Achieving Efficiencies over Theoretical Limits using Solar Thermophotovoltiac Cells

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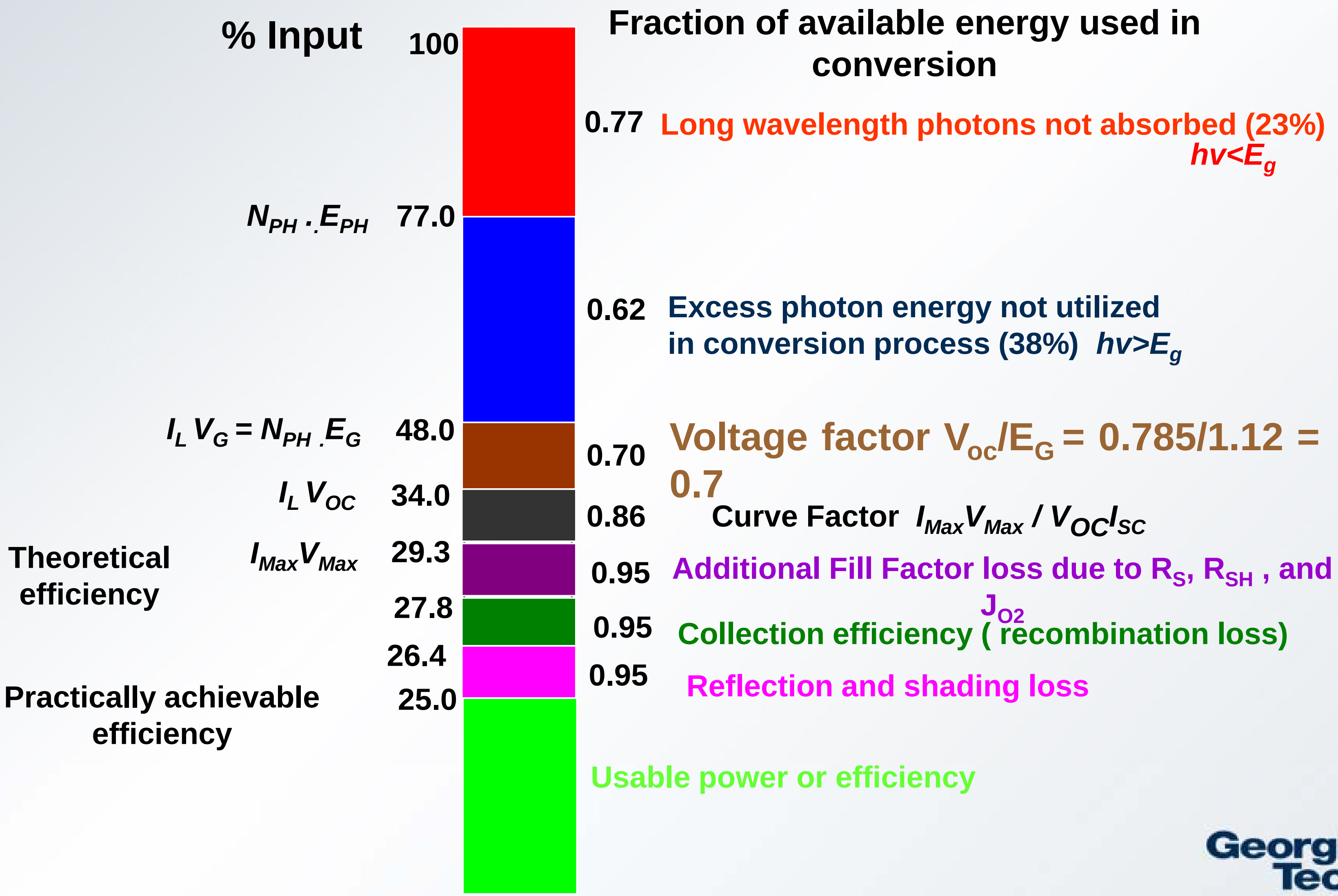
Shockley-Quiessler Limit

- Published in 1961, this limit dictates the maximum possible conversion efficiency for a single junction cell (@ 1.1 eV bandgap).
- For direct cells : 30%
- For concentrator cells (50,000x): 41%
- These numbers are realistically unattainable.

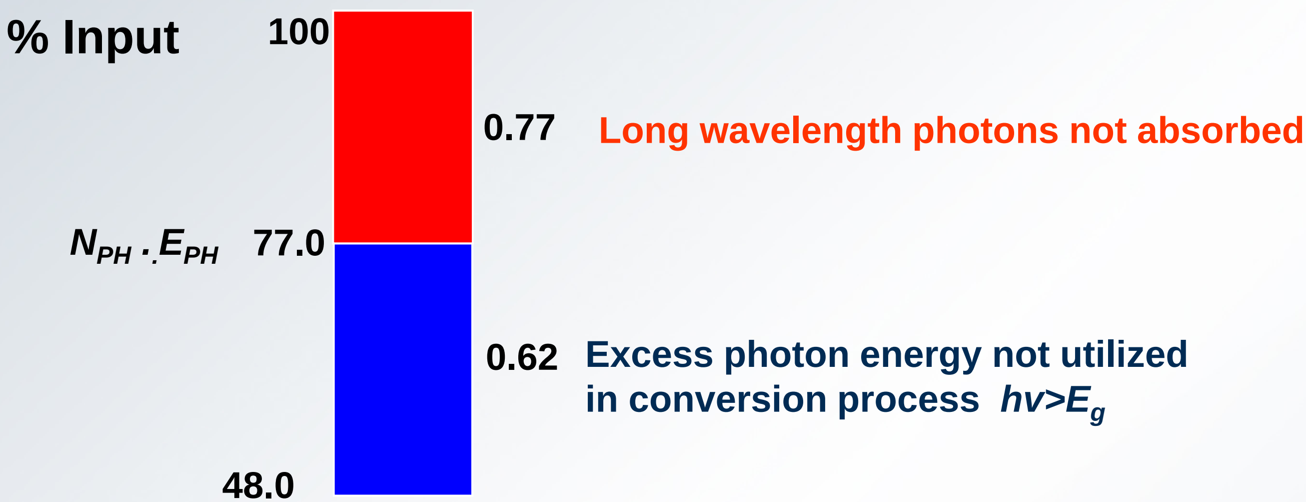
[1] W. Shockley, and H. J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells," J. Appl. Phys. 32(3), 510–519 (1961).

Sources of Efficiency Loss in Silicon



[2] A. Rohatgi, “ECE6456 Class Notes,” Georgia Institute of Technology, Fall 2009

Effect of Wide Spectrum

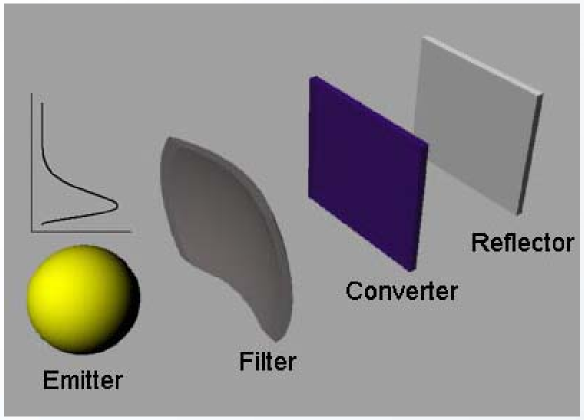


- Due to the loss of photons above and below the bandgap, 52% of the solar spectrum is lost.
- If the entire spectrum was at the bandgap of silicon, efficiency would be:

$$100*(.7*.86*.95*.95*.95) = \mathbf{52\%}$$

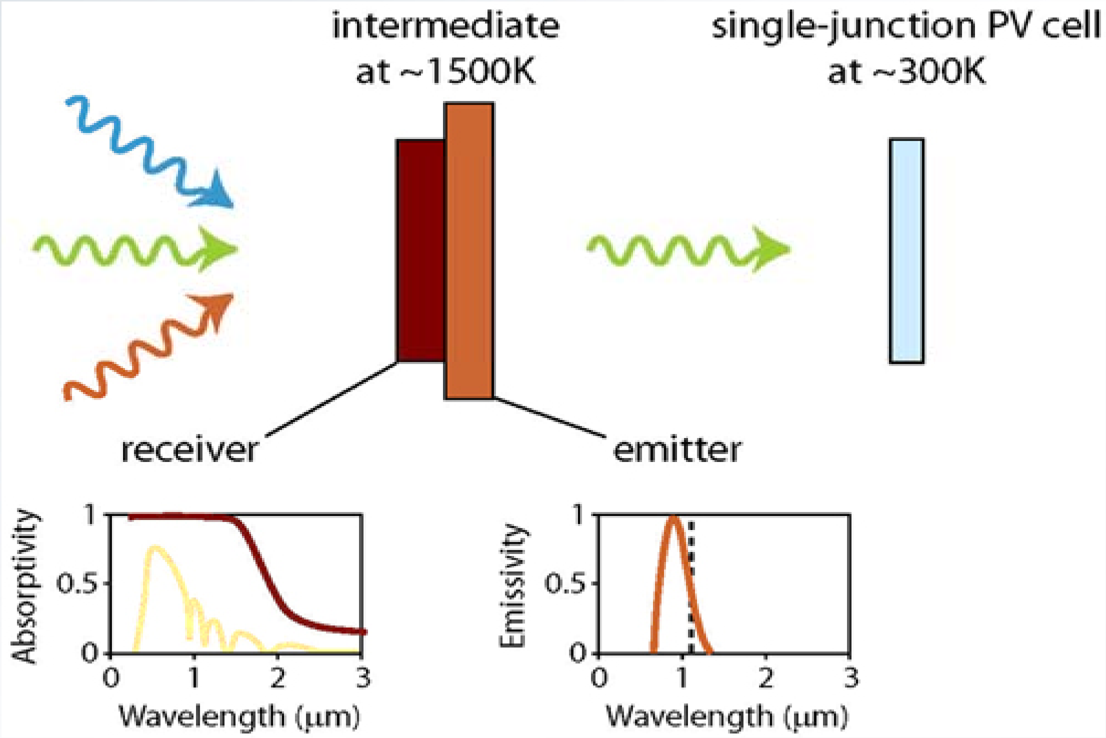
Traditional Thermophotovoltaics

- Uses non-solar heat source to create blackbody emission
  - Combustion is most likely
- Typically operates in the 900-1500°C Range
- This creates blackbody emission, but with mostly IR radiation (2000°K centered at 1.45 micron vs. 501 nm)
- Desired emission is filtered and collected, the rest is reflected back to further heat emitter.



[3] Wikipedia, "Thermophotovoltiacs"

Solar Thermophotovoltaic Cell



- Create intermediate device (absorber/emitter)
- Absorber uses concentrated photons to heat
- Emitter "upconverts" heat to narrow spectrum

[4] S. Fan and P. Peumans, " Ultra-High Efficiency Thermophotovoltaic Solar Cells Using Metallic Photonic Crystals as Intermediate Absorber and Emitter." Stanford University Global Climate and Energy Project, [Online] Available: http://gcep.stanford.edu/research/factsheets/ultrahigh_thermosolar.html. Sept. 2008.

Solar Thermophotovoltaic Cell

- Research currently conducted at:
  - Stanford University
  - University of New South Wales
  - RPI
  - Minnesota
- Main obstacles are creation of absorber and emitter
  - Absorber: Capable of turning entire spectrum to heat
  - Emitter: Photonic crystal with reflection peak at desired energy level corresponding to bandgap of PV Cell.

Absorber

- Requires a material with:
  - Extremely high optical loss (thus converting to heat)
  - High melting point
  - Operation at wide array of angles
  - Impedance matching with free space ($n_1\sin(\theta_1)= n_2\sin(\theta_2)$)
- Designs explored include:
  - Cermet (ceramic-metallic)
  - Films (MgO–Au, Cr_2O_3–Cr)
  - Low-density carbon nanotube arrays
  - Metallodielectric photonic crystals
  - Tungsten Pyramid Structure

[5] E.Rephali and S. Fan, "Tungsten black absorber for solar light with wide angular operation range", Applied Physics Letters, 92, 2008

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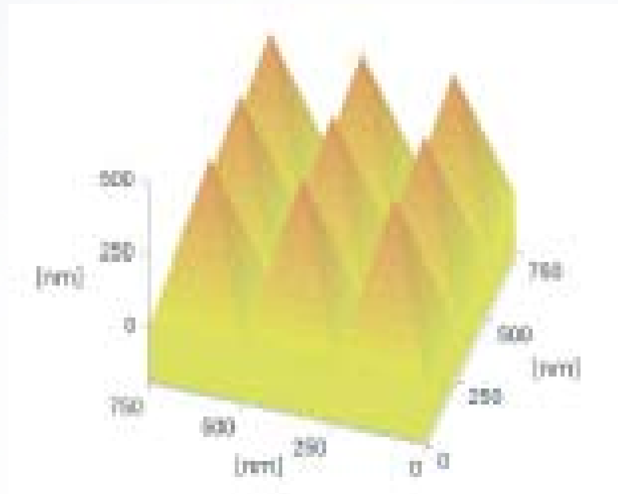
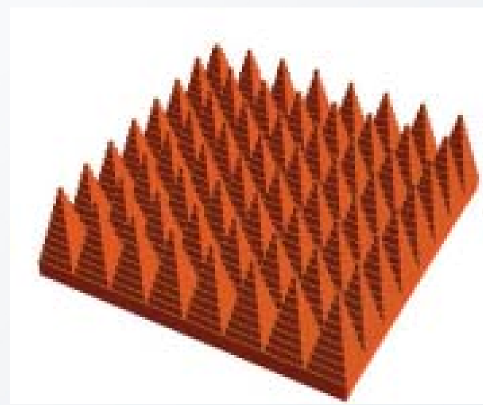
Absorber – Tungsten Pyramid Structure

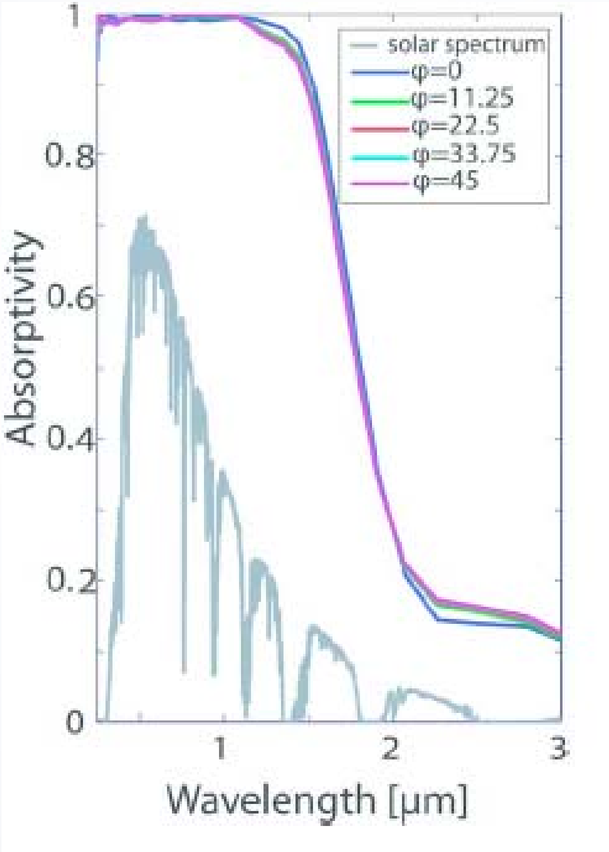
- Tungsten has highest melting point of any metal.
- Typical slab is not impedance matched nor a good absorber.
- Creation of periodic lattice of 250x250x500 nm pyramids.[5]
- Within pyramid, tapered sub-wavelength grating (SWG)
  - Incident light absorbed within the grating





Absorber – Simulated Absorptivity

- Flat slab of Tungsten has ~50% absorptivity
- Pyramid structure has absorptivity of 1 for wavelength less than 2 micron.[5]
- Even at different angles of incidence – still same absorption.
  - Allows for consideration of 1.5G instead of 1.5D spectrum.



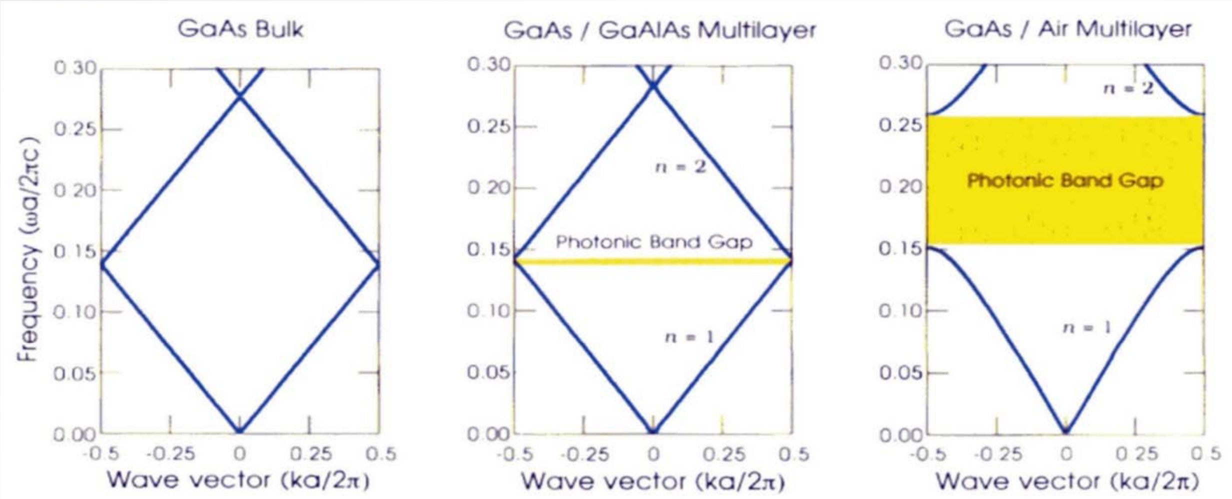
Emitter

- Difficult to create a material that can have a narrow reflection spectrum.
- Requires properties of photonic crystals.
- Explored designs include:
  - 1D or 2D Tungsten Gratings
  - 3D Tungsten Photonic Crystals (Inverse Opal)
  - 1D Dielectric Stack Photonic Crystal

[6] E.Rephali and S. Fan, “Absorber and emitter for solar thermophotovoltaic systems to achieve efficiency exceeding the Shockley-Queisser limit”, Optics Express, 17, 2009

Emitter - Photonic Crystals

- Alternating high-k/low-k dielectrics create a photonic bandgap – in this region frequencies of light can not exist.

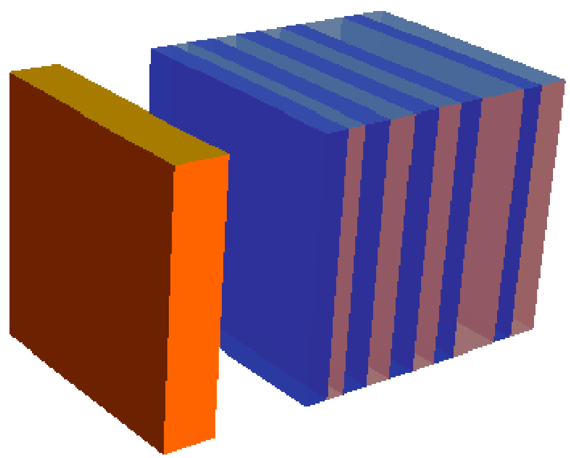


- Most common uses:
  - 1D : Filters, STPV Emitters?
  - 2D : Optical Fibers
  - 3D: ??? (Invisibility Cloaks, STPV Emitters?)

[7] C. Summers and Z. Kang, "MSE6405 Class Notes," Georgia Institute of Technology, Spring 2010

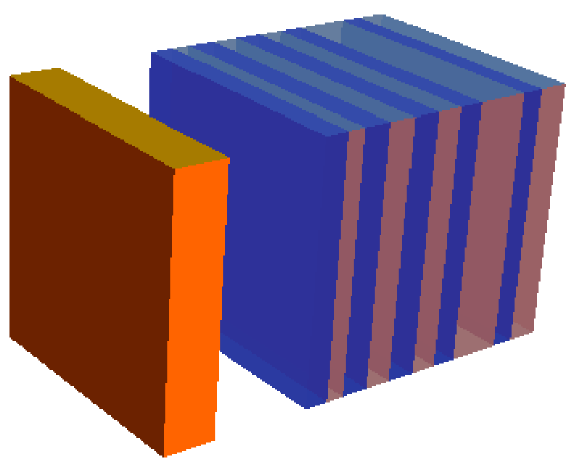
Emitter - 1-D Dielectric Stack

- Multilayer dielectric stack near a Tungsten surface
- An air-filled cavity layer separating the dielectric stack from the Tungsten.
- The proposed dielectric stack is found below[6].
  - Red - SiO_2, Blue – Si
  - The sizes are based on desired resonance and PBG



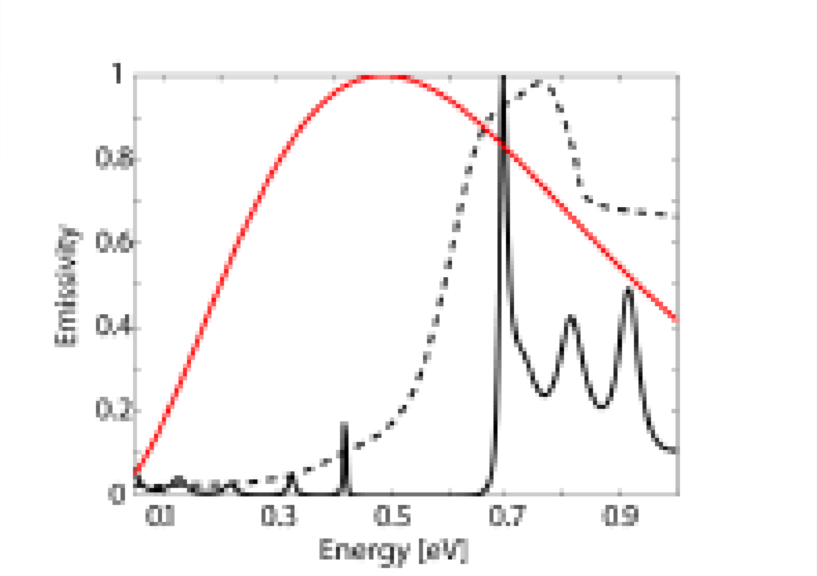
Emitter - 1-D Dielectric Stack

- The dielectric stack creates a photonic bandgap
  - Exhibits strong reflection and low (zero) transmission.
  - A sharp emissivity peak at the middle of PBG
    - Match the stacks' transmissivity to the metal slabs' absorptivity at the peak wavelength.
    - Choose the appropriate width of the cavity layer so there is cavity resonance at the peak wavelength.



Emitter – Predicted Emissivity

- Predicted emissivity is found below [6]
  - Red – Typical blackbody emission @2000°K
  - Dashed – 3D Inverse Opal Emitter
  - Solid – 1D stack Emitter
- Note that desired PV cell should have a bandgap of .7eV



PV Cell

- By far the easiest part of the design.
- Uses any solar cell with a bandgap matched to the desired peak of emission.
- Two main bandgaps explored:
  - 1.1 eV (approximately Silicon and easy to compare to SQ)
  - .7 eV (Standard TPV cell)[7]
- For .7 eV – GaSb, Ge, Ternary/Quaternary Compounds
- Designed using standard PV technology.
- Efficiency gained from focused spectra, losses of cell will still exist.

[7] O. Sulima and A. Bett, "Fabrication and simulation of GaSb thermophotovoltaic cells", Solar Energy and Solar Cells, 66, 2001

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Efficiency

- In order to justify the cost increase, considerable efficiency must be gained.
- The estimated efficiencies reported are staggering:
  - Wurfel (2002) – 85% (Theoretical Efficiency)[8]
  - Wurfel (2002) – 60% with "realistic" concentration and emitter to absorber surface area ratio
  - Rephali (2009) – 50.8% w/ .7 eV cell, 1000x concentration, ~16 area ratio[6]
  - Andreev (2005) – 10% (Experimental)[9]

[8] N. Harder and P. Wurfel, "Theoretical limits of thermophotovoltaic solar energy conversion", Semiconductor Science Technology, 18, 2003

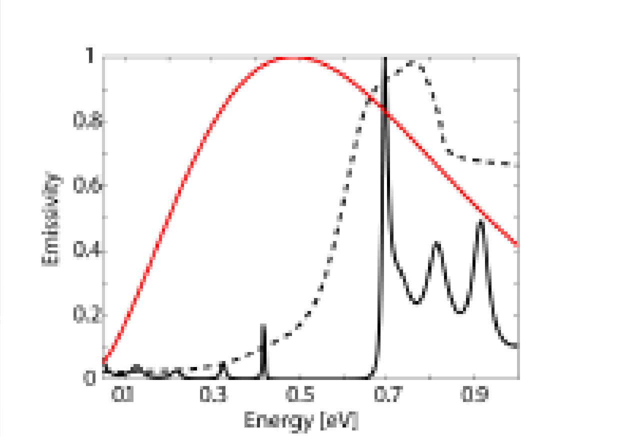
[9] V. Andreev, et al "Solar Thermophotovoltaic System with High Temperature Tungsten Emitter", IEEE Photovoltaic Specialists Conference, Florida, 2005

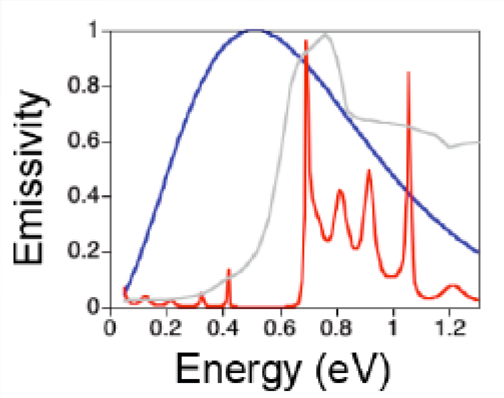
Realistic Constraints

- While the STPV design is great theoretically, a lot of “liberties” are taken in the calculations.
- The 85% efficiency assumes[8]:
  - Infinite ratio of emitter/absorber surface area
  - Perfect absorption/emission
  - No optical losses, only radiative recombination
- The other predictions still have noticeable issues:
  - All assume the PV cell will somehow stay at 300°K, despite close proximity to 2000°K assembly. (Experimental used liquid cooling[9])
  - All assume only radiative recombination
  - Perfect absorber/emitter despite small dimensions.

Realistic Constraints – Stanford Paper

- Some information on the most recent report is misleading (recent publishing on left, initial on right):



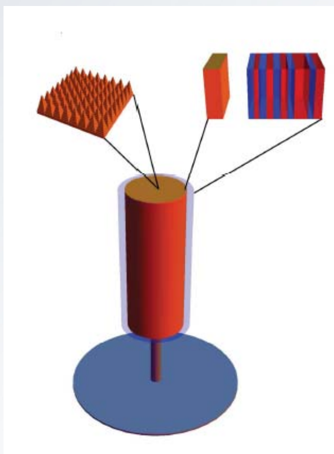


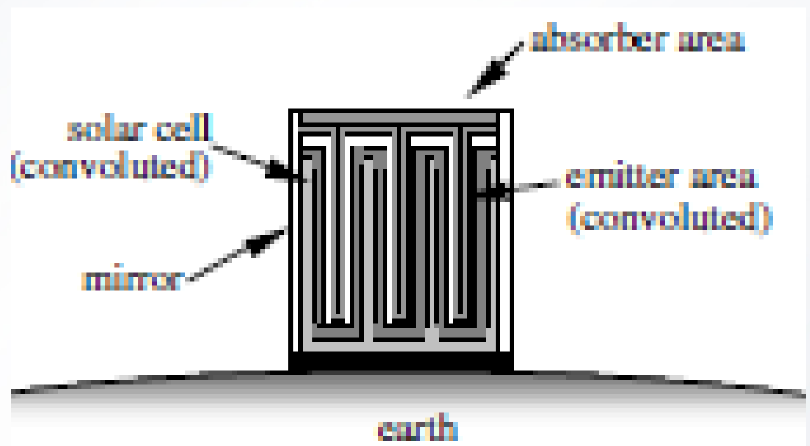
- Absurd cost
  - Requires complex patterning and fabrication techniques
  - Highest triple junction cell is over 40%.
  - If, at best, a 10% efficiency can be gained. May not be justified vs. the cost.

[10] E.Rephali and S. Fan, "Progess Report on GCEP Project, Year 1", 2008

Future Work

- Create designs that effectively thermally couple the emitter and absorber while maintaining a high ratio of emitter to absorber surface area (Rephali[6] and Wurfel[8]).





- Make the process cheaper
  - Self Assembly of Opal Structure
  - Optimize for premade cells (Silicon instead of GaSb)
- Actually build it!

Final Thoughts

- With improved methods for creating photonic crystals, devices like this will become more promising.
- While the theoretical limits of this technology are very high, many are fundamentally flawed.
- However, successful creation of the absorber or emitter would have many other useful applications.

Questions?

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