Optimization and analysis of multilayer anti-reflection coating for thin-film Si selective solar absorber

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ECE695 Final Project

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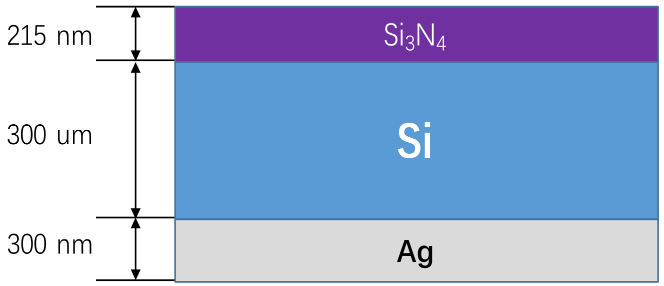
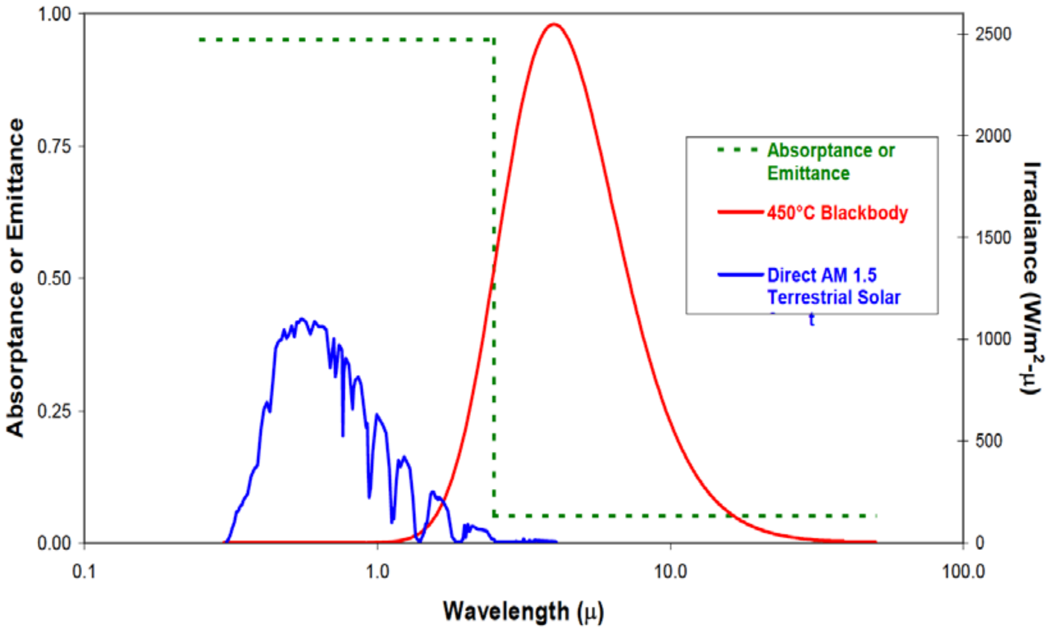
Introduction: Selective absorber

Goal: absorb most sun light while suppress thermal re-radiation

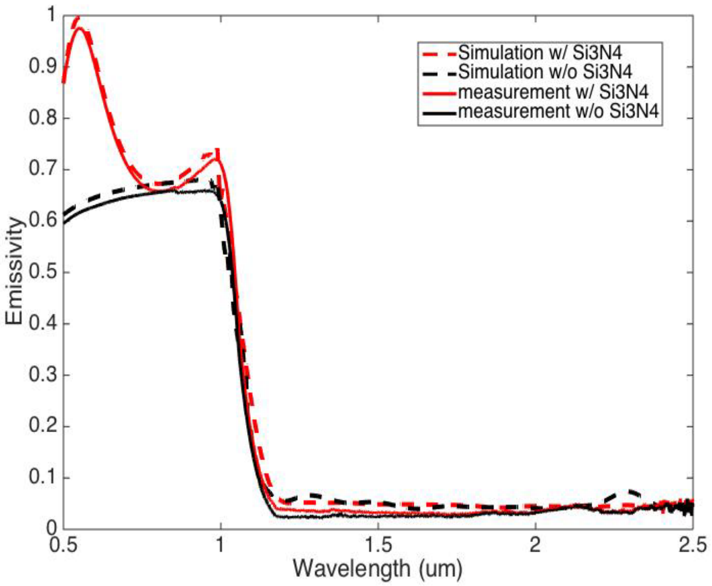
Kirchoff's law $\varepsilon(\lambda) = \alpha(\lambda)$

Si_3N_4: front anti-reflection coating
Si: selective absorbing layer
Ag: back reflector

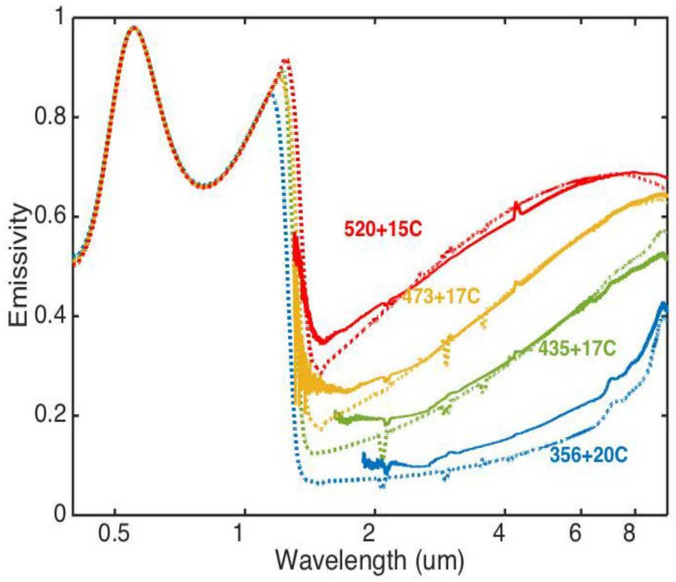




Ideal Selective solar absorber emissivity/absorbtivity



Room temperature



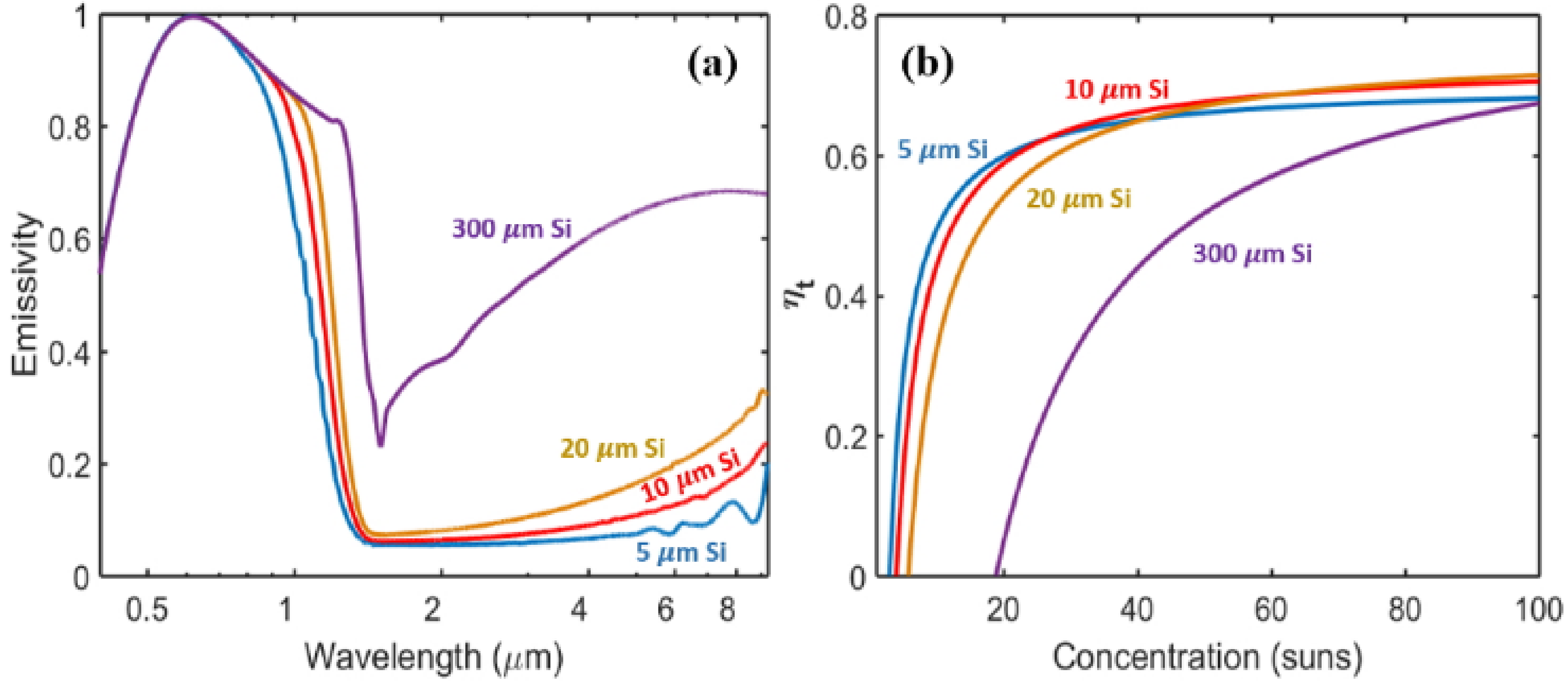
High temperature

Kennedy, Cheryl E. Vol. 1617. Golden, Colo, USA: National Renewable Energy Laboratory, 2002.
Tian, Hao, et al. *Applied Physics Letters* 110.14 (2017): 141101.

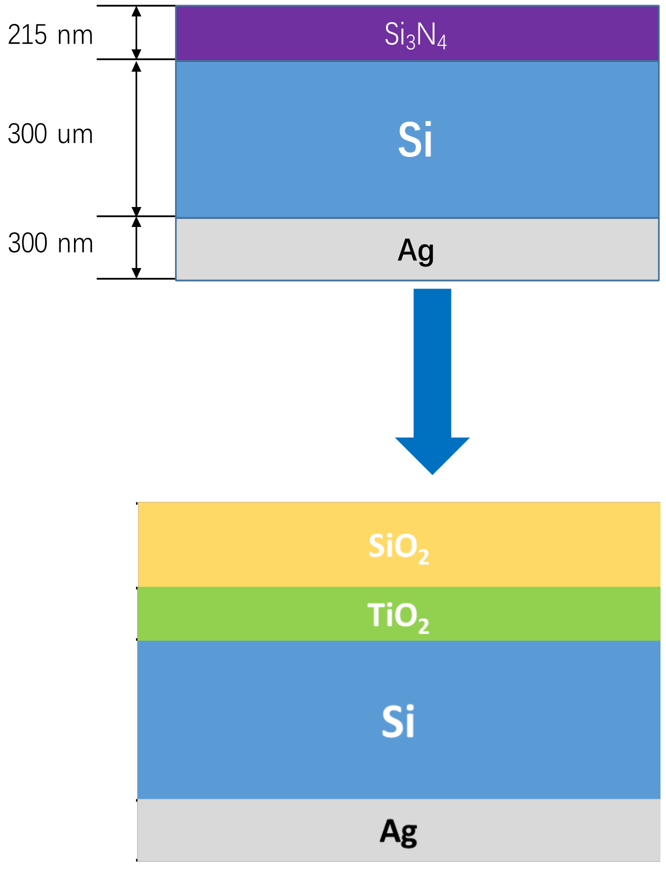
Introduction: Selective absorber

Two ways to increase the efficiency of the absorber:

1. Reduce thermal re-radiation: decrease Si thickness
2. Increase solar absorption: optimize anti-reflection coating using multi-layer coating.



Thin Si film simulation at 550°C for different Si thicknesses.



Optimize it to get increased solar absorption.

Tian, Hao, et al. *Applied Physics Letters* 110.14 (2017): 141101.

Mathematical Model for Selective Absorber

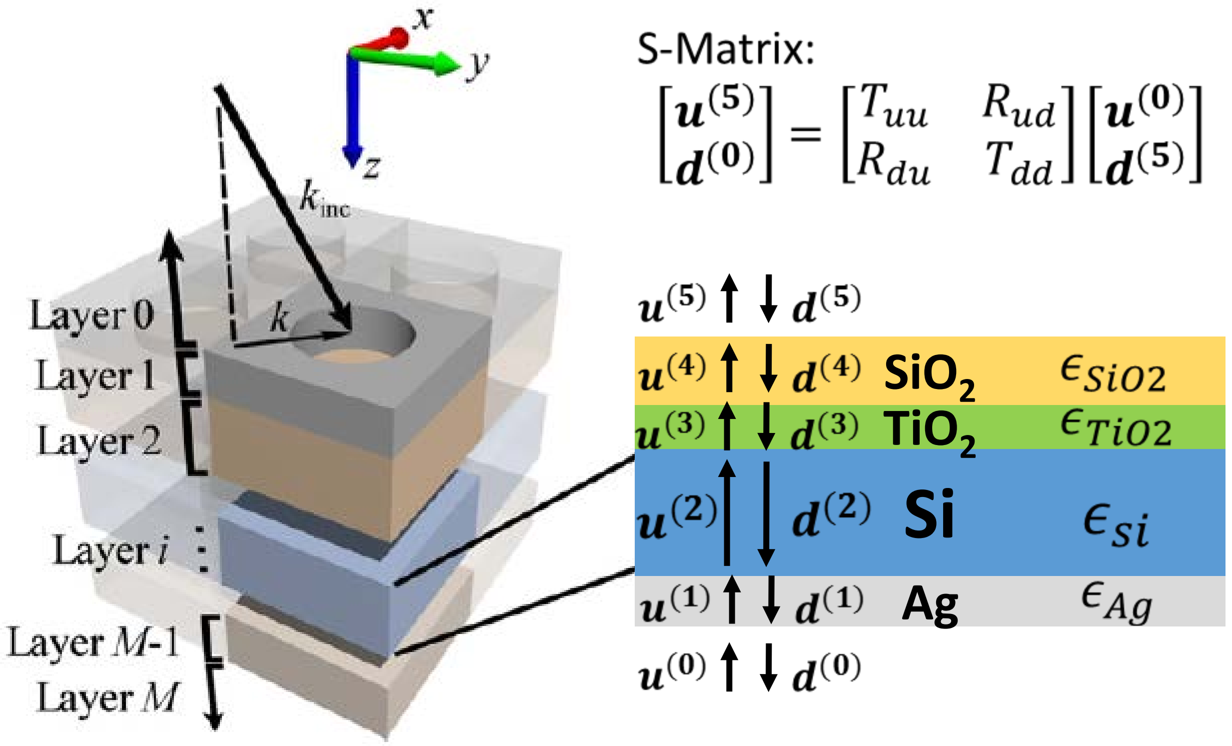
Maxwell's equation in layer:

$$\nabla \times \boldsymbol{H} = -i\omega\epsilon_0\epsilon\boldsymbol{E}$$

$$\nabla \times \boldsymbol{E} = i\omega\mu_0\boldsymbol{H}$$

S-Matrix:

$$\begin{bmatrix} \boldsymbol{u}^{(5)} \\ \boldsymbol{d}^{(0)} \end{bmatrix} = \begin{bmatrix} T_{uu} & R_{ud} \\ R_{du} & T_{dd} \end{bmatrix} \begin{bmatrix} \boldsymbol{u}^{(0)} \\ \boldsymbol{d}^{(5)} \end{bmatrix}$$



Material data (ϵ) are found from literatures:

ϵ_{SiO2}: Malitson 1965 + Kischkat 2012

ϵ_{TiO2}: Kischkat 2012

Si: Green and Keevers 1995+Salzberg and Villa 1957+Bermel 2010

Ag: Rakić 1998

Thermal transfer efficiency:

$$\eta_t = \bar{\alpha} - \frac{\bar{\varepsilon}\sigma T^4}{CI}$$

$$\bar{\varepsilon} = \frac{\int_0^\infty d\lambda\, \varepsilon(\lambda) / \{\lambda^5[\exp\left(\frac{hc}{\lambda kT}\right) - 1]\}}{\int_0^\infty d\lambda\ / \{\lambda^5[\exp\left(\frac{hc}{\lambda kT}\right) - 1]\}}$$

$$\bar{\alpha} = (1/I)\int_0^\infty d\lambda\, \varepsilon(\lambda)\, dI/d\lambda$$

σ - Stefan–Boltzmann constant,

T - temperature, C - solar concentration,

I - solar intensity.

Liu, Victor, and Shanhui Fan. *Computer Physics Communications* 183.10 (2012): 2233-2244.

I.H. Malitson. *J. Opt. Soc. Am.* 55, 1205-1208 (1965)

J. Kischkat, et al. Appl. Opt. 51, 6789-6798 (2012)

M. A. Green and M. J. Keevers, Prog. Photovoltaics Res. Appl. 3, 189 (1995).

C. D. Salzberg and J. J. Villa, J. Opt. Soc. Am. 47, 244 (1957).

P. Bermel, et al., Opt. Express 18, A314 (2010).

A. Rakic, A. Djurisic, J. Elazar, and M. Majewski, Appl. Opt. 37, 5271 (1998).

Mathematical Model for optical property of Si at high temperatures

	Wavelength range		Semi-empirical equtions
α (or equivalently $k = \alpha\lambda/(4\pi)$)	0.4-0.8um	k	$k(h\nu,T) = k_0(h\nu)\exp(T/T_0(h\nu))$
	1-10um	α_{BG}	$\alpha_{BG}(h\nu,T) = \sum_{i=1}^{4}[\alpha_{ia}(h\nu,T) + \alpha_{ie}(h\nu,T)]$
		α_{FC}	$\alpha_{FC} = 4.15\times10^{-5}\lambda^{1.51}T^{2.95}\exp(-7000/T)$
		α_L	α_L is assumed to be constant and can be deduced from the experimental results of Sato
n	0.4-1um		$n(h\nu,T) = \sqrt{4.386 - 0.00343T + (99.14 + 0.062T)/(E_g^2 - (h\nu)^2)}$
	1-10um		$n(\lambda,T) = \sqrt{\varepsilon_r(T) + \frac{L(T)}{\lambda^2}(A_0 + A_1T + A_2T^2)}$,

Roozeboom, Fred, ed. *Advances in rapid thermal and integrated processing*. Vol. 318. Springer Science & Business Media, 2013.

T. Sato, Jpn. J. Appl. Phys., Part 1 6, 339 (1967).

Numerical Approach and Validation

S4: the calculation of the reflection R of the stratified structure.
The absorptivity is calculated by:

$$\alpha = 1 - R.$$

The emissivity is calculated according to Kirchoff's law:

$$\varepsilon = \alpha$$

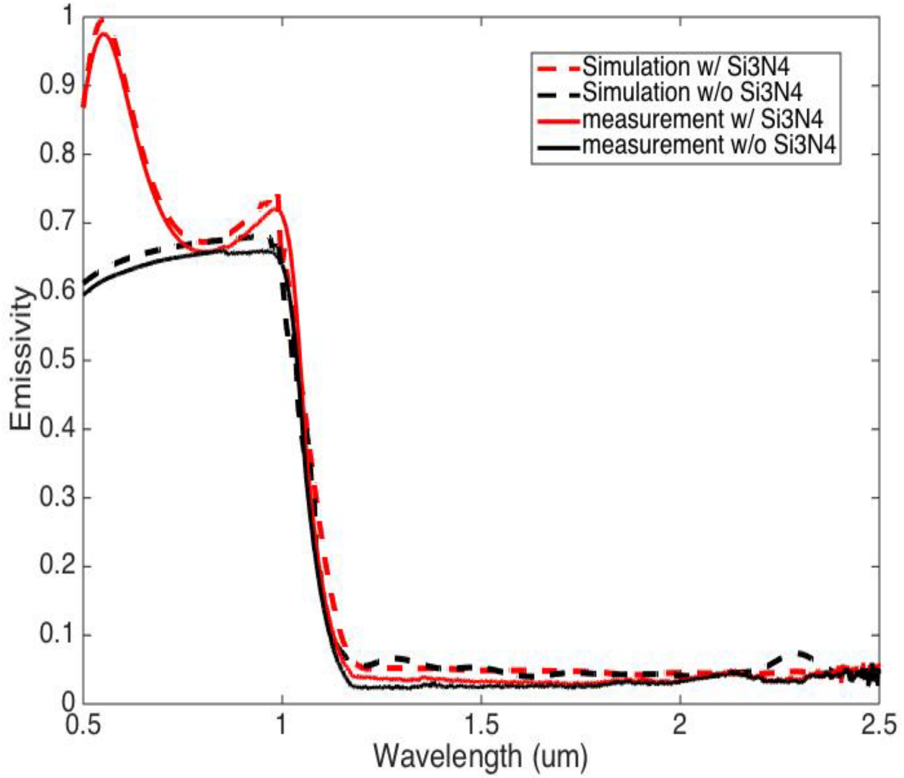
S4 code:

```
S = S4.NewSimulation()
S:SetLattice({1.000000,0.000000},{0.000000,1.000000})
S:SetNumG(1)
S:AddMaterial("vacuum", {1.00000000000,0.00000000000})
S:AddMaterial("SIO2", {2.161619071947,0.00000000000})
S:AddMaterial("TIO2", {8.612985358210,0.00000000000})
S:AddMaterial("SICR", {34.418445511694,8.597409413696})
S:AddMaterial("AG", {-3.593775076486,0.534195073204})
a=1;
S:AddLayer('Layer_Above', 0.000000, 'vacuum')
S:AddLayer('layer_1', 0.1/a, 'SIO2')
S:AddLayer('layer_2', 0.05/a, 'TIO2')
S:AddLayer('layer_3', 20/a, 'SICR')
S:AddLayer('layer_4', 0.3/a, 'AG')
S:AddLayerCopy('Layer_Below', 0.000000, 'Layer_Above')
S:SetExcitationPlanewave({0.000000,0.000000},{1.000000,0.000000},{1.000000
,0.000000})
```

Normal incident light with both polarization

Assumptions:

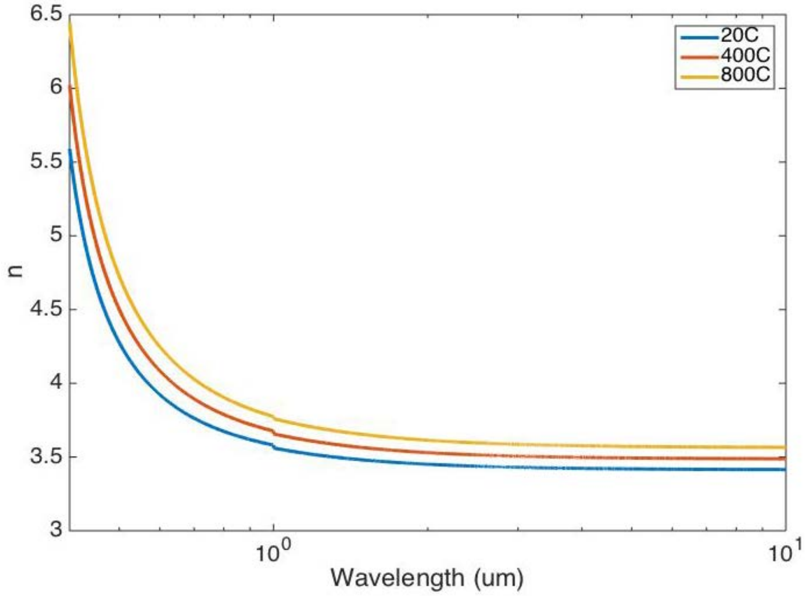
Each layer is ideally flat without any fluctuation



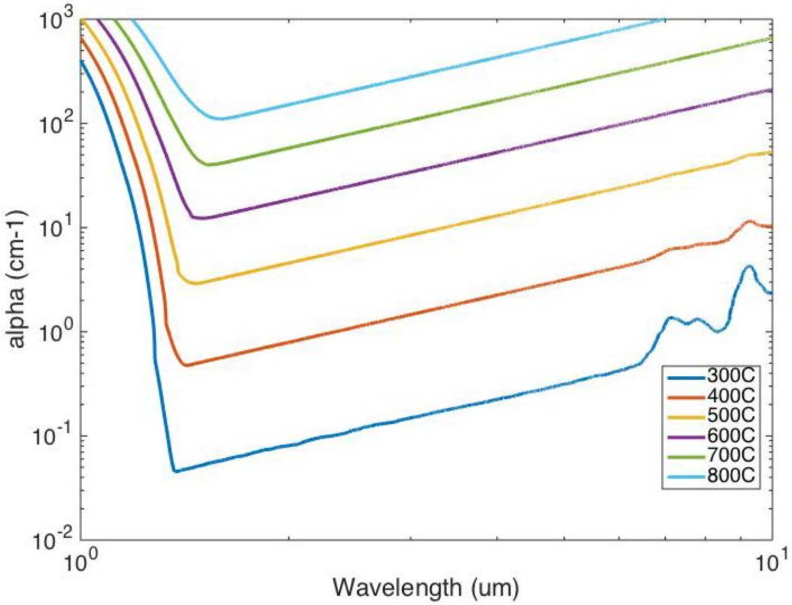
The S4 model is validated through our previous experimental results

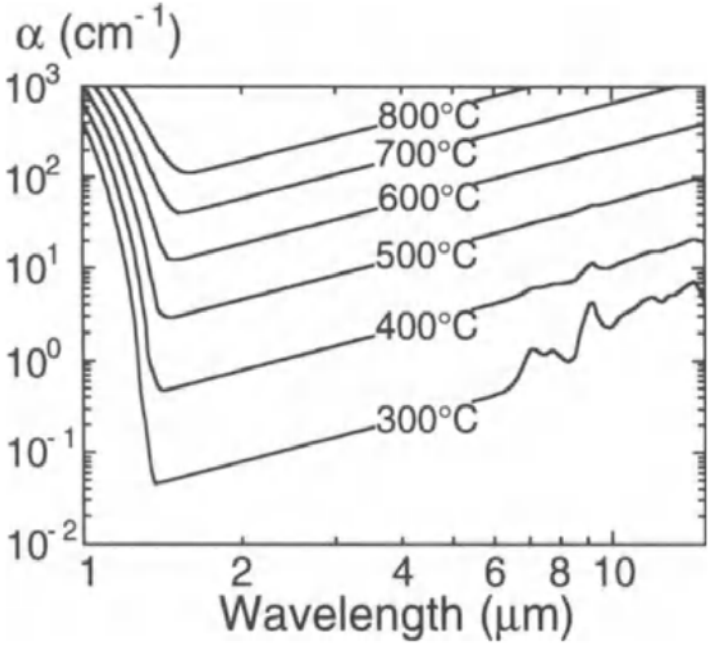
Numerical Approach and Validation

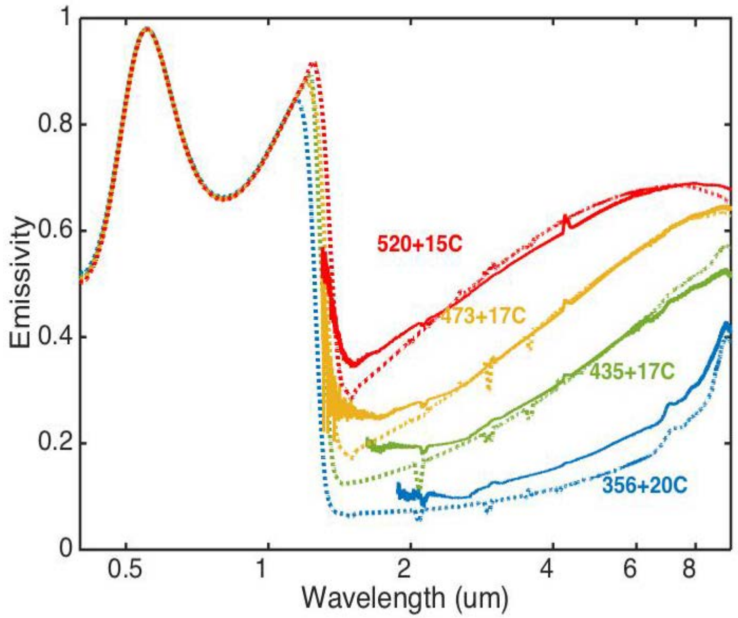
The optical property of Si at high temperature is calculated in Matlab using the empirical equations.



Absorption coefficient





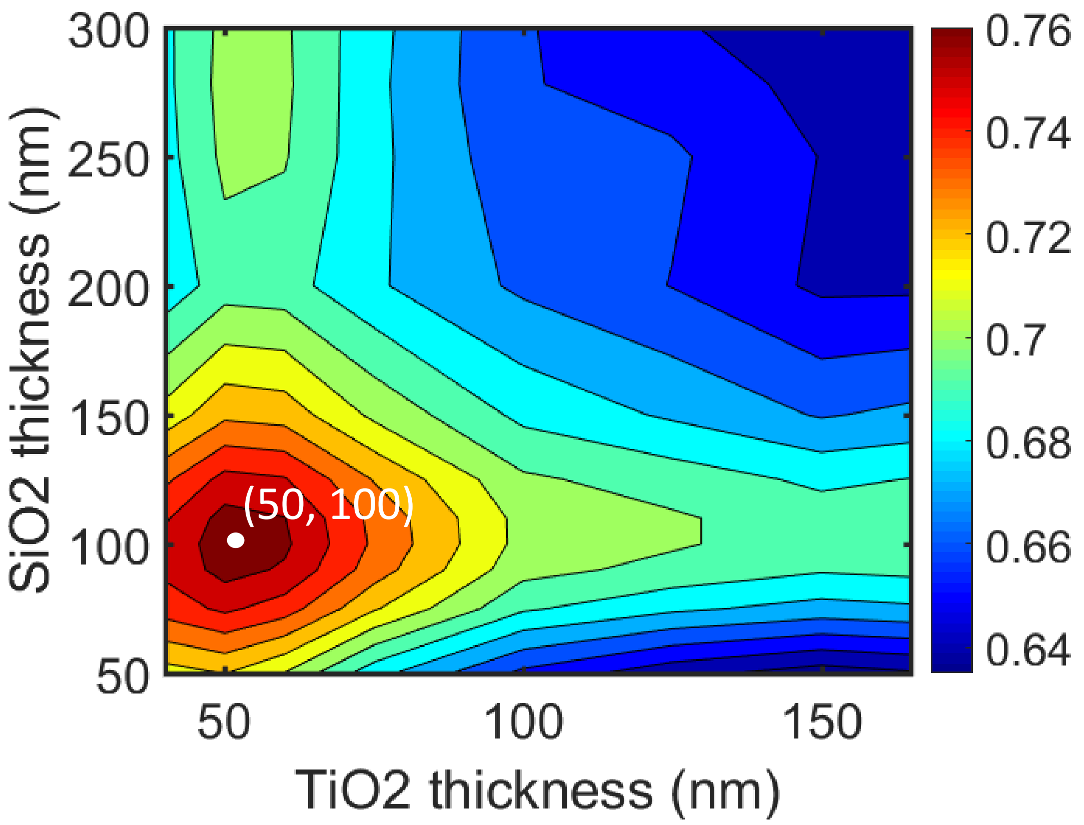


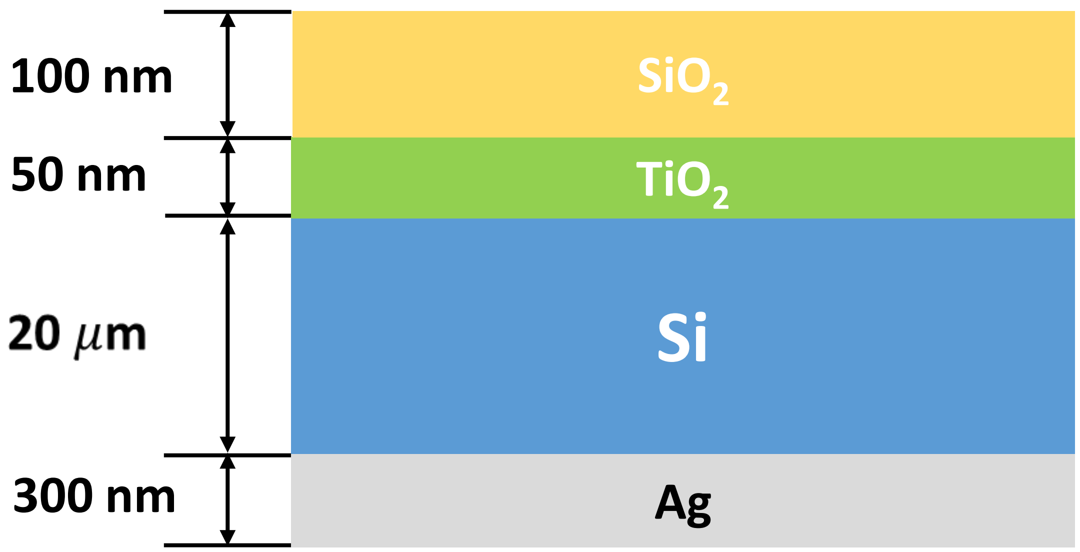
F. Roozeboom, Advances in Rapid Thermal and Integrated Processing (Springer Science & Business Media, 2013).

Tian, Hao, et al. *Applied Physics Letters* 110.14 (2017): 141101.

Optimization of TiO_2 and SiO_2 thickness

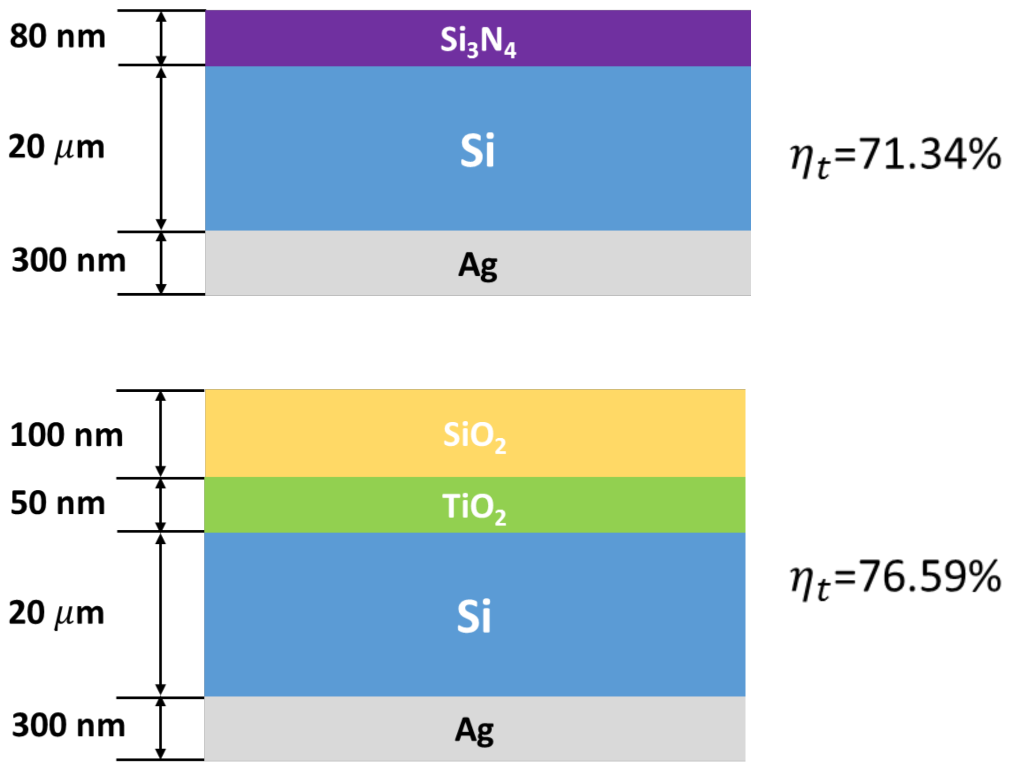
The targeted temperature is 550°C, Si 20um, Ag 300nm under 100 suns.
Optimal TiO_2 and SiO_2 thicknesses are 50 nm and 100nm, which generates thermal transfer efficiency 76.59%.



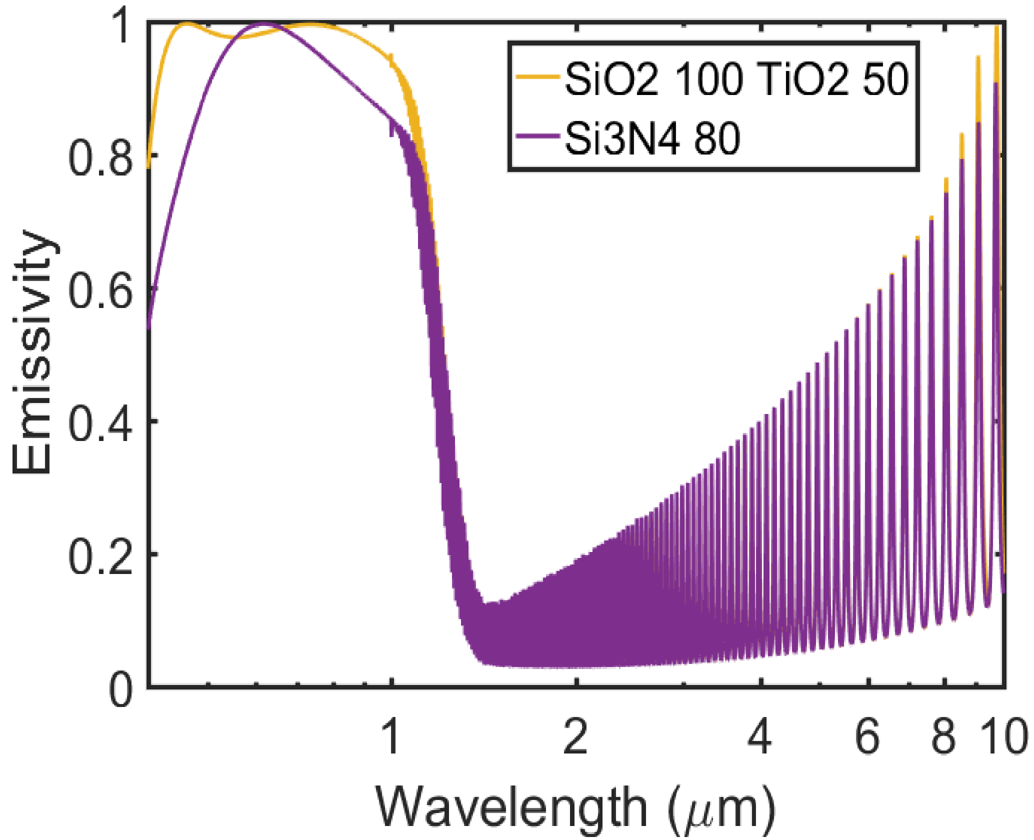


Optimization of TiO_2 and SiO_2 thickness

T=550C, C=100 suns.



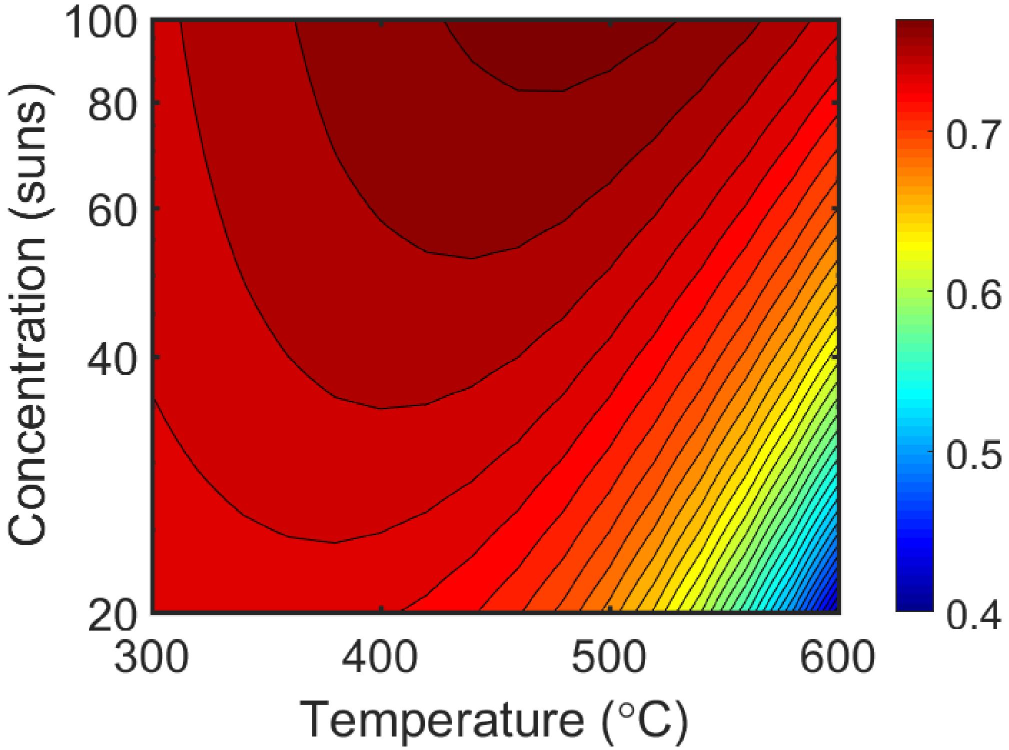
Comparison between one layer (Si_3N_4) and multilayer (SiO_2+TiO_2) anti-reflection coating



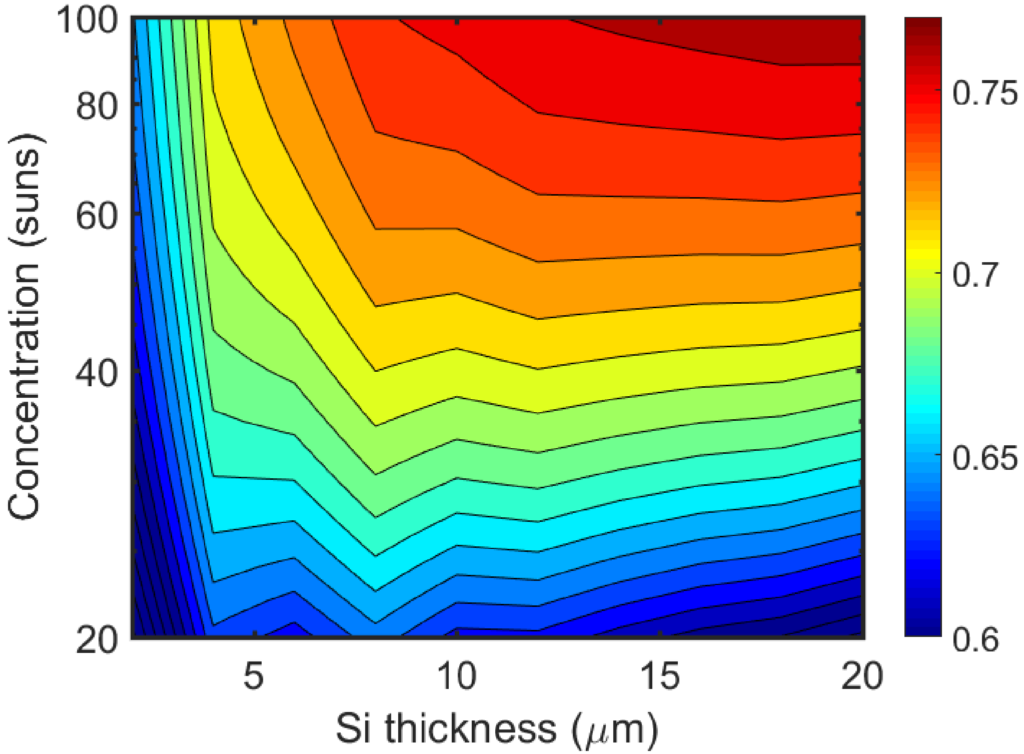
Efficiency under different temperatures for different Si thicknesses

The optimal temperature decreases as the concentration decreases.
For 20um Si, the optimal temperature at 100 suns is 480°C, with maximum efficiency 77.42%.

As we increase the concentration, the optimal Si thickness increases, since the absorption will increase.



Efficiency under different temperatures for 20 um Si



Efficiency for different Si thickness under 550°C

Conclusions

- Model based on S4 for the calculation of the reflection of the selective solar absorber is established.
- High temperature Si model is established using Matlab which is useful for the optical simulation of Si at high temperatures
- To increase the absorption of sunlight, multilayer antireflection coating is designed and analyzed. The optimal thicknesses for SiO_2 and TiO_2 are 100nm and 50nm respectively.
- The optimized structure shows increased absorption while thermal re-radiation is not influenced.
- The thermal transfer efficiency at 550°C for 20um Si is increased to 76.59%.
- The Efficiency and optimal temperature increase as the concentration is increasing for 20um Si.
- The optimal Si thickness decreases as the concentration decreases.

Thank you very much!

Questions?