Key Research Challenges in TPV

• Integrate new high-performance components: selective solar absorbers, selective thermal emitters, filters, and TPV cells
• Characterize and model materials degradation under operating conditions
• Demonstrate long-term reliability and reproducibility of system performance
• Incorporate radiative cooling where needed
TPV experiment setup

- Silver paste
- Copper wire
- Heater
- Shield (Niobium)
- GaSb PV diode
- ErAlGa emitter
- W wires
- Inside the shield
- W slab
- Graphite foil
- Graphite foil
- ErAlGa emitter
- Heater shield (Niobium)
- GaSb PV diode
- Silver paste
- Copper wire

4/10/2017
TPV characterization experiment

- A custom-built TPV experiment setup
- Isc roll-over happens at high temperature
- GaSb PV diode provided by JX Crystal
- Thermal source by Tectra
- Initial measurements using 2 separate emitters
Direct Thermal Emission Measurement (DTEM) for STPV

- Looking through the CaF$_2$ window
- A thermal power sensor is placed outside the window
**I_{sc}** vs. Heater Temperature

- Isc is directly measured from the GaSb diode
- Heater temperature is directly measured by a type-C thermocouple
- Isc roll-over is observed > 600 °C
- Heat shield temperature is assumed to be 150 °C below heater temperature
- Built simulation tool (TPVexpt) to compare directly to data
- Heat shield temperature does not cause the Isc roll-over
Non-idealities in experiment

- Heat shield is radiating (considered in TPVexpt simulation)
- Temperature gradient

\[ k(T_{heater} - T_{emitter}) = \sigma \varepsilon_{ave} (T_{emitter}) T_{emitter}^4 \]

Power transferred through conduction

Power dissipated through radiation

- PV diode temperature

<table>
<thead>
<tr>
<th>Heater Temperature/ °C</th>
<th>Diode Temperature/ °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>108</td>
</tr>
<tr>
<td>700</td>
<td>130</td>
</tr>
</tbody>
</table>

Coarse \( T_C \) measurement
Prior work: active cooling methods

Heat sink
Chunky;
Limited to the ambient temperature

Coolant
Extra power consumption
Double Heat Shielding for Improved DTEM

- Double Heat Shield Reduces Excess Radiation significantly
- Allows for close match to theoretical models
Passive Copper Cooling

The heater temperature (°C) vs. Cu tube temperature (°C) for passively cooled conditions.

- Heater temperature
- Cu Tube temperature

Passively cooled
Radiative Cooling for Passive Thermal Management

3 K microwave background

Photonic Crystal

The sky transparency window allows radiative cooling outdoors

Questions:
1. Any alternative coolers to PhCs?
2. What is the temperature reduction and performance improvement by applying radiative cooling to hybrid or STPV systems?

Most PV cells experience heating from sub-bandgap absorption

In c-Si cells, degradation processes with activation energy of 0.85 eV are accelerated almost a factor of 2 for every 10 K temperature difference

X. Sun et al., IEEE J. Photovolt. (submitted, July 2016)
Radiative cooling on PV devices

Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody

Linxiao Zhu, Aaswath P. Raman, and Shanhui Fan

*Department of Applied Physics, Stanford University, Stanford, CA 94305; and *Ginzton Laboratory, Department of Electrical Engineering, Stanford University, Stanford, CA 94305

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Bare absorber

Bare absorber +silica

Bare absorber +silica PhC

• Silica/silica PhC layer should at least preserve the solar absorption of the absorber
• Silica/silica PhC layer is expected to enhance the thermal emittance at the IR window
Radiative cooling on PV devices

Solar absorption of the three structures

Emissivity spectra of the three structures at the IR window
Experimental setup


Periodicity: 6 μm;
Depth: 10 μm;

The container allows control over convection
Effects of radiative cooling

Without convection

With convection

Benefits of radiative cooling extend across many PV technologies and installations

X. Sun et al., IEEE J. Photovolt. (submitted, July 2016)
Thermal emitter Spectrum

$T_{\text{emit}} = 1500 \, K$

Selectie Emitter

Intelect

Blackbody Radiation at 1500 K

Ideal Emitter Bandwidth:
~0.07 eV ($T_{\text{cell}} = 300 \, K$)

PV diode bandgap: ~0.7 eV (e.g., GaSb)

We are investigating the optimal scenario for TPV.
Self-Consistent Modeling of Radiative Cooling for Passive Thermal Management

\[ F_{\text{emitter-diode}} = 1 \]

- \( P_{\text{emit}} \): emission power from thermal emitter at \( T_E \)
- \( P_{\text{rad,cell}} \): radiative recombination of the PV diode at \( T_C \)
- \( P_{\text{out}} \): electrical output power from PV diode (SQ Limit)
- \( P_{\text{rad}} \): radiation power from the cooling emitter at \( T_C \)
- \( P_{\text{atm}} \): radiation power from atmosphere (300 K)
- \( P_{\text{conv}} \): convection power at the exposed surface

\[ R = \frac{A_{\text{cooler}}}{A_{\text{cell}}} \] (Area ratio)

\[ P_{\text{emit}}(T_E, E > E_g) + R \cdot P_{\text{atm}} = P_{\text{out}}(T_C) + P_{\text{rad,cell}}(T_C) + R \cdot P_{\text{rad}}(T_C) + (2R - 1) \cdot P_{\text{conv}} \]

S4sim: an RCWA simulation tool
https://nanohub.org/tools/s4sim/

Cooling Effects (Ideal Emitter)

- Both ideal coolers (2.5 to 40 um and 3 – 8 um) can provide below-ambient cooling.
- It is desirable to reduce convection for below-ambient cooling.
Ideal Radiative Cooling Reduces Temperature and Improves Performance Substantially

Ideal Emitter vs. Bare glass

2.5 – 40 um vs soda-lime

Above Ambient Cooling


8-13 um vs sapphire

Below Ambient Cooling

Palik, Edward D. Handbook of optical constants of solids.
Cooling Effects (Realistic Emitter)

\[ h = 2.5 \text{ W/(K.m}^2\text{)} \]

With practical emitter materials (e.g., bare soda-lime) we can achieve below-ambient cooling.
How to improve soda-lime glass/ sapphire cooling emitter?

- The dips in mid-infrared are caused by high reflectance
- Complex refractive ensures absorption
- Anti-reflection coating may be an easier approach

Porous Glass AR vs. Glass PhC

\[
V_g \frac{\varepsilon_g - \varepsilon}{\varepsilon_g + 2\varepsilon} + (1 - V_g) \frac{\varepsilon_a - \varepsilon}{\varepsilon_a + 2\varepsilon} = 0
\]

Bruggeman Approximation

\[\varepsilon_g = \text{dielectric constant of glass; } \varepsilon_a = 1\]

R. Landauer, “Electrical conductivity in inhomogeneous media”

\begin{align*}
\text{Soda-lime glass} & \\
\text{Porous soda-lime glass } v_g=0.25 & \\
\text{Wavelength [\mu m]} & \\
-1 & 0 & 1 & 2 & 3 & 4 & 5
\end{align*}
We have an alternative (possibly cheaper) to enhance radiative cooling.
Porous Sapphire AR vs. Sapphire PhC

- Porous glass ARC
  - t = 4.62 micron
  - t = 500 micron
- Sapphire PhC
  - Silver back reflector
  - t = 1 micron

Re(\varepsilon)

Im(\varepsilon)

Wavelength (\mu m)

Emittance

[Graphs showing reflectance and imaginary parts of the permittivity for bare sapphire and 45% porous sapphire]
Design for STPV cooling

Porous glass ARC (2.28 μm)

\[ t_{\text{glass}} = 1500 \mu m \]
Low-iron soda-lime glass

Silver back reflector

Drude model silver back reflector

\[ t_{\text{silver}} = 1 \mu m \]

soda-lime glass + porous AR coating
soda-lime glass photonic crystal

bare soda-lime glass

\[ \text{wavelength [μm]} \]

Emittance spectra

Porous Soda Lime Glass + ARC Temperature & Efficiency versus Area Ratios

- The structure with a porous ARC outperforms bare low-iron soda-lime glass.
- Convection coefficient $h = 2.5 \text{ W/}(\text{m}^2\text{K})$ assumed for both figures
Soda Lime Glass + Porous ARC: Radiative Cooling

Temperatures versus convection

- The area ratio is fixed as $A_{Cooler}/A_{Cell} = 100$.
- The soda lime glass + porous ARC cooler significantly outperforms the bare soda lime glass cooler.
Experimental Setup

- Outdoor test
- Commercial LED Source
- GaSb Cell (0.7 eV)
- Polyethylene Sealing
- 3D print (with Solidworks)

Sky

Polyethylene cover

thermocouple

electrical feedthrough

Copper heat spreader

Commercial LED source
Conclusions

• Self-heating of PV diodes is a major challenge for thermophotovoltaics, which could benefit from radiative cooling
• Non-ideal mid-IR emittance of realistic materials (soda-lime and sapphire) can be improved by porous AR coatings (same material)
• Even below ambient cooling can be achieved by using soda-lime glass or sapphire emitters
• Operating temperatures, system efficiencies, and reliability should be improved considerably by realistic radiative cooling structures we have designed
• The implementation of radiative cooling in a TPV system should be verified by further experiments
Next Class

• Next time: we will continue finite-difference time domain techniques, as applied to solar hybrid systems