Review of Lecture 9

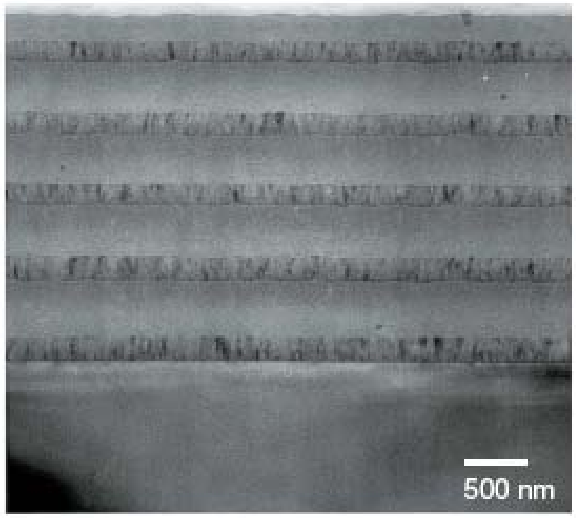
- Solar hot water systems
- Maximum solar concentration
- Methods for concentration
- Nontracking and tracking
- Solar thermal-mechanical energy conversion
- EM wave calculation of surface properties

Review of Lecture 10

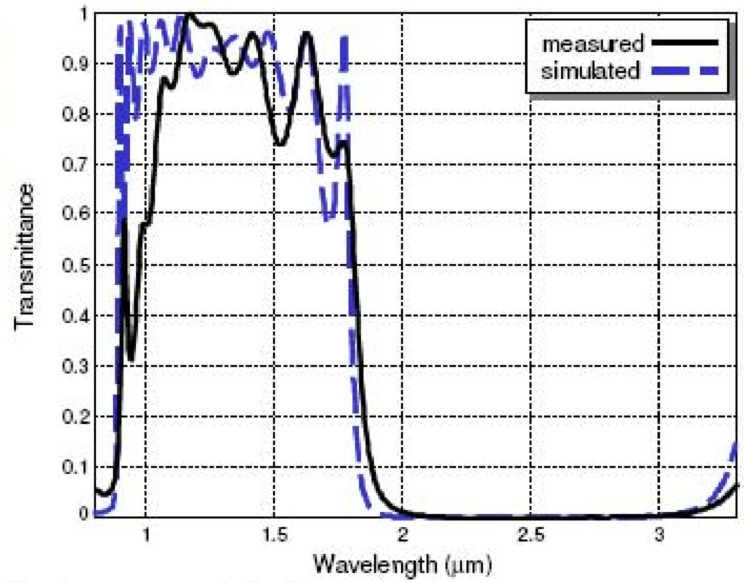
By C. Schuh

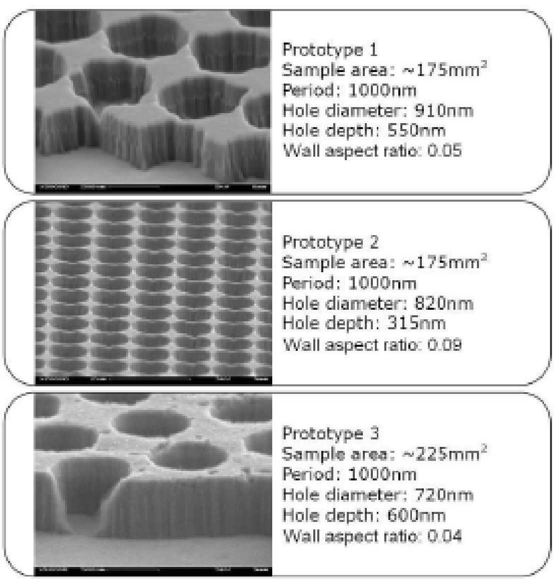
Review of Lecture 11

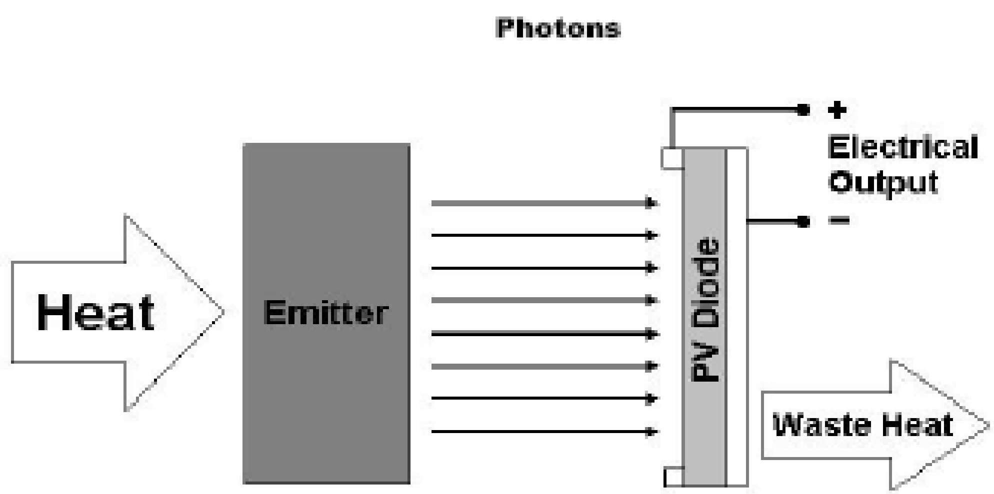
By I. Celanovic



TEM cross section of LPCVD* grown quarter-wave stack filter with half-layer at the top







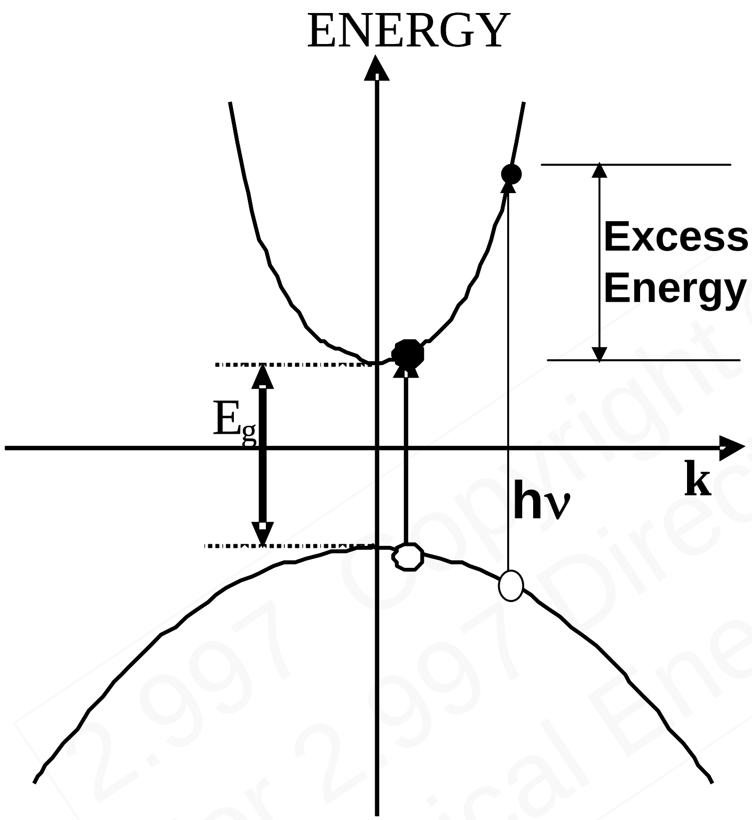
Lecture 12 Solid-State Solar-Thermal Energy Conversion

- Solar thermophovoltaics
- Solar thermophotonics
- Solar thermoelectrics

Shockley-Queisser Limit of Solar Cells (Lec.7)

Shockley, W. and Queisser, H.J., Journal of Applied Physics, 32, 510 (1961).
Henry, C.H., Journal of Applied Physics, 51, 4494 (1980).

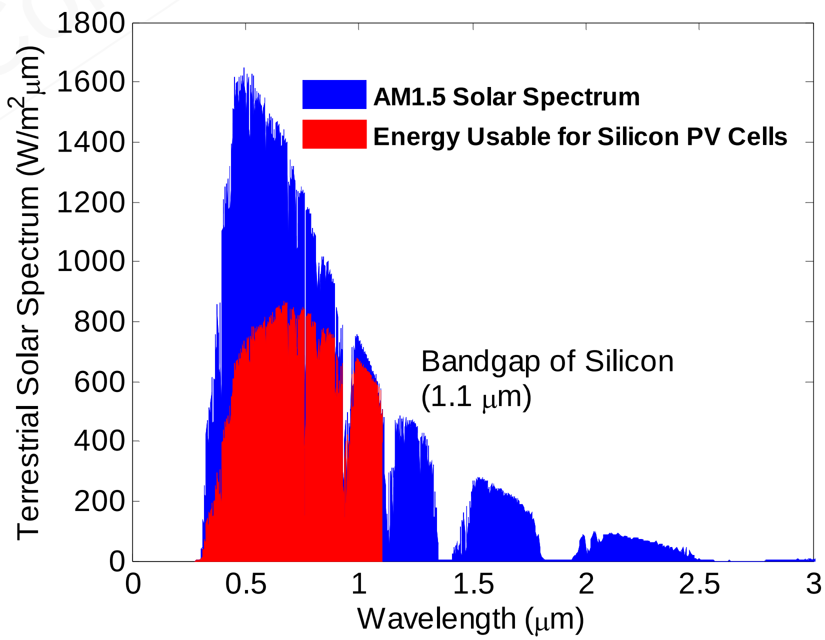
Where is energy lost?



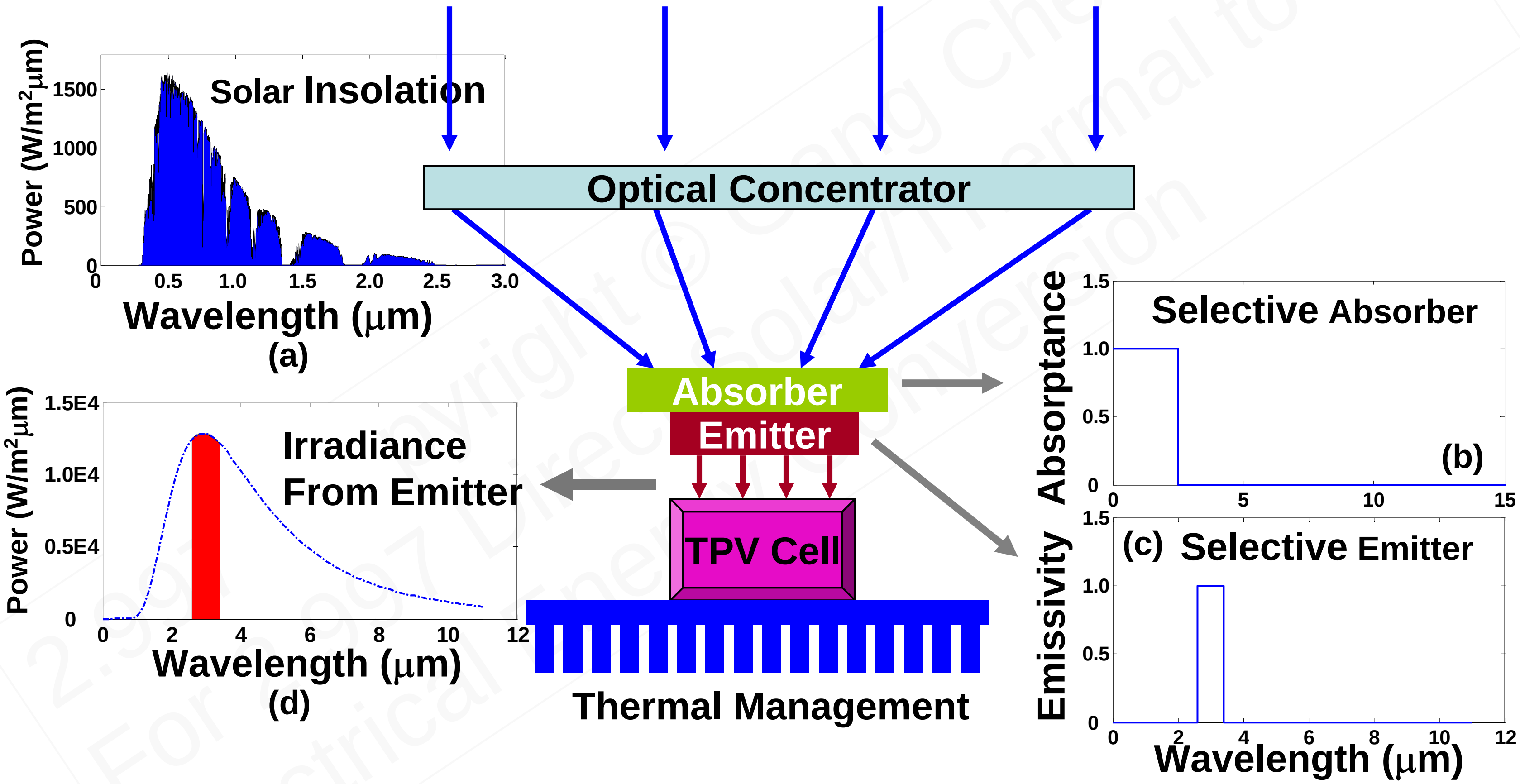
For E_g=1 eV

- **Energy below the gap: 20%**
- **Average photon energy above gap: 1.9 eV**
- **Chemical potential: 0.7 eV**

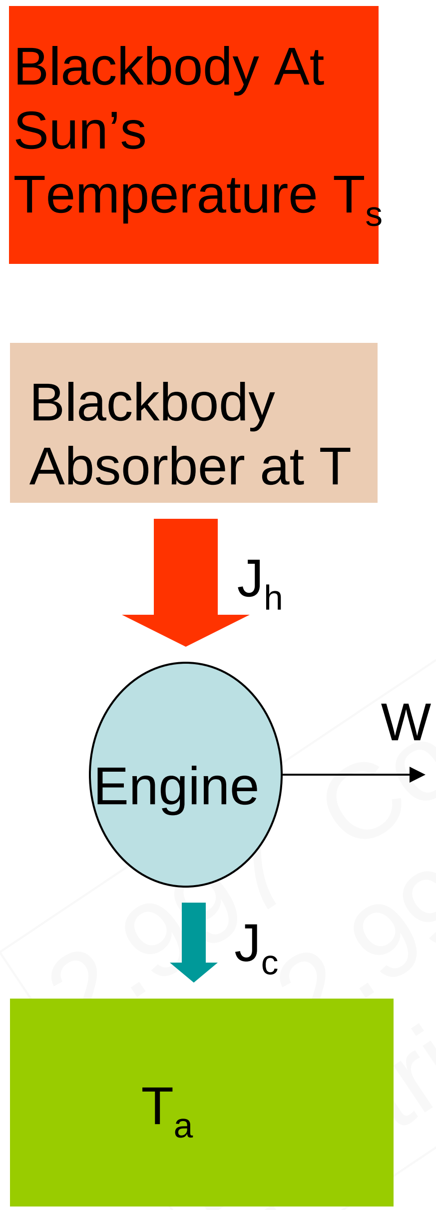
$$\eta = 0.8 \times \frac{1eV}{1.9eV} \times \frac{0.7eV}{1eV} = 0.3$$



Solar Thermophotovoltaics



Maximum Efficiency of a Solar Thermal Engine (Lec.8)



Heat Transferred to Absorber

$$Q_h = \sigma\left(T_s^{\,4} - T^4\right)$$

Thermal Efficiency

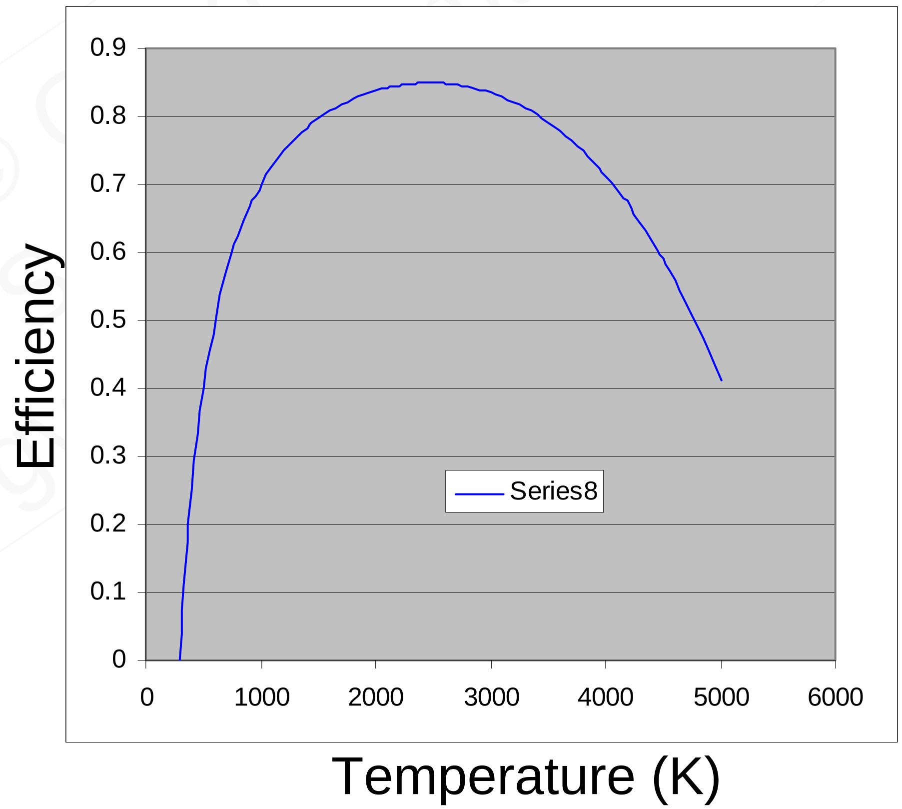
$$\eta_{th} = \frac{\sigma\left(T_s^{\,4} - T^4\right)}{\sigma T_s^{\,4}} = 1 - \frac{T^4}{T_s^{\,4}}$$

Carnot Efficiency

$$\eta = 1 - \frac{T_a}{T}$$

Maximum Efficiency of a Solar Thermal Engine (Lec.8)

$$\eta = \eta_{th}\eta_C = \left(1 - \frac{T^4}{T_s^4}\right)\left(1 - \frac{T_a}{T}\right)$$



Maximum: 85% @ T=2450K

For T_a=300 K

Problems

- Needs very narrow bandwidth to achieve Carnot efficiency solar cells.
- Solar absorption and radiation from absorber does not balance at 2450 K.
- Difficult to operate at 2450 K.
- Ideal selective surfaces do not exist.

Wuerfel and Ruppel Analysis – Black Absorber

Images removed due to copyright restrictions.
Please see Fig. 1, 3, 4 in Würfel, Peter, and Wolfgang Ruppel.
"Upper Limit of Thermophotovoltaic Solar-Energy Conversion."
IEEE Transactions on Electron Devices ED-27 (April 1980): 745-750.

Wuerfel and Ruppel, IEEE Trans. Elec. Devices, ED-27, 745, 1980

Wuerfel and Ruppel Analysis – Selective Absorber

Images removed due to copyright restrictions.
Please see Fig. 6 and 7 in Würfel, Peter, and Wolfgang Ruppel.
"Upper Limit of Thermophotovoltaic Solar-Energy Conversion."
IEEE Transactions on Electron Devices ED-27 (April 1980): 745-750.

Wuerfel and Ruppel, IEEE Trans. Elec. Devices, ED-27, 745, 1980

Wuerfel and Ruppel Analysis – Selective Absorber + Filter

Images removed due to copyright restrictions.
Please see Fig. 9-11 in Würfel, Peter, and Wolfgang Ruppel.
"Upper Limit of Thermophotovoltaic Solar-Energy Conversion."
IEEE Transactions on Electron Devices ED-27 (April 1980): 745-750.

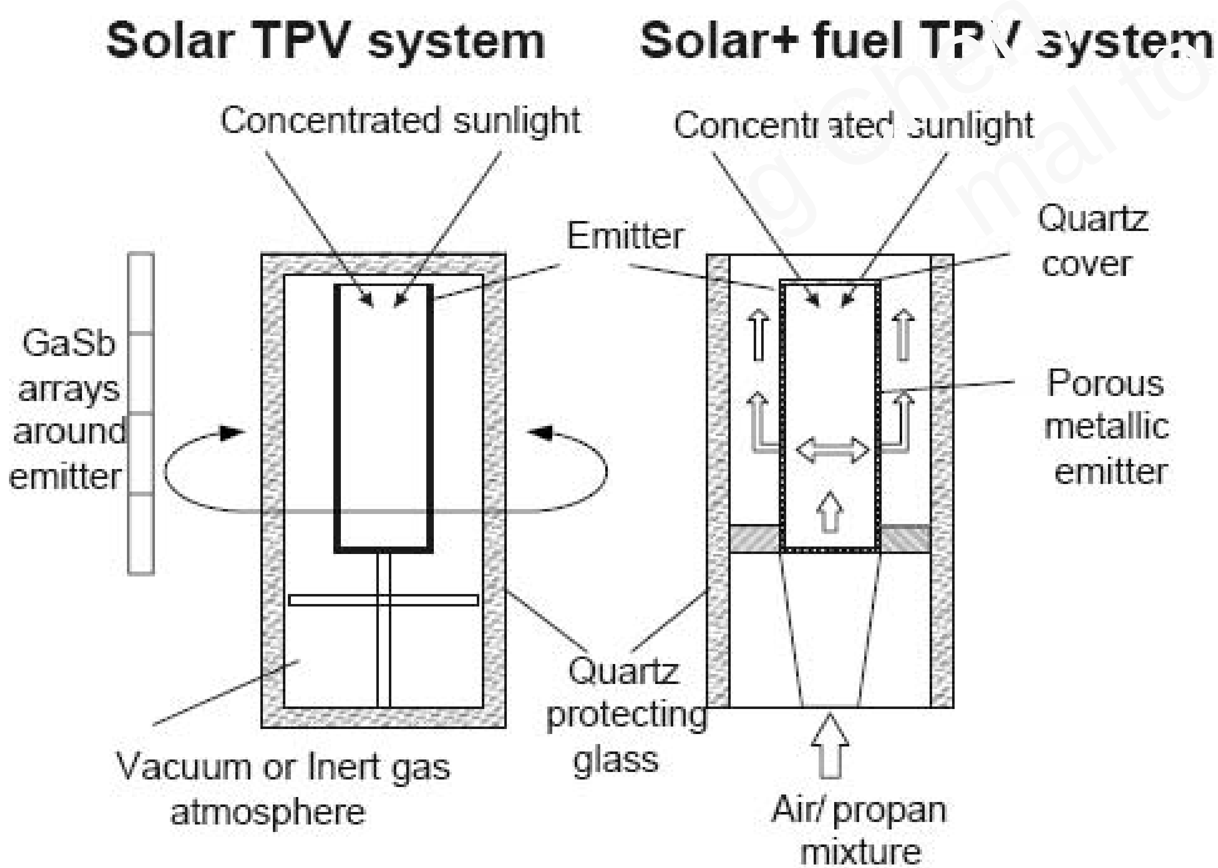
Wuerfel and Ruppel, IEEE Trans. Elec. Devices, ED-27, 745, 1980

Optimal Bandgap & Temperature

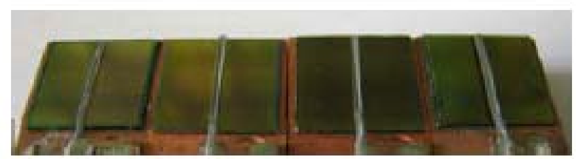
Please see Fig. 5 in Tobias, I., and A. Luque.
"Ideal Efficiency and Potential of Solar Thermophotonic
Converters Under Optically and Thermally Concentrated Power Flux."
IEEE Transactions on Electron Devices 49 (November 2002): 2024-2030.

Tobias and Luque, IEEE Trans. Electron Dev. 49, 2024 (2002)

Andreev et al.,



Some Examples



GaSb Cell

pvlab.ioffe.ru/technology/tpv.html

Solar Thermophotonics

Tobias and Luque, IEEE Trans. Electron Dev. 49, 2024 (2002)

TPH---Monochromatic Limit

$$\frac{i_{EMI}(v, T, E_G, E_{SUP})}{q} = \frac{2\pi A}{h^3 c^2} \int_{E_G}^{E_{SUP}} \frac{E^2\, dE}{\exp\left(\frac{E-qv}{kT}\right) - 1} \qquad (1)$$

$$i_{CEL} = i_{LED} = i = \frac{2q\pi A}{h^3 c^2} \left(\frac{E_G^2}{\exp\left(\frac{E_G - qv_{LED}}{kT_{LED}}\right) - 1} - \frac{E_G^2}{\exp\left(\frac{E_G - qv_{CEL}}{kT_{CEL}}\right) - 1} \right) \Delta E = \frac{q p_{RAD}}{E_G} \qquad (8)$$

$$i = 0 \Rightarrow \frac{E_G - qv_{LED}}{kT_{LED}} = \frac{E_G - qv_{CEL}}{kT_{CEL}} \Rightarrow v_{CEL}$$

$$\eta_{TPH} = \frac{(v_{CEL} - v_{LED})\, i}{p_{RAD} - v_{LED}\, i} = \frac{v_{CEL} - v_{LED}}{E_G/q - v_{LED}} = 1 - \frac{T_{cell}}{T_{LED}}$$

STPH---No Filter

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Please see Fig. 3 in Tobias, I., and A. Luque.
"Ideal Efficiency and Potential of Solar Thermophotonic
Converters Under Optically and Thermally Concentrated Power Flux."
IEEE Transactions on Electron Devices 49 (November 2002): 2024-2030.

STPH---With Filter

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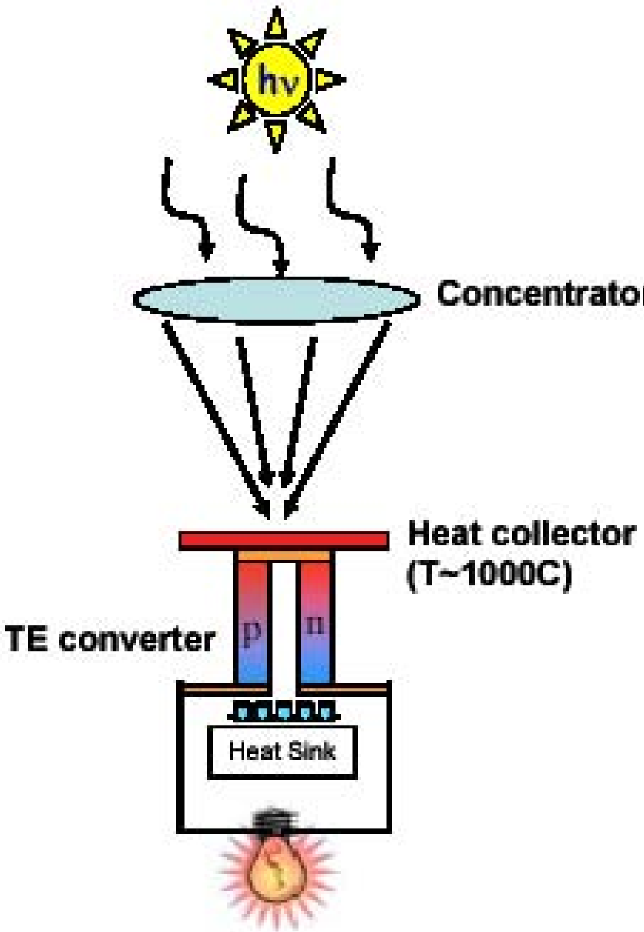
Please see Fig. 4 in Tobias, I., and A. Luque.
"Ideal Efficiency and Potential of Solar Thermophotonic
Converters Under Optically and Thermally Concentrated Power Flux."
IEEE Transactions on Electron Devices 49 (November 2002): 2024-2030.

Solar Thermoelectrics



- **US Patent No. 389124: E. Weston in 1888**
- **M. Telkes, JAP, 765, 1954**

Image removed due to copyright restrictions.
Please see Fig. 6 in Telkes, Maria. "Solar Thermoelectric Generators." *Journal of Applied Physics* 25 (June 1954): 765-777.

Efficiency: 0.63%

Solar Thermoelectrics – Flat Panel Prototypes

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Please see Fig. 6 in Telkes, Maria. "Solar Thermoelectric Generators." *Journal of Applied Physics* 25 (June 1954): 765-777.

Solar Thermoelectric Generator ---Concentrated Prototypes

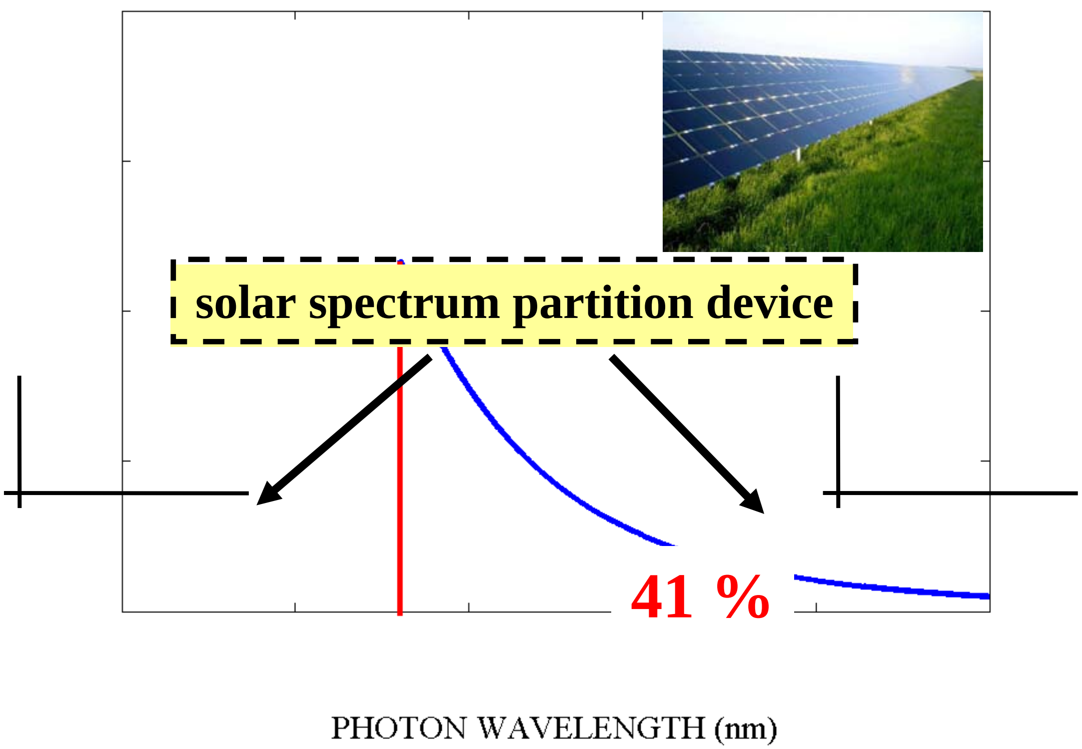
Please see Fig. 3, 10 and Table III in Dent, C. L., and M. H. Cobble. "A Solar Thermoelectric Generator Experiment and Analysis." *Proceedings of the International Conference on Thermoelectric Energy Conversion* 4 (1982): 75-78.

Hybrid PV and TE

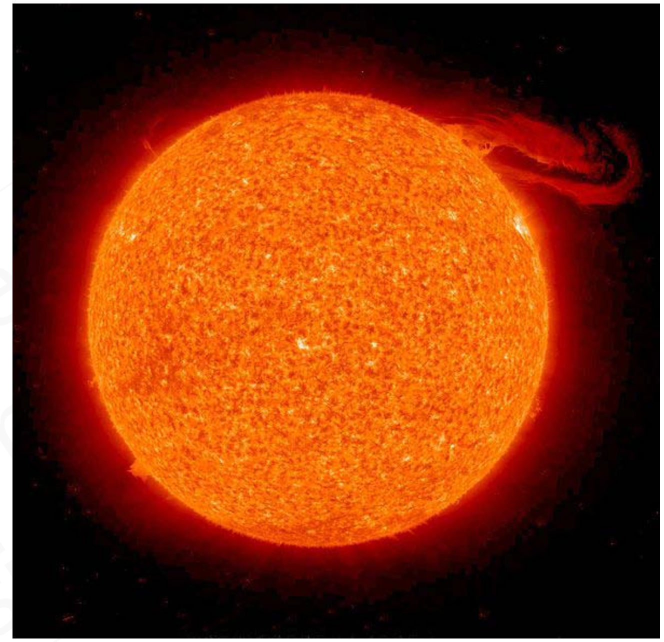
Solid-State Solar-Thermal Energy Conversion Center (S[3]TEC Center)

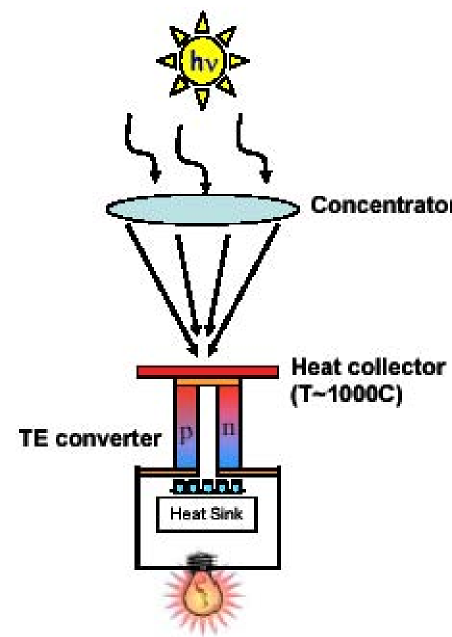
Gang Chen (Director) **http://s3tec.mit.edu/**

Kraemer et al.
APL, June 2008



Courtesy of DOE/NREL, Credit - Beck Energy.





Courtesy of NASA.

Two Configurations

Image removed due to copyright restrictions.
Please see Fig. 1 in Vorobiev, Y. V., et al. "Analysis of Potential Conversion Efficiency of a Solar Hybrid System with a High-Temperature Stage." *Journal of Solar Energy Engineering* 128 (May 2006): 258-260.

Vorobiev et al., J. Solar Energy Eng., 128, 258, 2006.