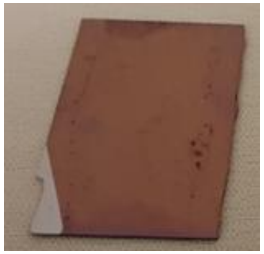
- Samples should be oxidized at 300 ºC

Fabrication Parametric Study

Furnace Oxidation Time



- Thin films are all the same thickness
- Oxidized at 300 ºC, 0.5 SLPM O_2 with N_2
- Transmittance change varies ***strongly*** with time

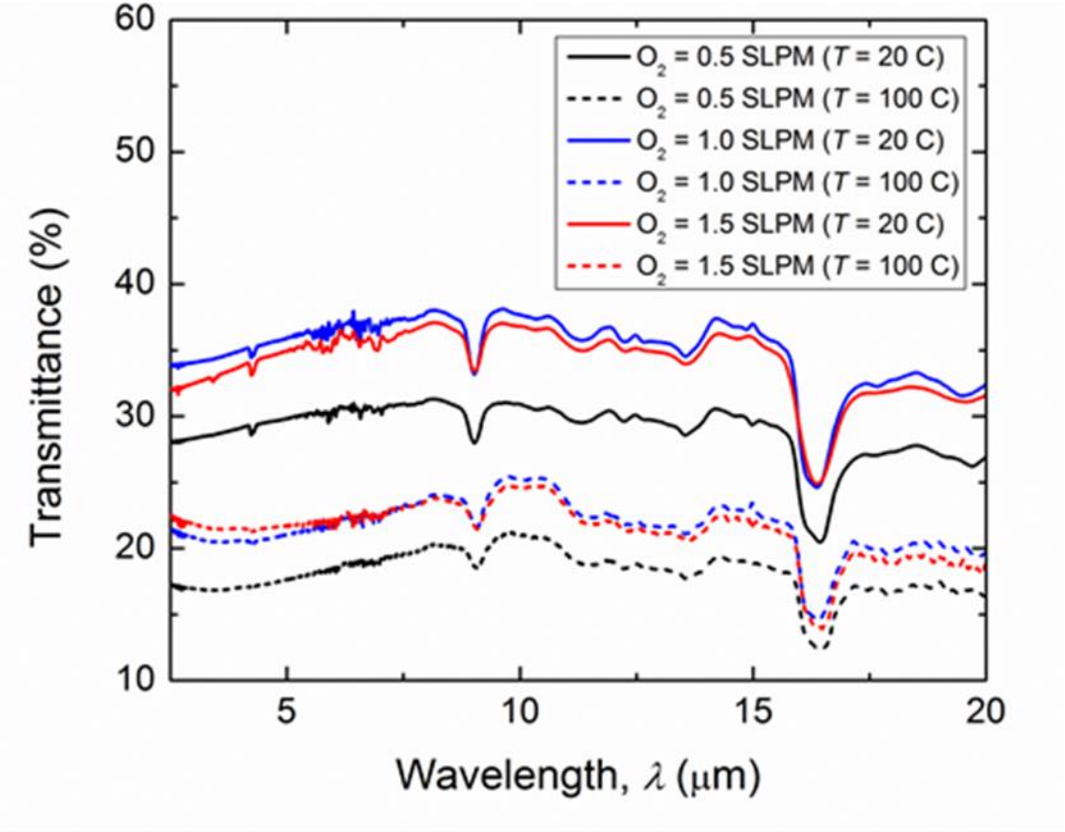


t = 1 hr

t = 2 hr

t = 3 hr

Oxygen Flow Rate



- Transmittance varies *weakly* with O_2 flow rate

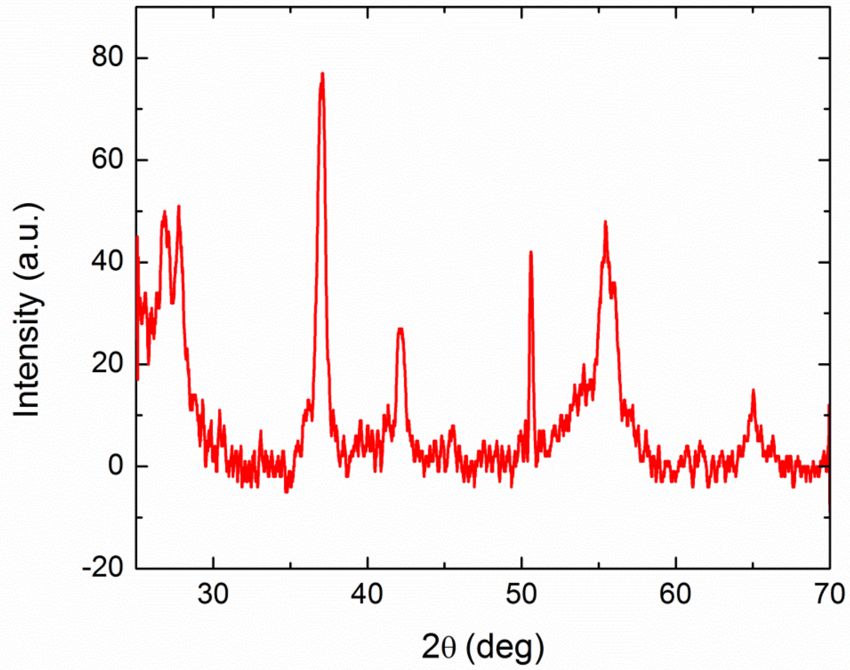
Fabrication Parametric Study

Other Factors Studied

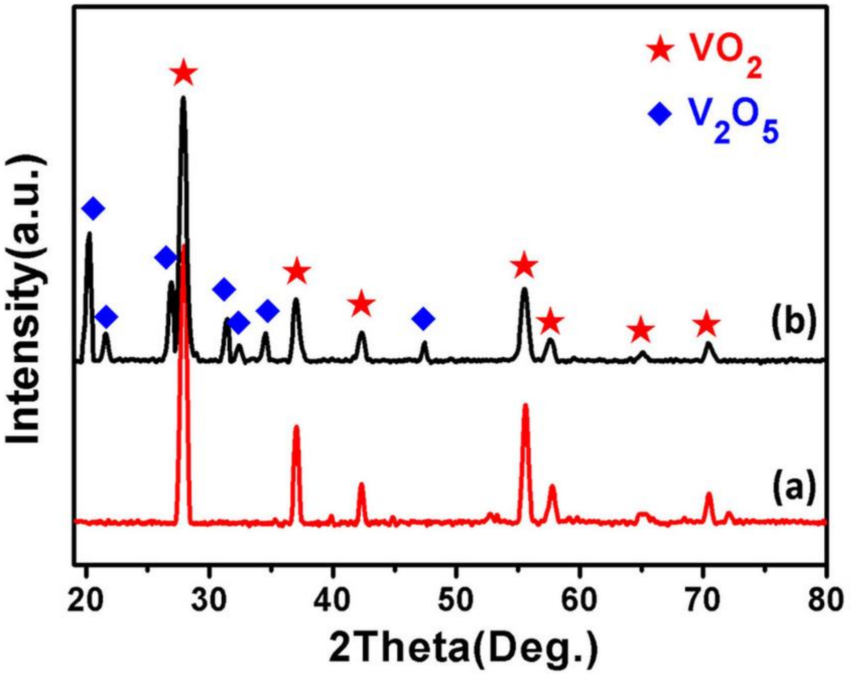
- N_2 flow rate during oxidation → No effect
- Heating rate before oxidation → No effect
- Cooling time after oxidation → No effect
- Vanadium starting film thickness → ***Strong*** effect, need to adjust oxidation time accordingly

Composition Characterization

Measured XRD Pattern



Published XRD Pattern

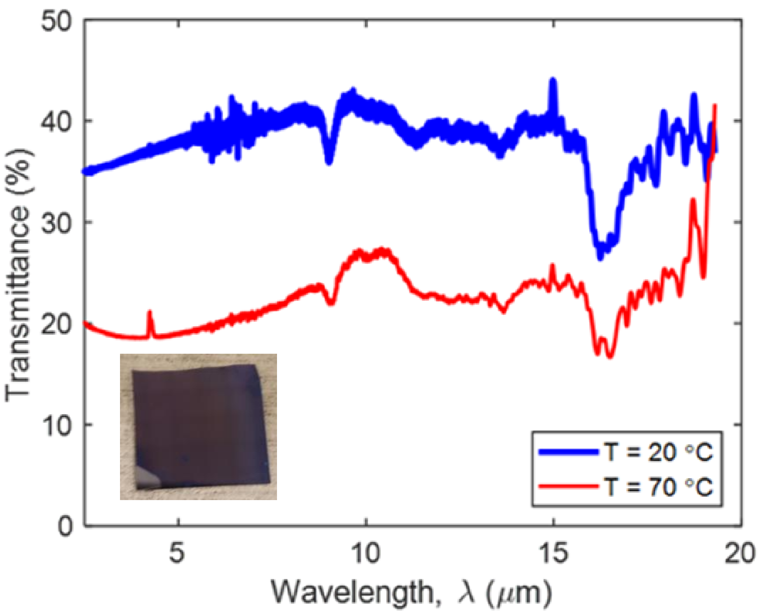


- XRD peaks correspond to published and catalog patterns for VO_2

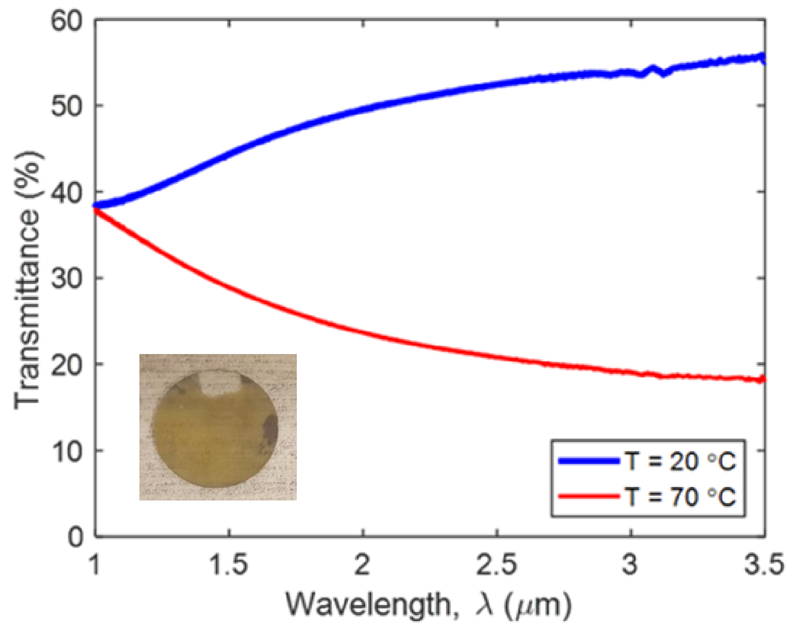
Zhao et al., Scientific Reports ***4****, (2014)*

Spectral Radiative Properties

VO_2 Thin Film on Silicon

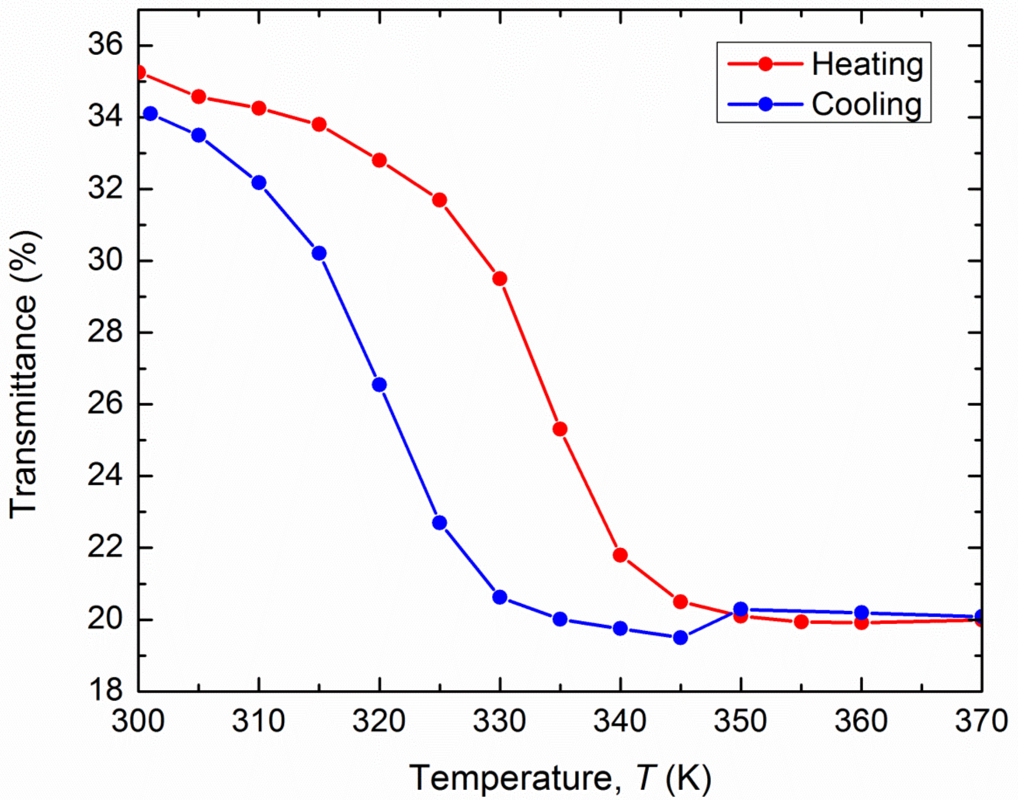


VO_2 Thin Film on Quartz



- VO_2 on Si has an average transmittance change of 15%
- VO_2 on quartz has an average mid-infrared transmittance change of 36%

Heating and Cooling Curves



- Transitions between 320 K and 340 K (heating)
- Transitions between 310 K and 330 K (cooling)
- 15% change in transmittance (λ = 2.5 μm)

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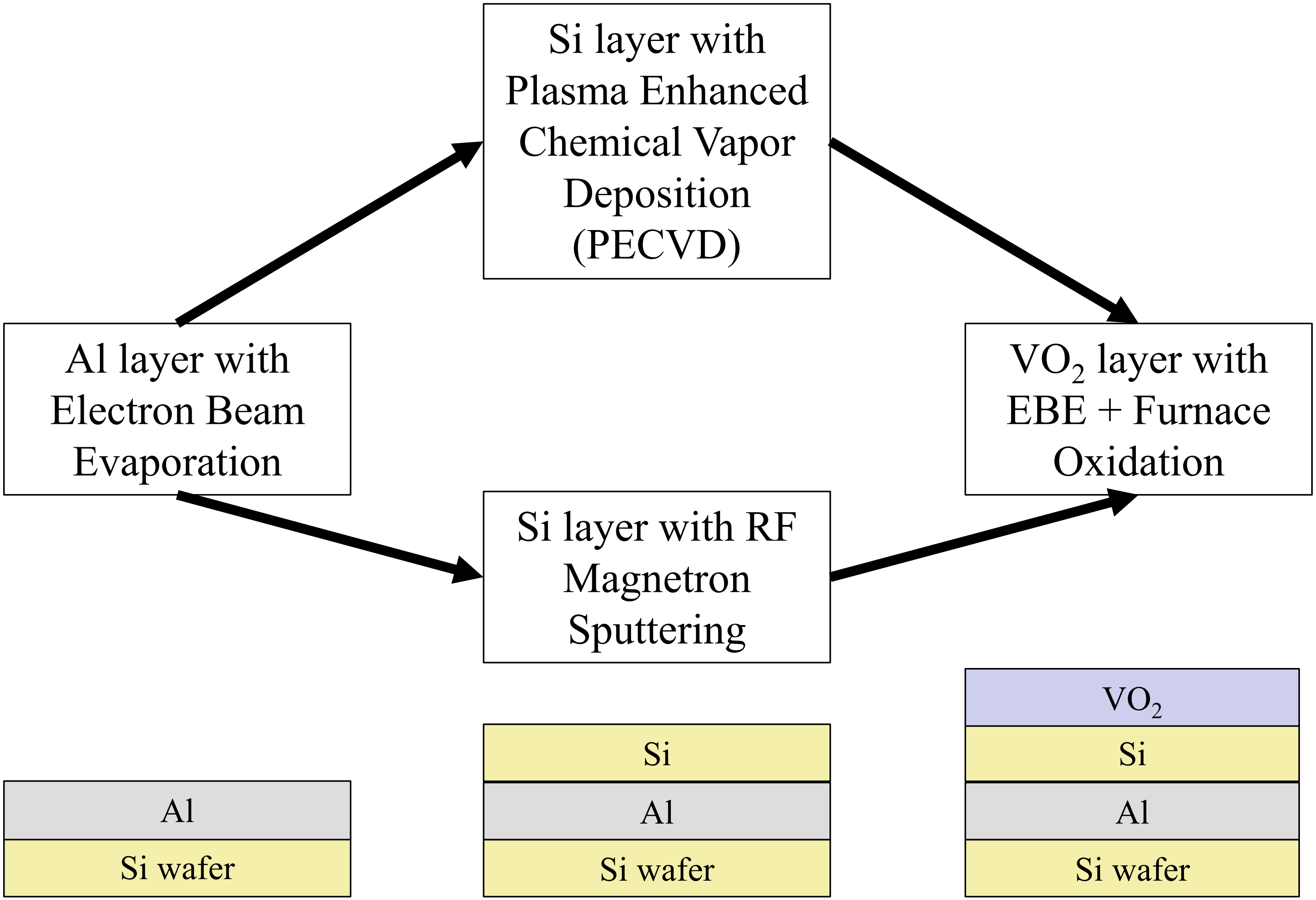
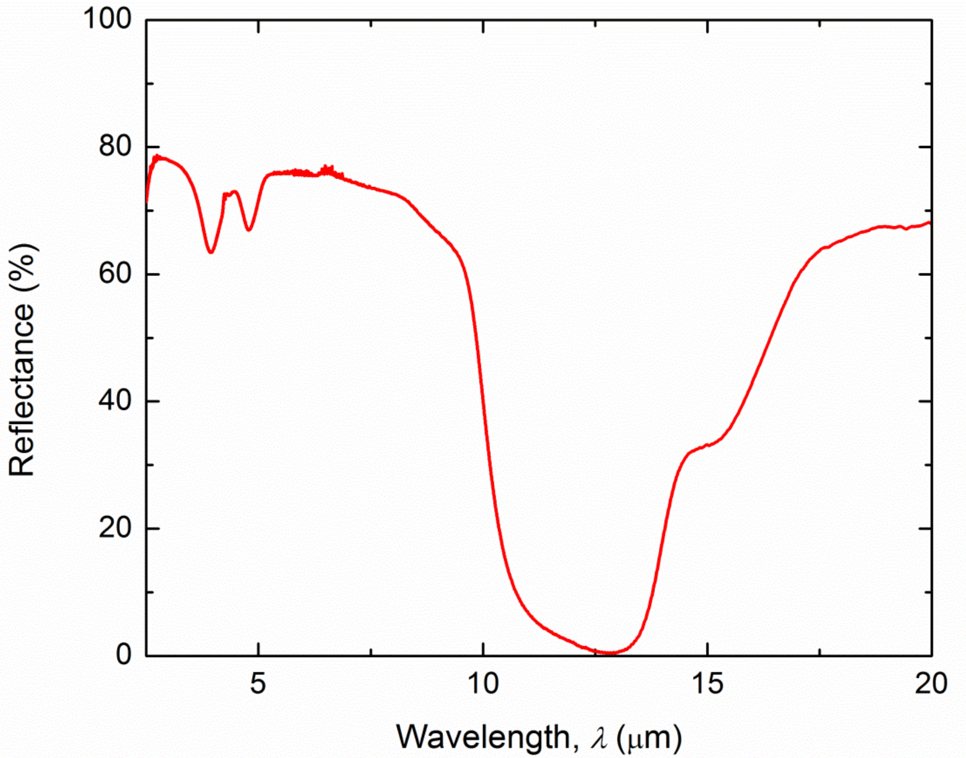
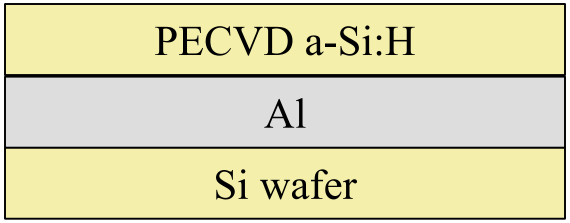
Fabrication Process



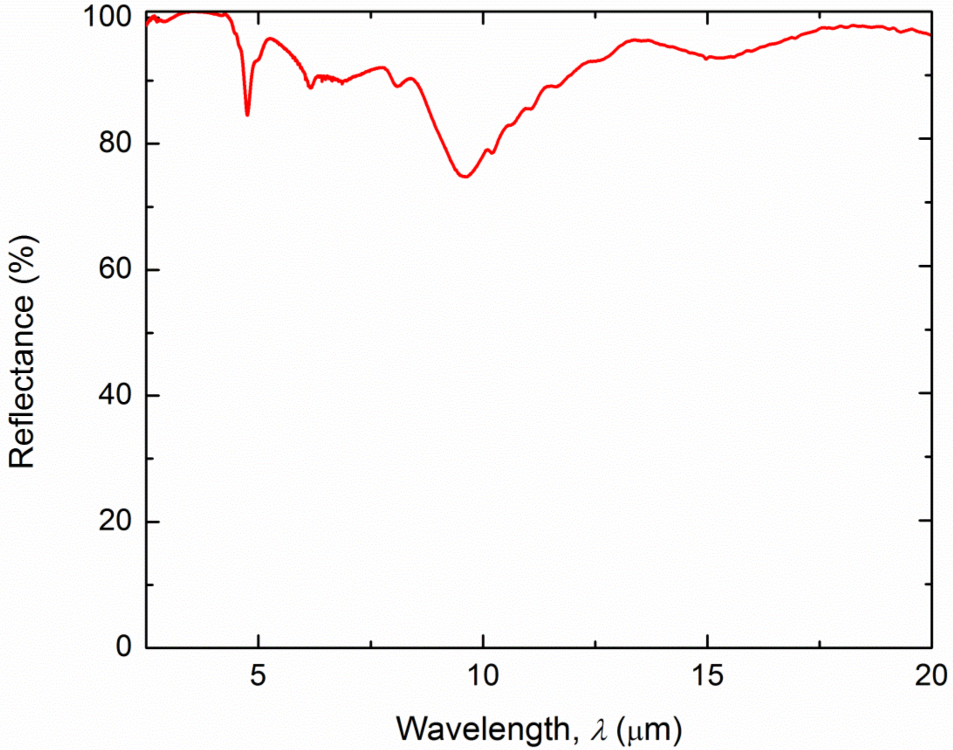
Current Fabrication Work

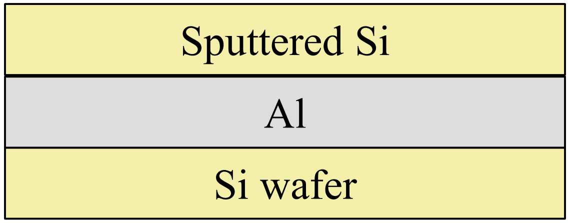




- Overall lower reflectance than expected
- Very strong absorption modes in the 5 to 20 μm wavelength range

Current Fabrication Work





- Low reflectance in the mid-infrared wavelength regime
- Sputtered Si film is rough and possibly porous → discontinuous VO_2

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Summary

- ✓ Developed a tube furnace oxidation method for fabricating quality VO_2 films
- ✓ Confirmed the composition of fabricated samples via materials characterization
- ✓ Studied the effect of various fabrication parameters such as oxygen flow rates and furnace oxidation times
- ✓ Demonstrated the temperature-dependent properties of fabricated VO_2 thin films
- ✓ Preliminary Fabry-Perot emitter samples fabricated and fabrication challenges identified

Future Work

- Continue Fabry-Perot emitter sample fabrication
- Fabricate larger scale Fabry-Perot emitter sample
- Investigate lowering the transition temperature of the VO_2 via impurity doping, defect engineering, etc. (goal transition regime is 5 to 15 ^{o}C)
- Investigate the effect of environmental factors on VO_2-based variable emittance coatings

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