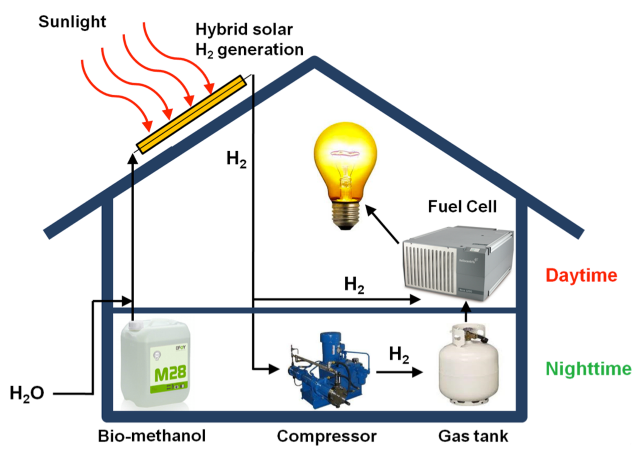
Optimization and fabrication of a high-temperature selective absorption coating for concentrated solar thermal collectors

Shomik Verma, Qingyu Xiao, Nico Hotz

Thermodynamics and Sustainable Energy Laboratory, Department of Mechanical Engineering and Materials Science, Duke University

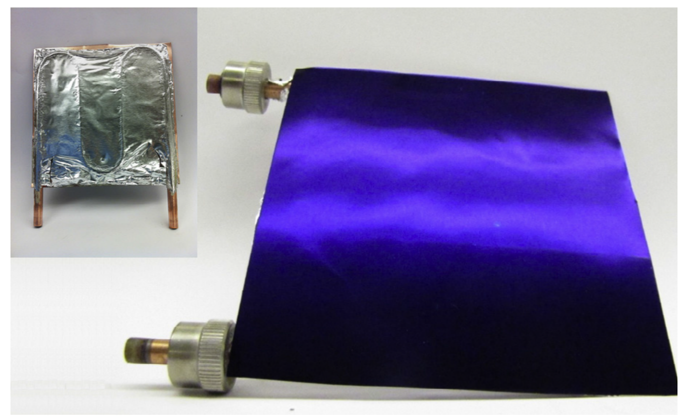
Introduction

There are tremendous research efforts focused on capturing thermal energy from the sun. Our current application is using this heat for steam reforming of biofuels into hydrogen. Stable biofuels such as methane require higher temperatures, meaning CSP is necessary. The challenge of CSP is its high operating temperatures (~1000K), as most absorption coatings are only rated to ~600K.



Objectives

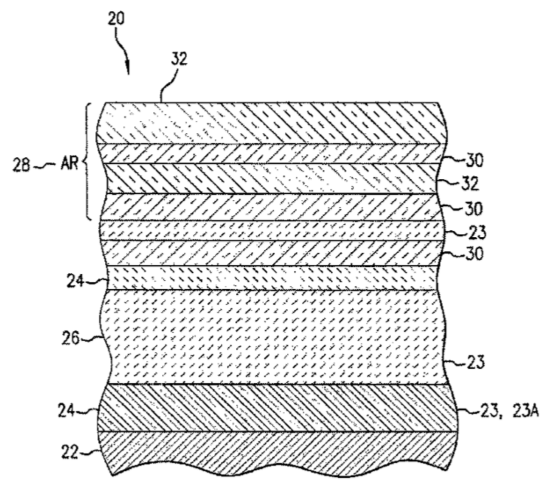
- Develop a high-temperature selective absorption coating with high solar absorptivity and low ambient emissivity
- Model the coating based on radiation principles, optimize based on efficiency and ease of fabrication
- Fabricate the coating and test with experimental setup consisting of flat plate collector inside an insulting vacuum



Modeling

NREL #6A

Layer	Material	Thickness (nm)
1	SiO_2	58.61
2	TiO_2	3.91
3	SiO_2	34.75
4	TiO_2	31.92
5	TiSi-a	2.75
6	TiO_2	32.68
7	TiSi-a	19.36
8	SiO_2	73.01
9	TiSi-a	383.41

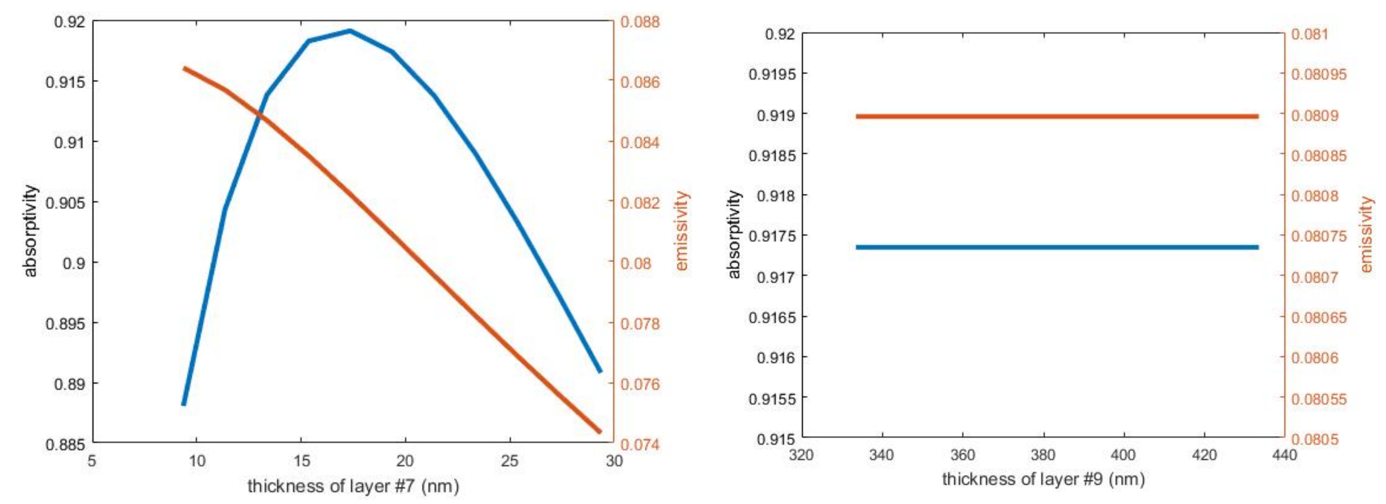


A coating designed by NREL (#6A) was considered. The use of high temperature resistant materials with optimal optical properties makes this ideal. The coating consists of a solar absorber (TiSi) with high solar absorptivity and low ambient emissivity. An IR reflector (TiO_2) with high solar transmissivity and high IR reflectivity is used to capture any reflected heat. An anti-reflective coating (SiO_2) is used to ensure all solar radiation is transmitted to the coating. A comparison of our model vs. NREL's is presented below:

	Absorptivity	Thermal Emissivity @ 25°C	100°C	200°C	300°C	350°C	400°C	450°C	500°C
NREL	0.959	0.027	0.033	0.040	0.048	0.053	0.061	0.070	0.073
This work	0.917	0.044	0.045	0.047	0.052	0.057	0.063	0.071	0.081

Sensitivity and Optimization

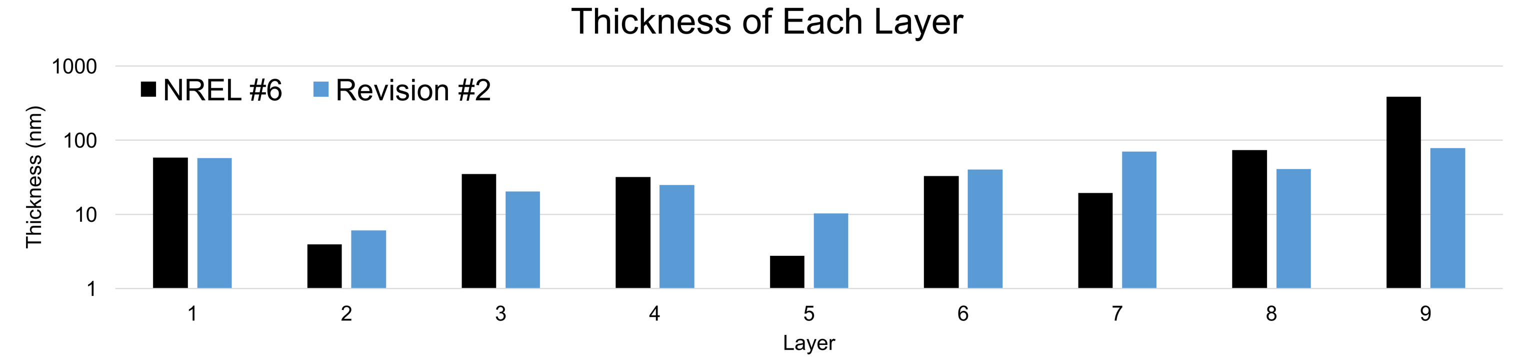
Deposition machines are often not able to achieve thicknesses with accuracy within hundredths of nanometers, as suggested by NREL #6A. Thus a sensitivity analysis was conducted to determine how accurate each layer thickness needed to be.



As seen, the thickness of layer 7 matters a lot, but layer 9 can be changed immensely with no significant change in overall operation. This suggests the design can be optimized to reduce material costs and manufacturing time. Our optimization algorithm uses differential evolution to maximum efficiency. We define efficiency as the amount of heat delivered to the biofuel from the absorption coating divided by the incident radiation. This is therefore defined as

$$\eta = \frac{\alpha - \epsilon\sigma T^4}{I}$$

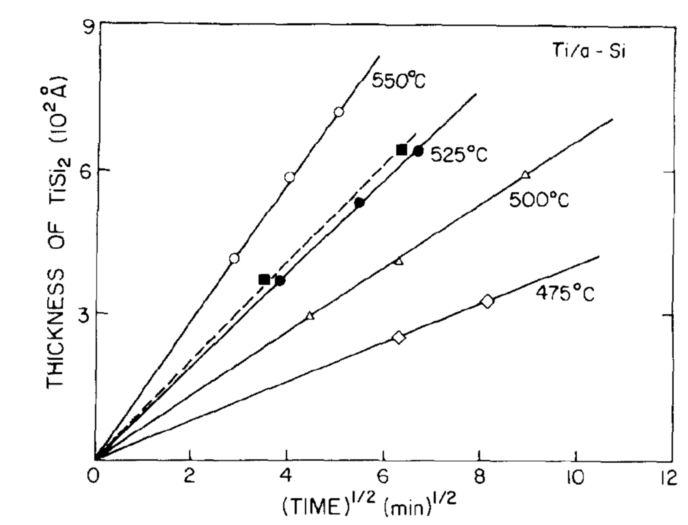
Using this objective function, we ran the optimization algorithm which returned the following results in log scale:

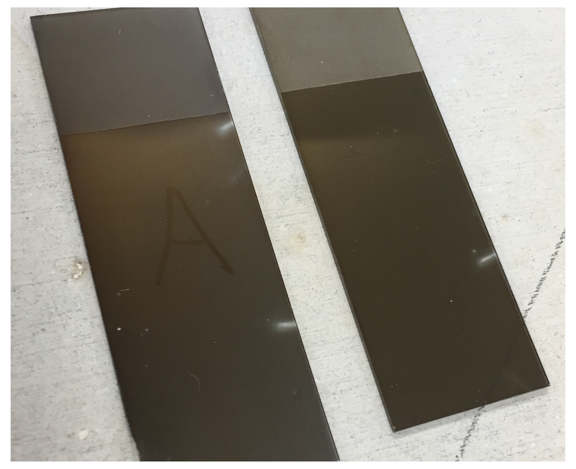


This optimized design maximizes efficiency while reducing the thickness of layer 9 by **4.8 times**.

Fabrication

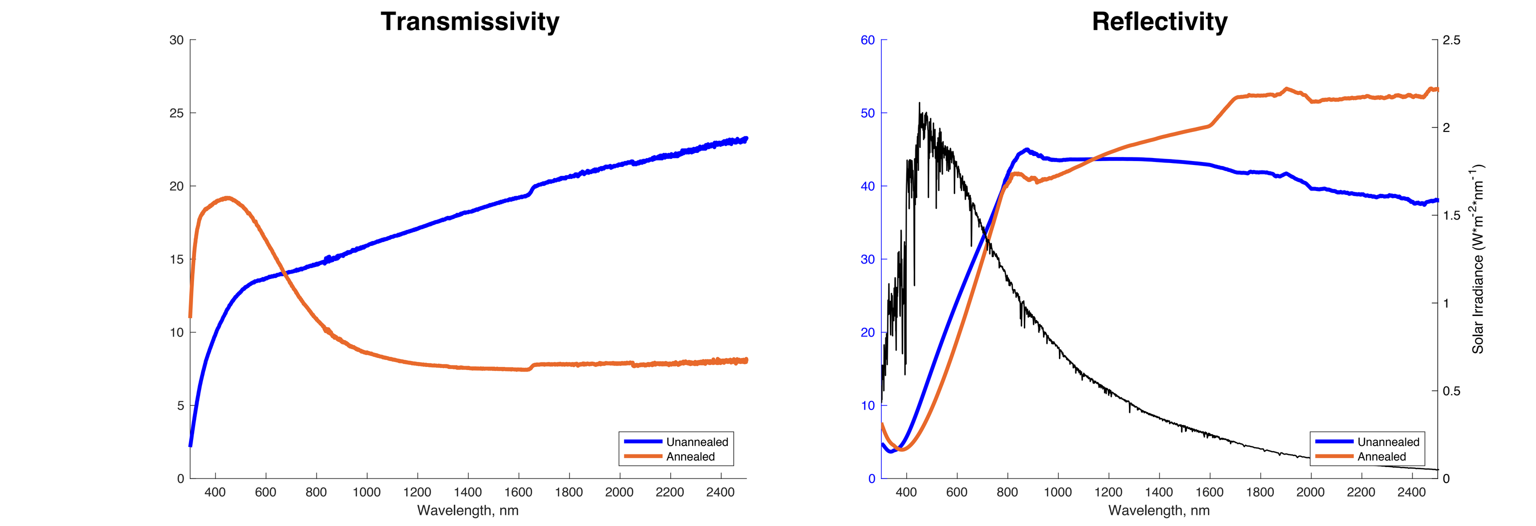
The coating is fabricated at the Shared Materials Instrumentation Facility (SMIF) at Duke University. DC and RF sputtering is used to deposit the thin films required for the coating. While TiO_2 can be directly sputtered, TiSi must be formed by separately depositing films of Ti and Si and then annealing to promote interdiffusion. SiO_2 can be deposited using PECVD. The graph below shows annealing time vs. temperature. The picture on the right shows 10 nm Si on 50 nm Ti, annealed vs. unannealed.





Characterization

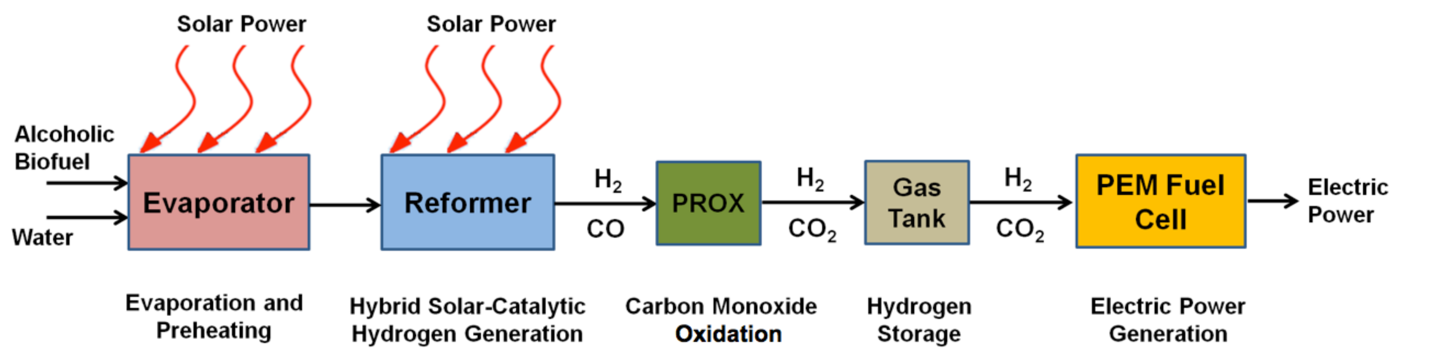
The preliminary absorber with solely TiSi was characterized with the UV-Vis-IR spectrophotometer to determine reflectivity and transmissivity of the sample.



As seen, the annealing step benefits in both measurements. It reduces the transmissivity (ideally the coating is opaque, but the thicknesses are too low for this to happen) and increases IR reflectivity. Comparing the reflectivity with the solar radiation spectrums shows ideal characteristics. Adding the TiO_2 and SiO_2 layers will help improve these optical properties further.

Conclusions and Next Steps

- Conclusions:
  - The model proposed by NREL (#6A) can be improved drastically to optimize efficiency and reduce material costs.
  - Fabricating the first layer gives promising results with high visible absorption and low IR emissivity
- Next steps:
  - Investigate diffusion of Si in Ti further. Impacts of multilayer deposition (i.e. 25 nm Ti, 10 nm Si, 25 nm Ti)
  - Deposition or IR reflector (TiO_2) and AR coating (SiO_2)
  - Re-characterization of optical properties with full coating
  - Comparison of substrates for temperature resistance and limited substrate diffusion into the coating (stainless steel, aluminum, copper, glass)
  - High-temperature resistance and thermal cycling analysis
  - Testing temperature in actual vacuum-insulated solar collector for use in steam methane (biogas) reforming



References

[1] Kennedy, Cheryl. "High temperature solar selective coatings" US Patent #8893711 B2. Nov 25, 2014.

[2] Hung, L.S. et al. "Kinetics of TiSi2 formation by thin Ti films on Si" Journal of Applied Physics. 1983.