Ultra-High Efficiency Thermo-Photovoltaic Cells Using Metallic Photonic Crystals as Intermediate Absorber and Emitter

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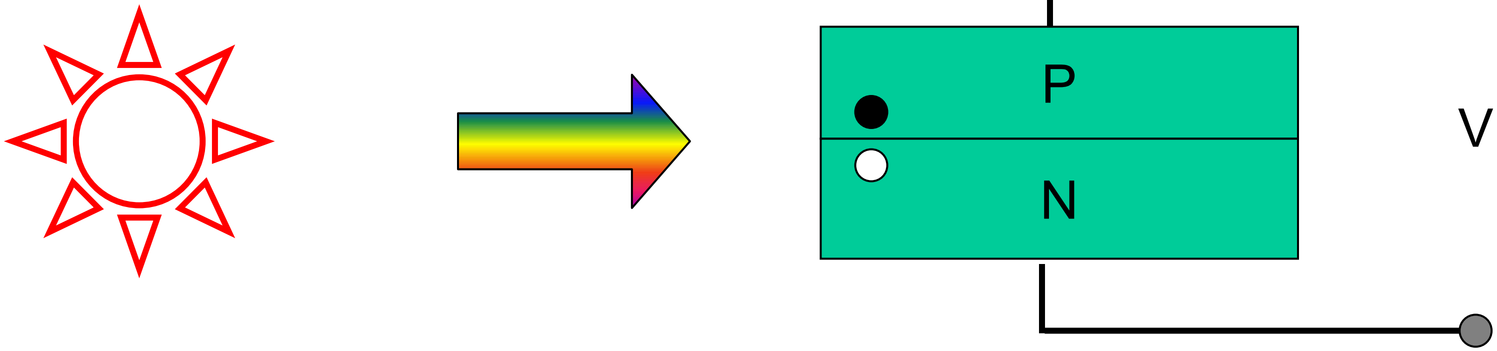
UIUC: P. Braun

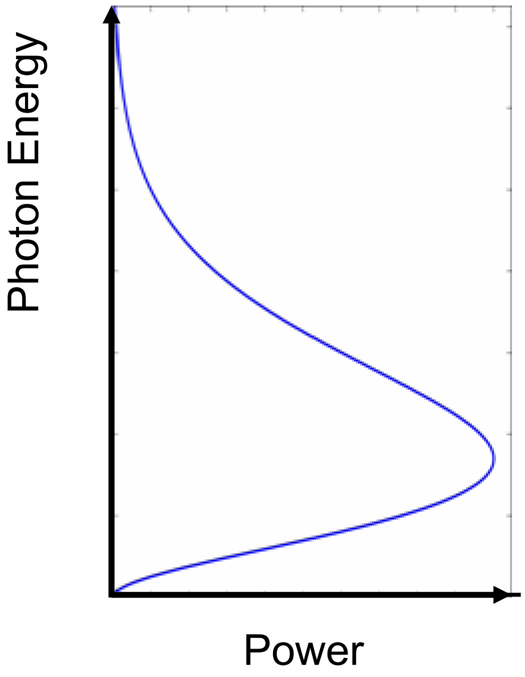
Improving Solar Cell Efficiency

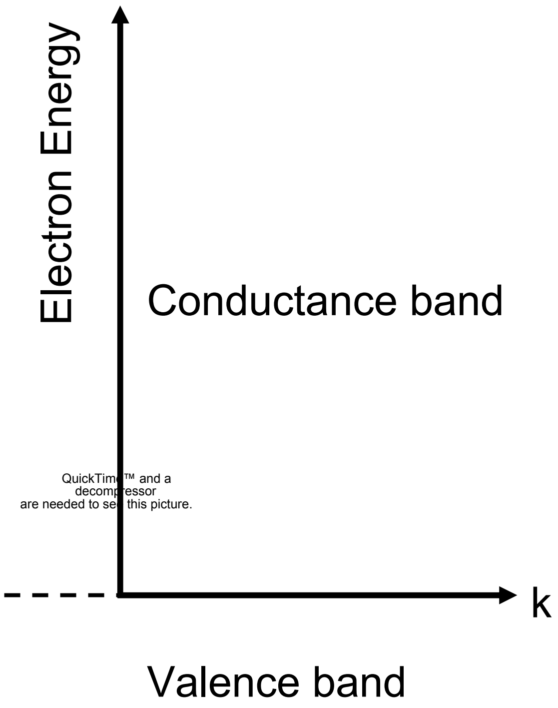


Sun

Semiconductor PN junction

Basic Semiconductor Physics

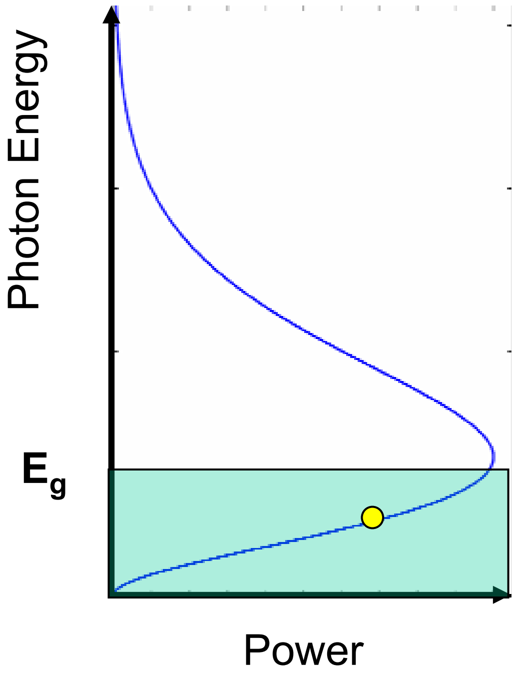




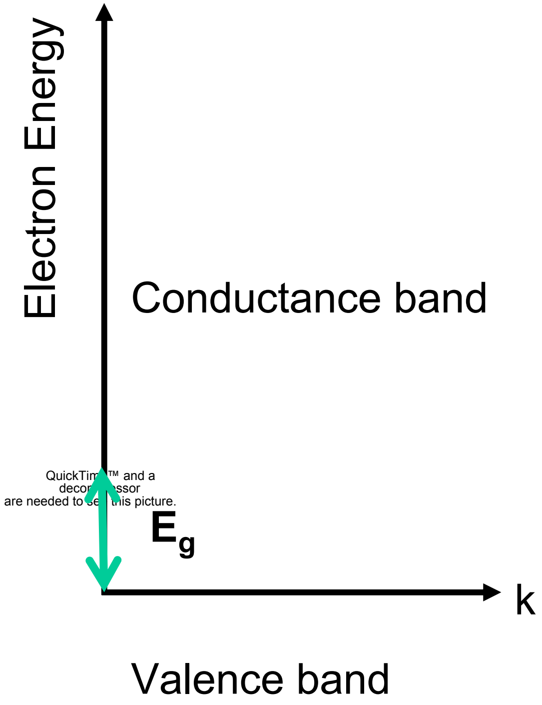
Solar Spectrum

Semiconductor Bandstructure

Photons with energy below the band gap



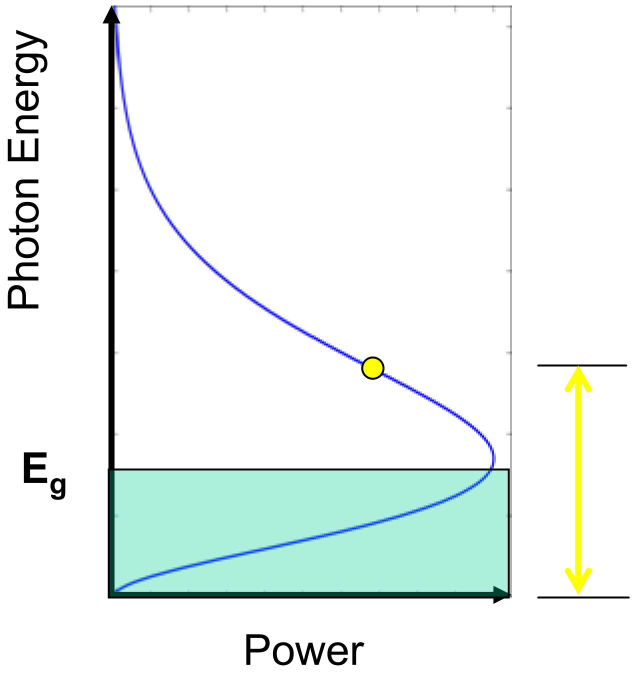
Solar Spectrum



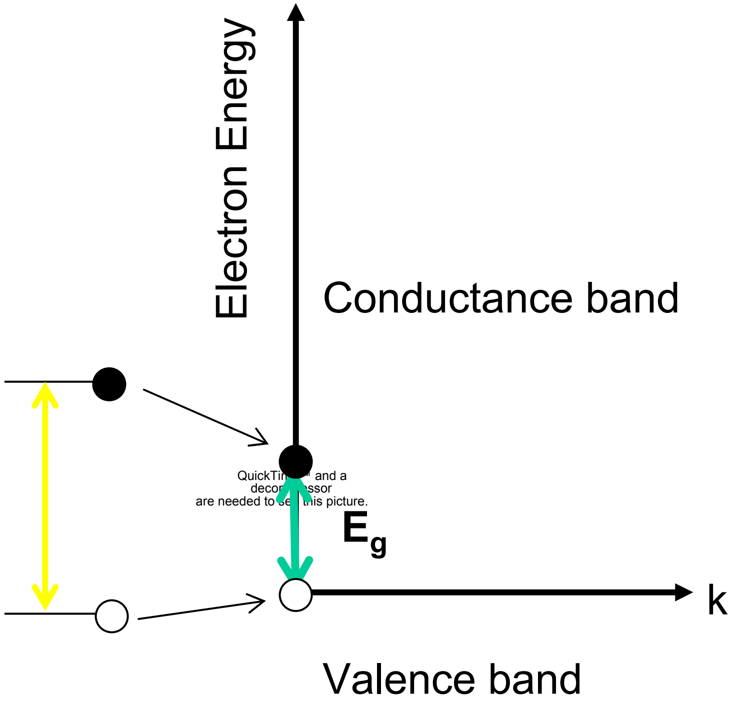
Semiconductor Bandstructure

They do not contribute.

Photons with energy above the band gap



Solar Spectrum

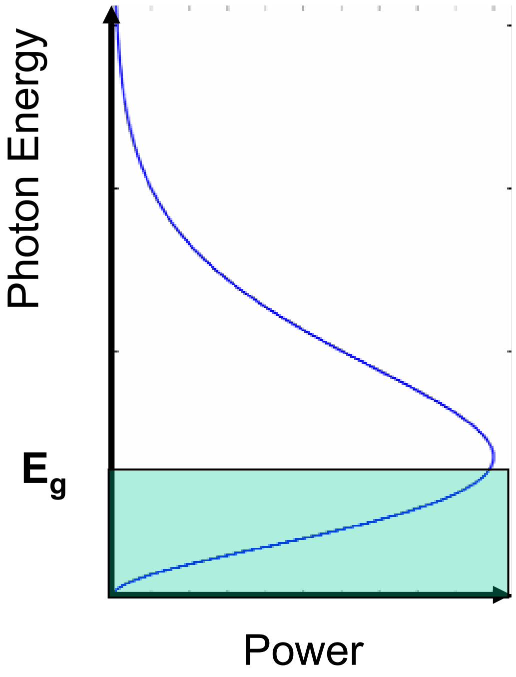


Semiconductor Bandstructure

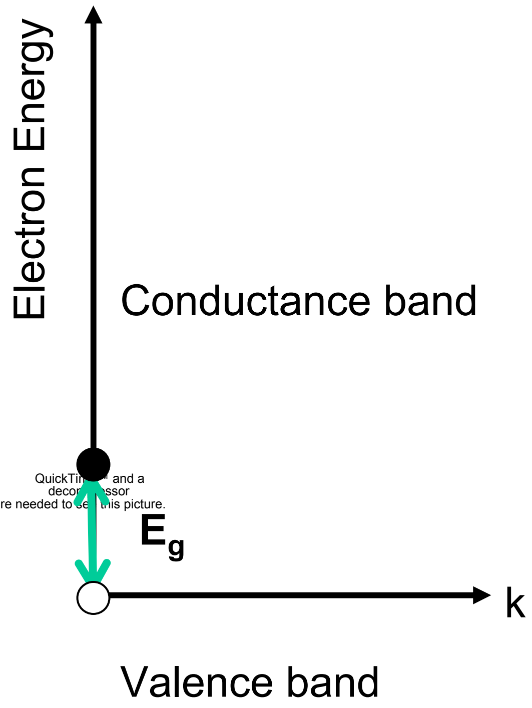
- They do contribute, but only partially.

- After absorption, each photon contributes to approximately E_g worth of the energy, the rest is lost due to thermalization.

Shockley-Queisser Limit



Solar Spectrum

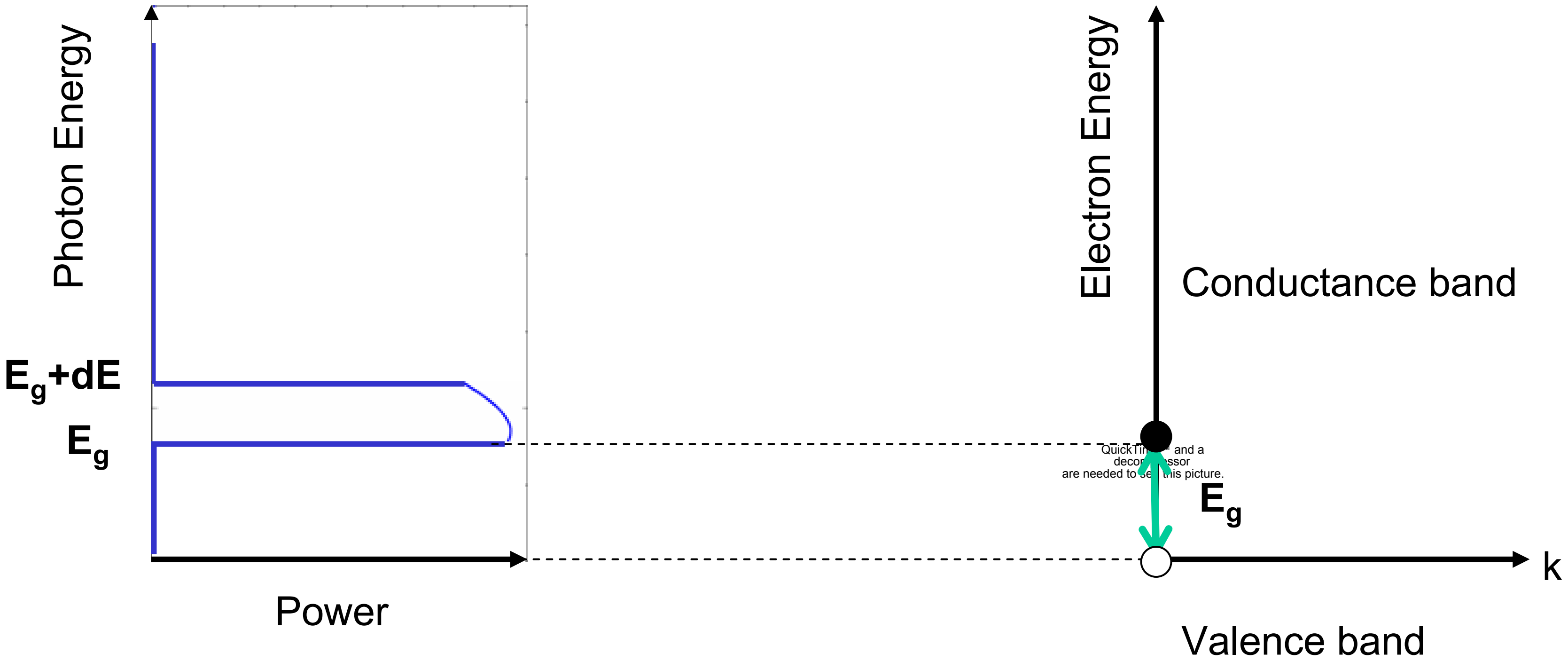


Semiconductor Bandstructure

A single-junction cell: maximal efficiency 41%.

“Detailed Balance Limit of Efficiency of p-n Junction Solar Cells”
William Shockley and Hans J. Queisser, *J. Appl. Phys*. 32, 510 (1961**)**

What if the sun was a narrow-band emitter?



Solar Spectrum (T_s=6000K) **Semiconductor Bandstructure (T_e=300K)**

$$\eta \simeq 1 - \frac{T_e}{T_s} = 95\%$$

Approach Thermodynamic Limit

Solar Thermo-Photovoltaics (STPV)

Sun (T_s = 6000K)

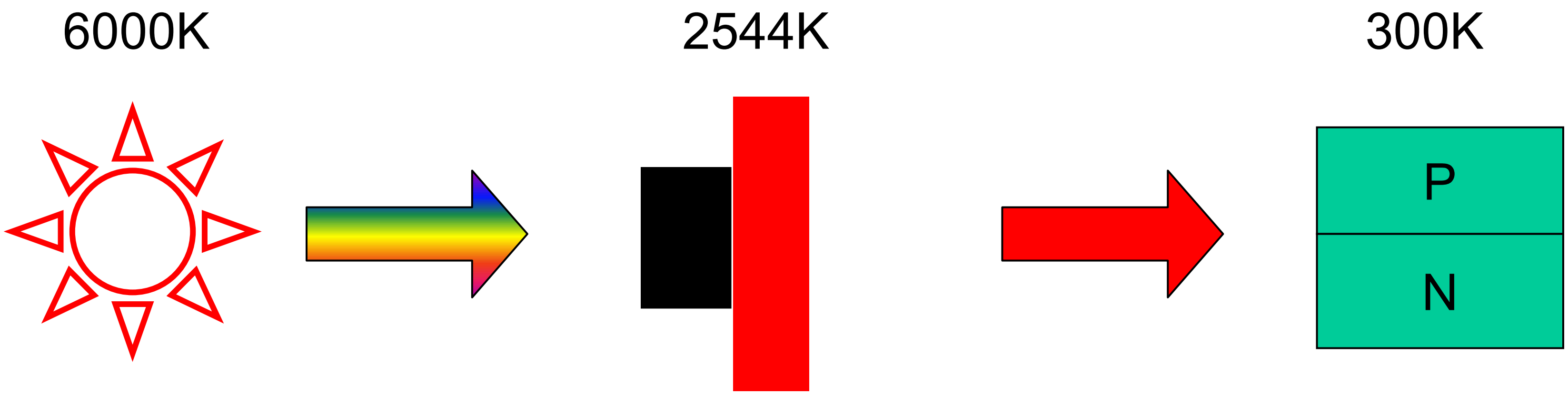
Intermediate Absorber and Emitter (T_i = 2544K)

Solar Cell (T_e = 300K)

$$\eta \simeq \underbrace{(1-\frac{T_i^4}{T_s^4})}_{\text{The sun to the intermediate}} \times \underbrace{(1-\frac{T_e}{T_i})}_{\text{The intermediate to the cell}} = 85.4\%$$

P. Harder and P. Wurfel, *Semicond. Sci. Technol*. 18, S151 (2003);

STPV: The Challenge

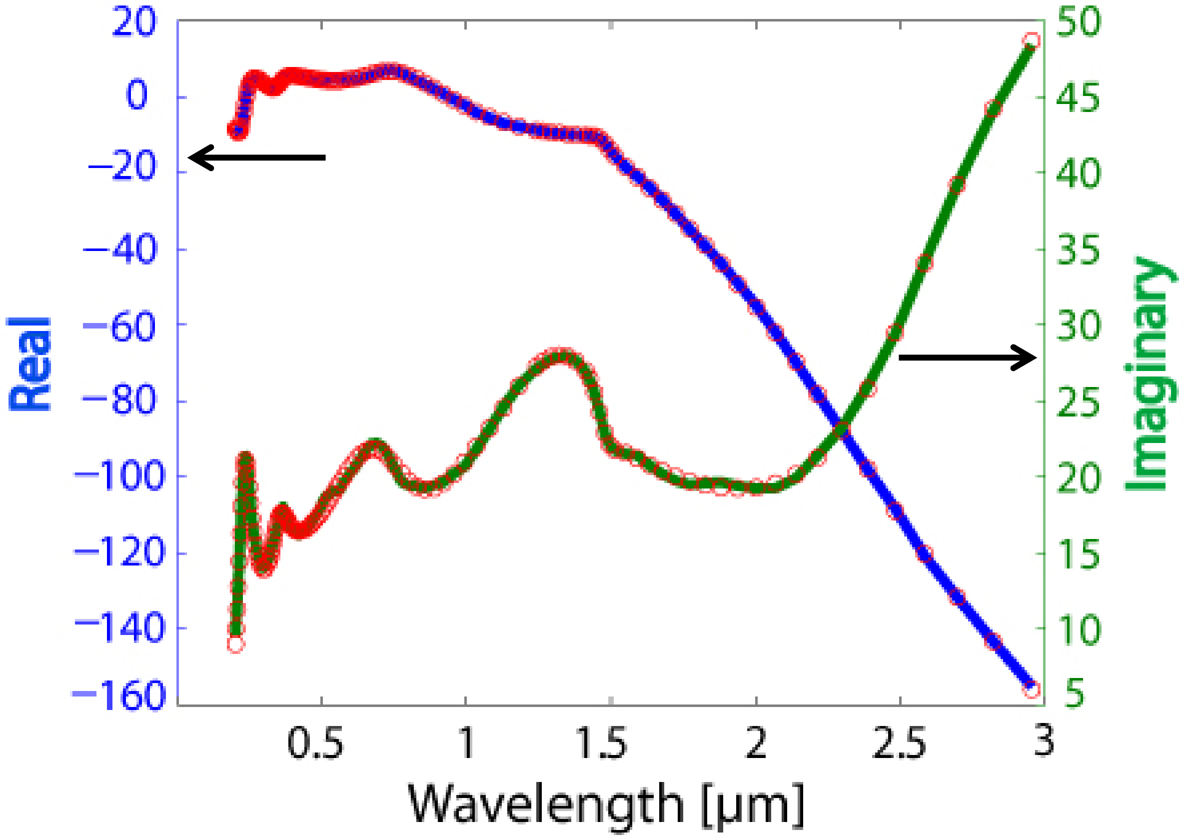


Design requirement for the intermediate
- Broad-band wide-angle absorber
- Narrow-band emitter

Material requirement for the intermediate
- Need to have large optical loss.
- Need to withstand high temperature.

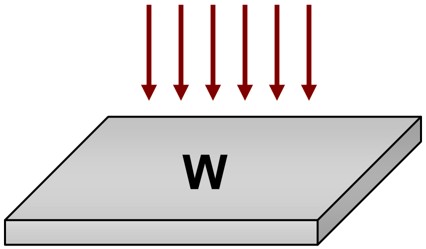
Tungsten is a natural choice of material.

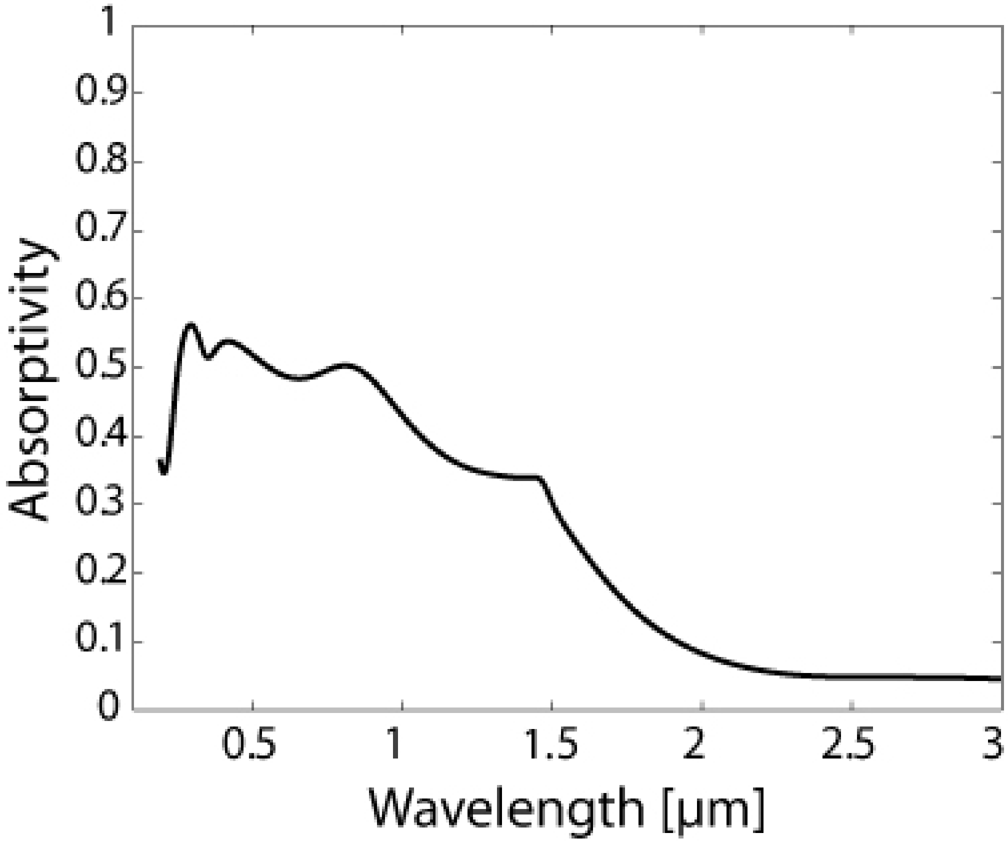
Dielectric Function of Tungsten



Tungsten is a very lossy material in the solar wavelength range.

Absorptivity of a semi-infinite slab of Tungsten

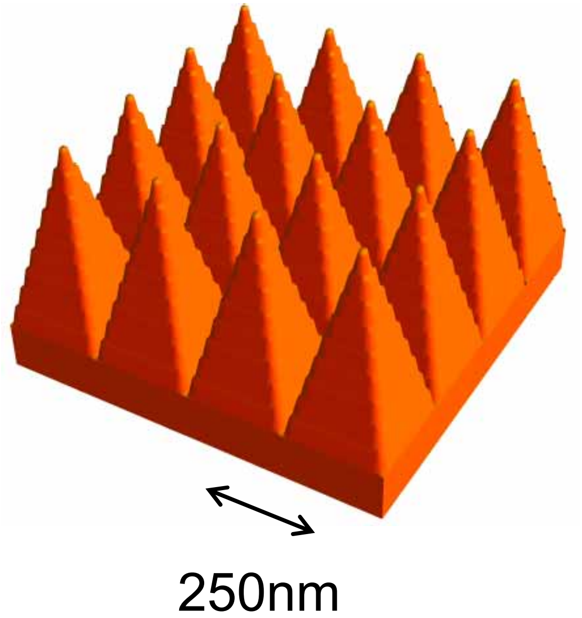




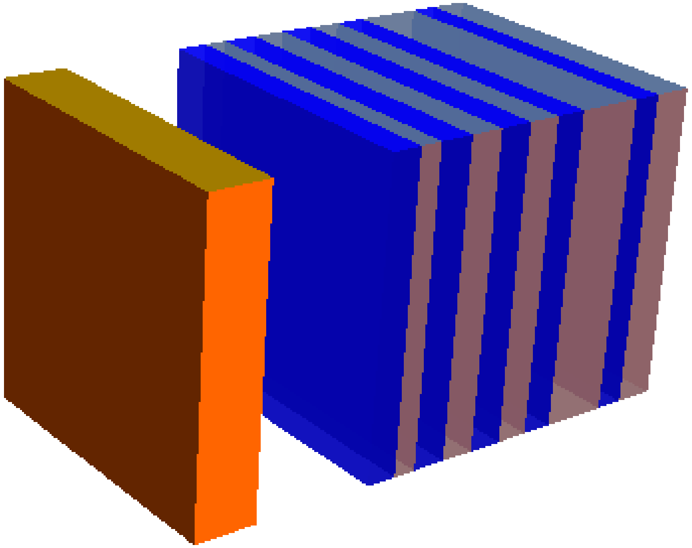
Neither a good absorber or a good emitter.

Nanostructured Tungsten Photonic Crystals

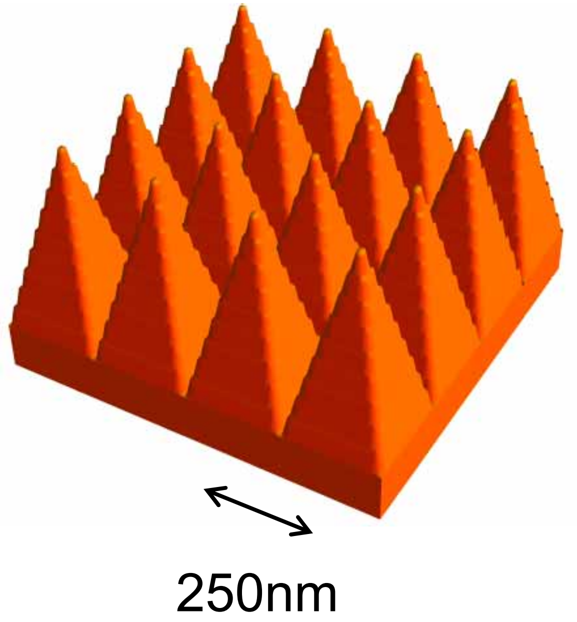
Broad-band absorber



Narrow-band Emitter



Absorber



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decompressor
are needed to see this picture.

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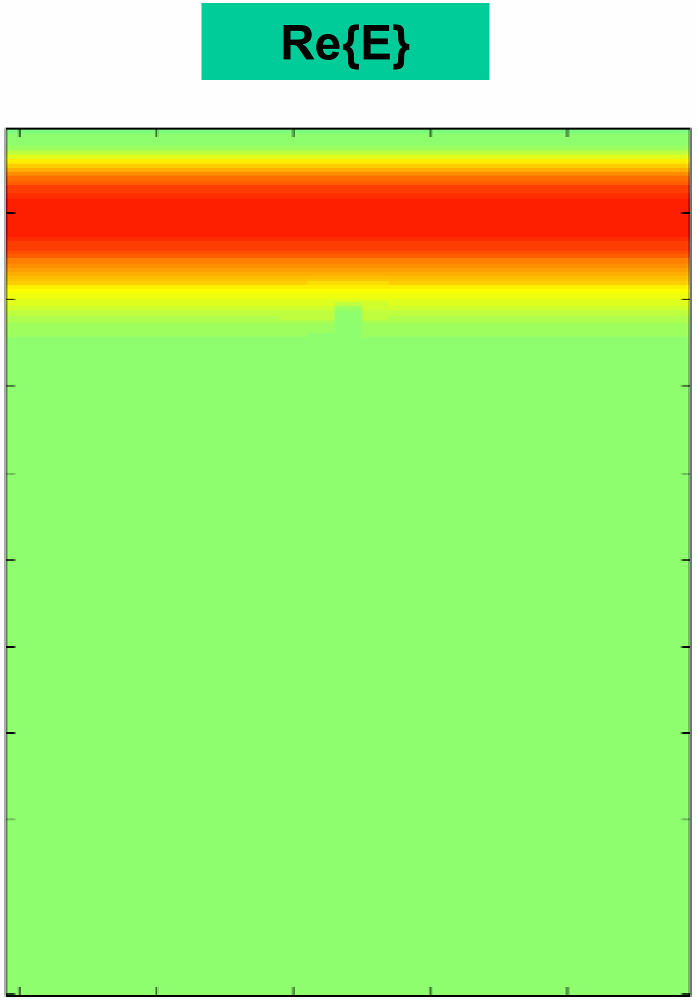
are needed to see this picture.

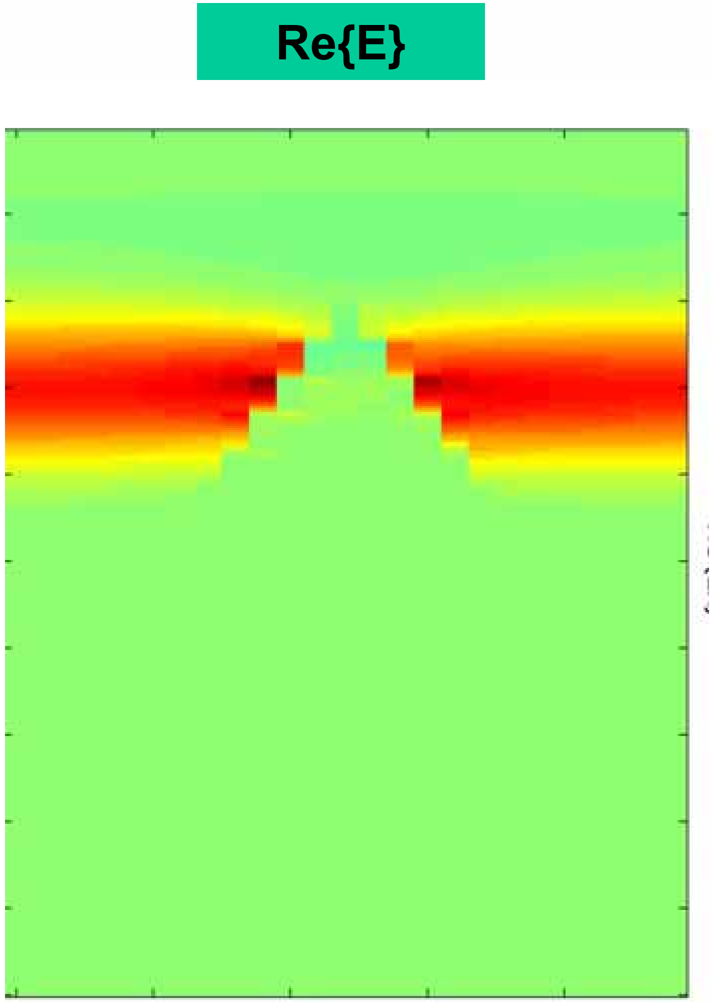
http://www.eyedesignbook.com/ch3/eyech3-c.html

- “Moth Eye” Design.
- Gradual change of impedance from air to Tungsten ensures penetration of light into the structure.

Absorber – impedance matching mechanism

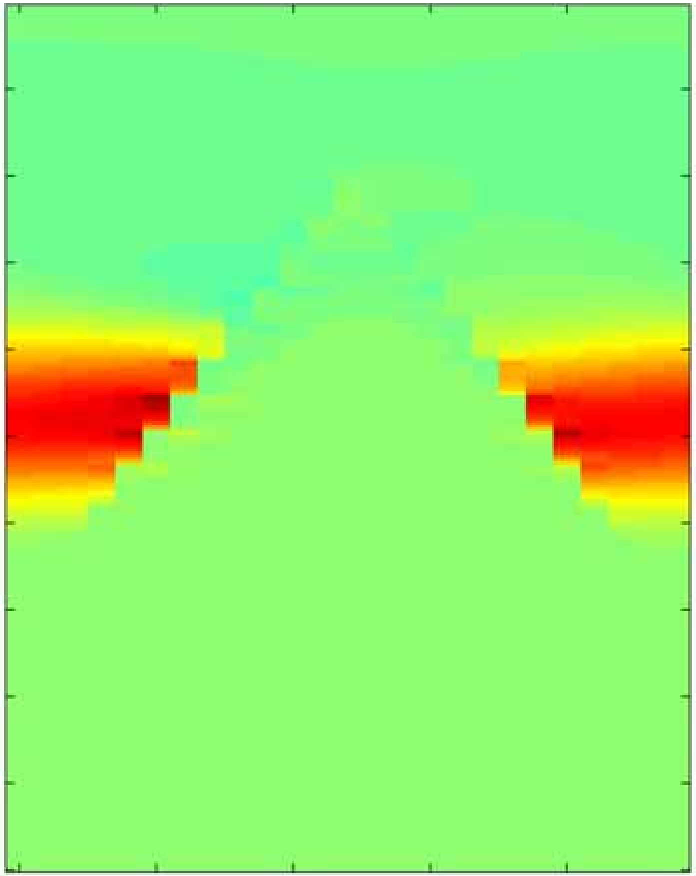


Absorber – impedance matching mechanism



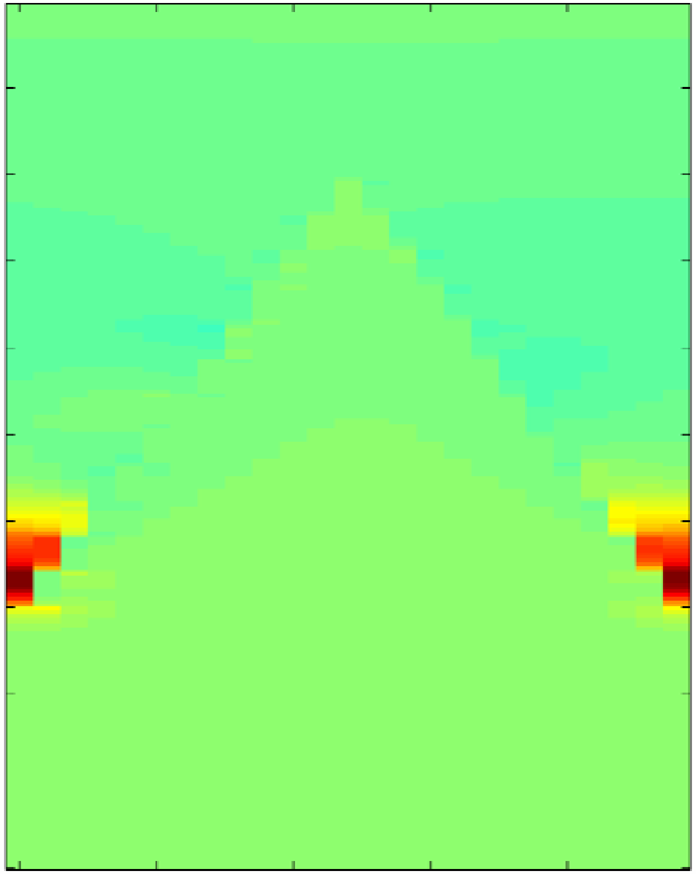
Absorber – impedance matching mechanism

Re{E}

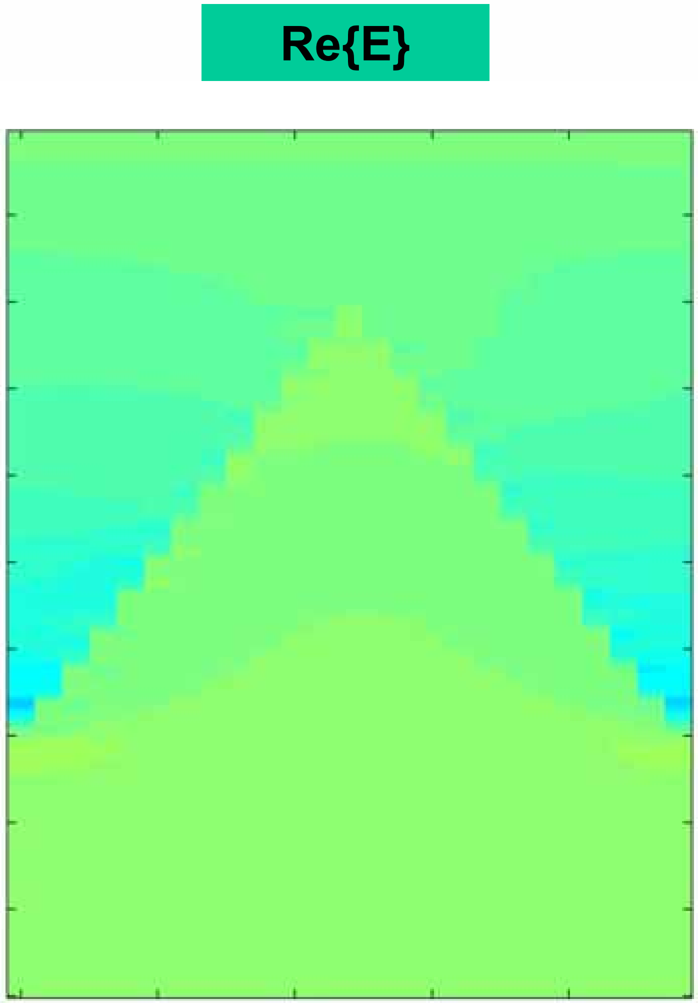


Absorber – impedance matching mechanism

Re{E}



Absorber – impedance matching mechanism



Tungsten Broad-Band Wide-Angle Absorber

QuickTime™ and a
decompressor
are needed to see this picture.

E. Rephaeli and S. Fan, Applied Physics Letters 92, 211107 (2008).

Thermal Emitter

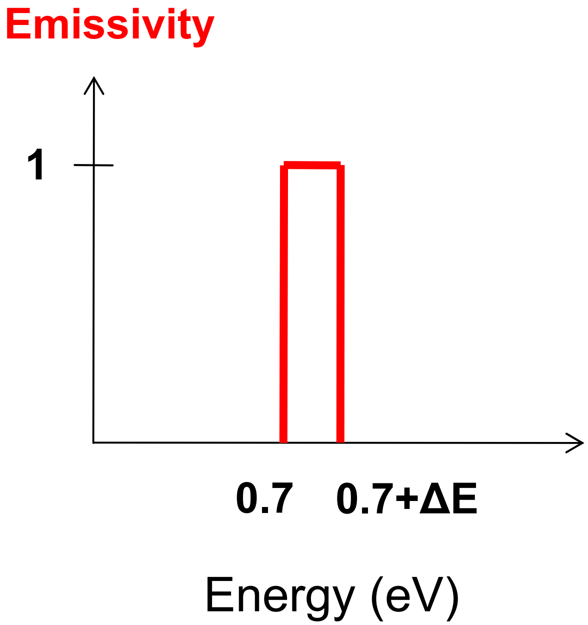
QuickTime™ and a
decompressor
are needed to see this picture.

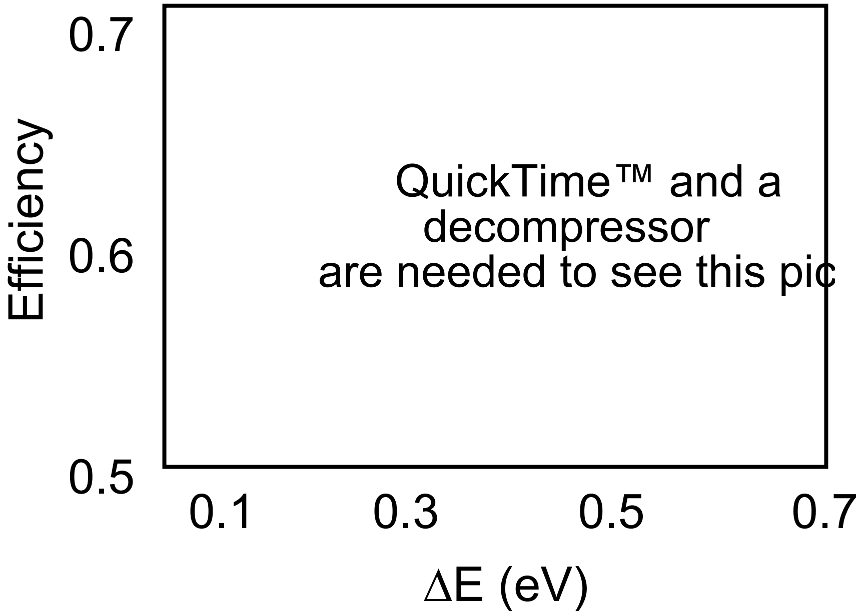
Vacuum Lamp:
1800 - 2700K

Gas Filled Lamp:
Up to 3200K

www.intl-lighttech.com/applications/appl-tungsten.pdf

Emitter Design Criterion

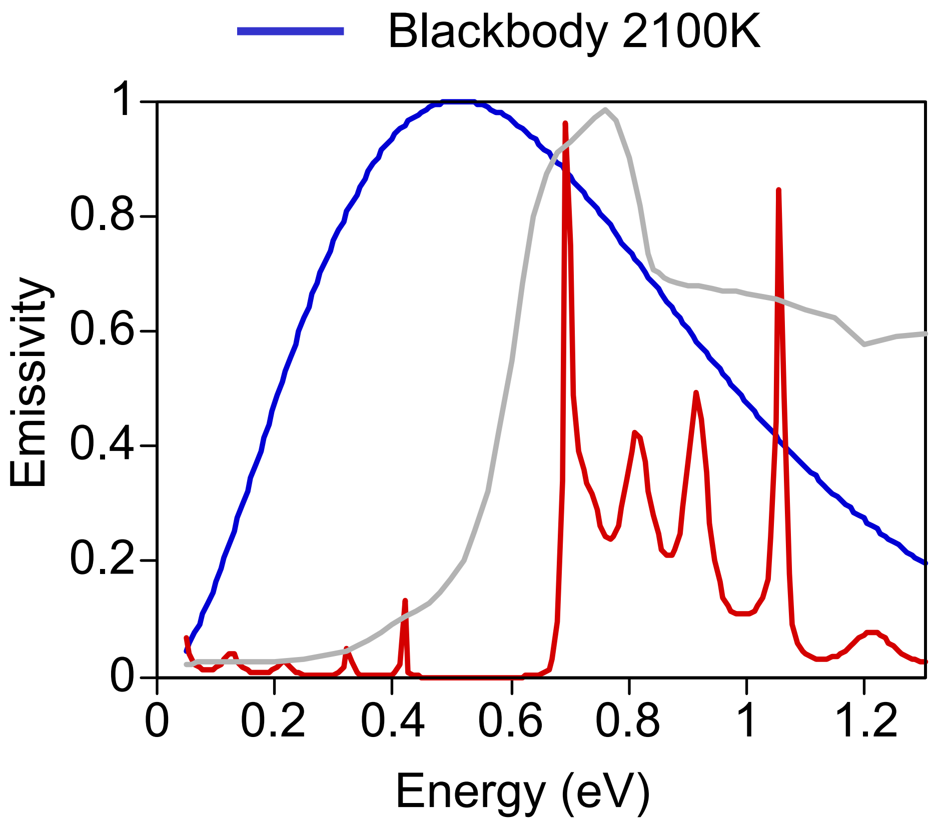


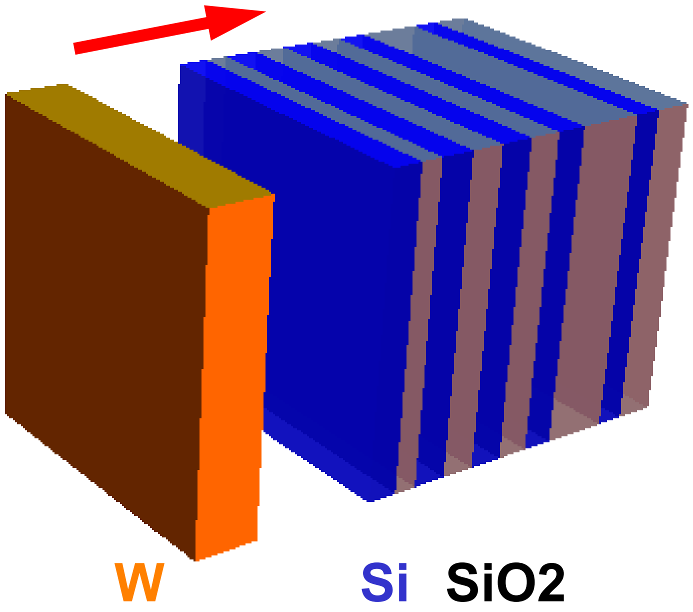


- Ideal 0.7eV cell.
- No photon-recycling between cell and emitter.
- Optimal bandwidth of the emitter ~ 0.07eV

E. Rephaeli and S. Fan, Optics Express 17, 15415 (2009).

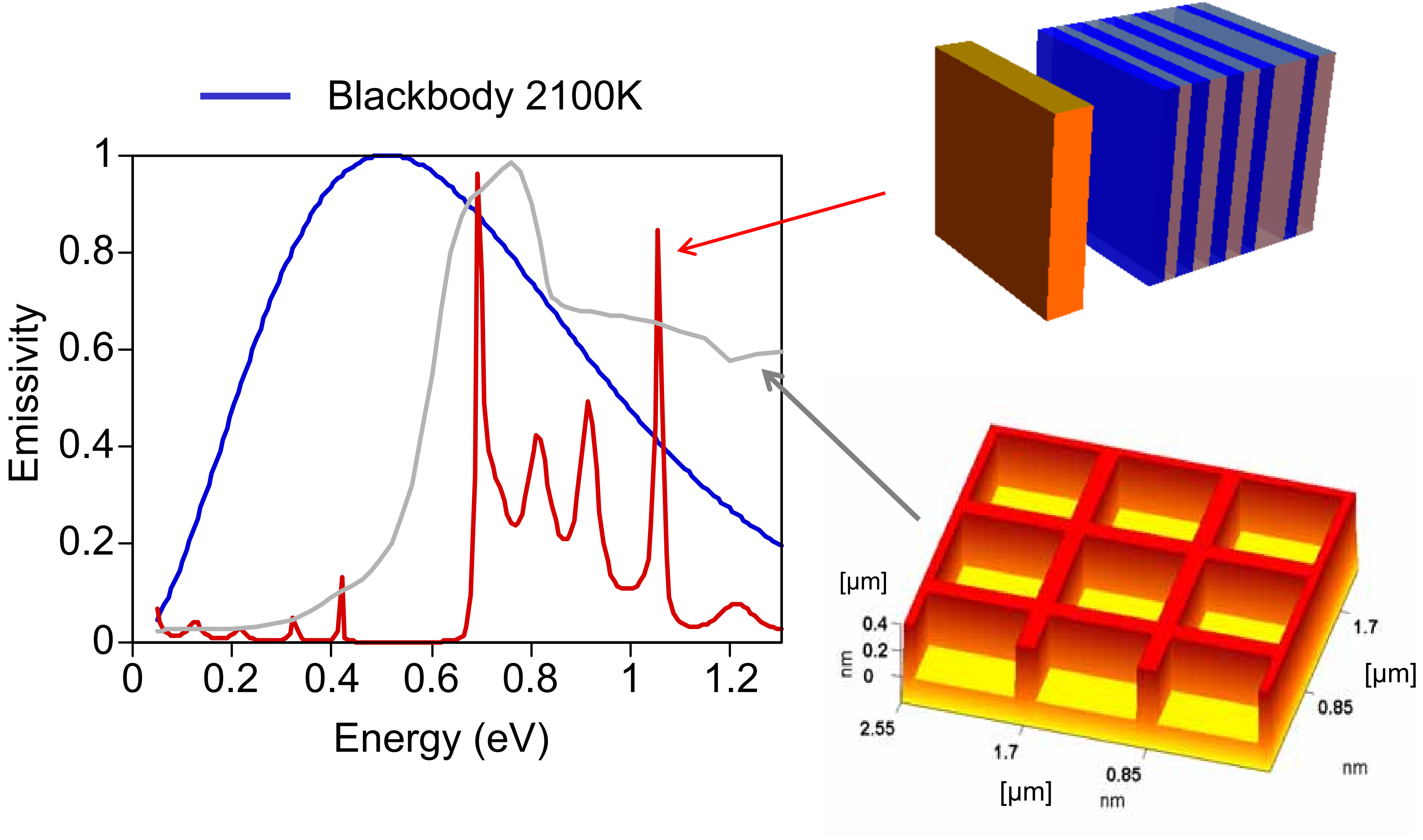
Narrow-band Tungsten emitter tuned to band gap of 0.7eV





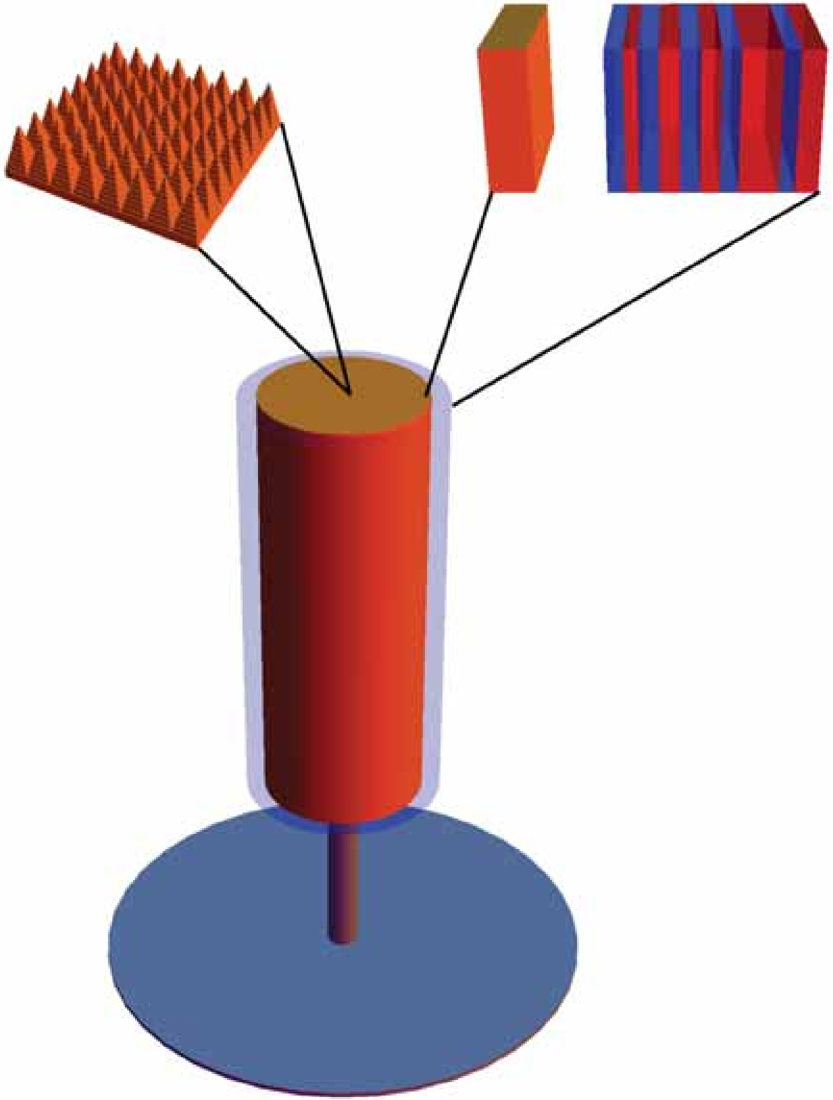
E. Rephaeli and S. Fan, Optics Express 17, 15415 (2009).

In contrast with earlier Tungsten emitter design

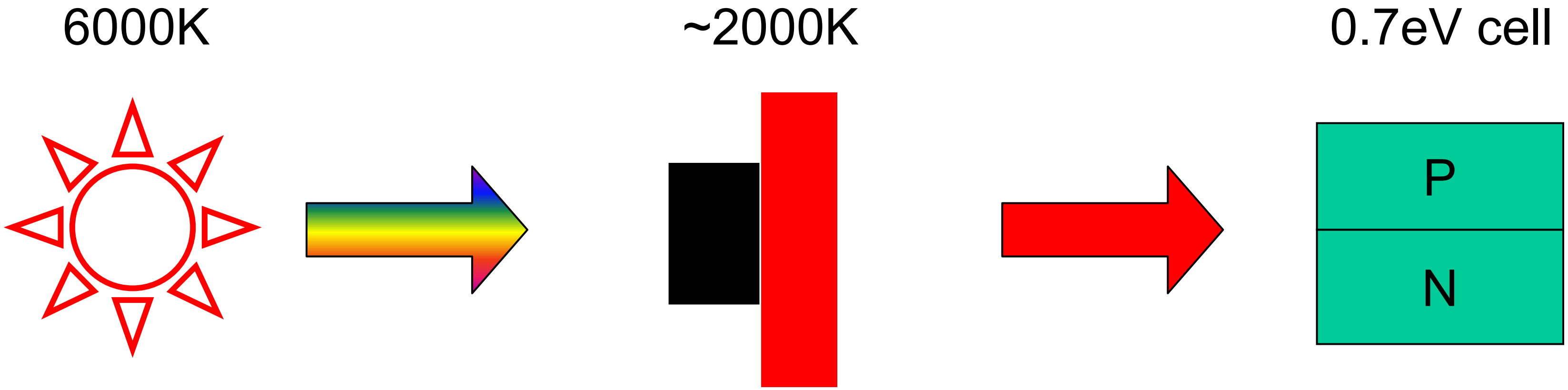


- Much stronger suppression of sub-band gap radiation compared with earlier design.

Schematic Incorporating both Absorber and Emitter



Beating Shockley-Queisser Limit



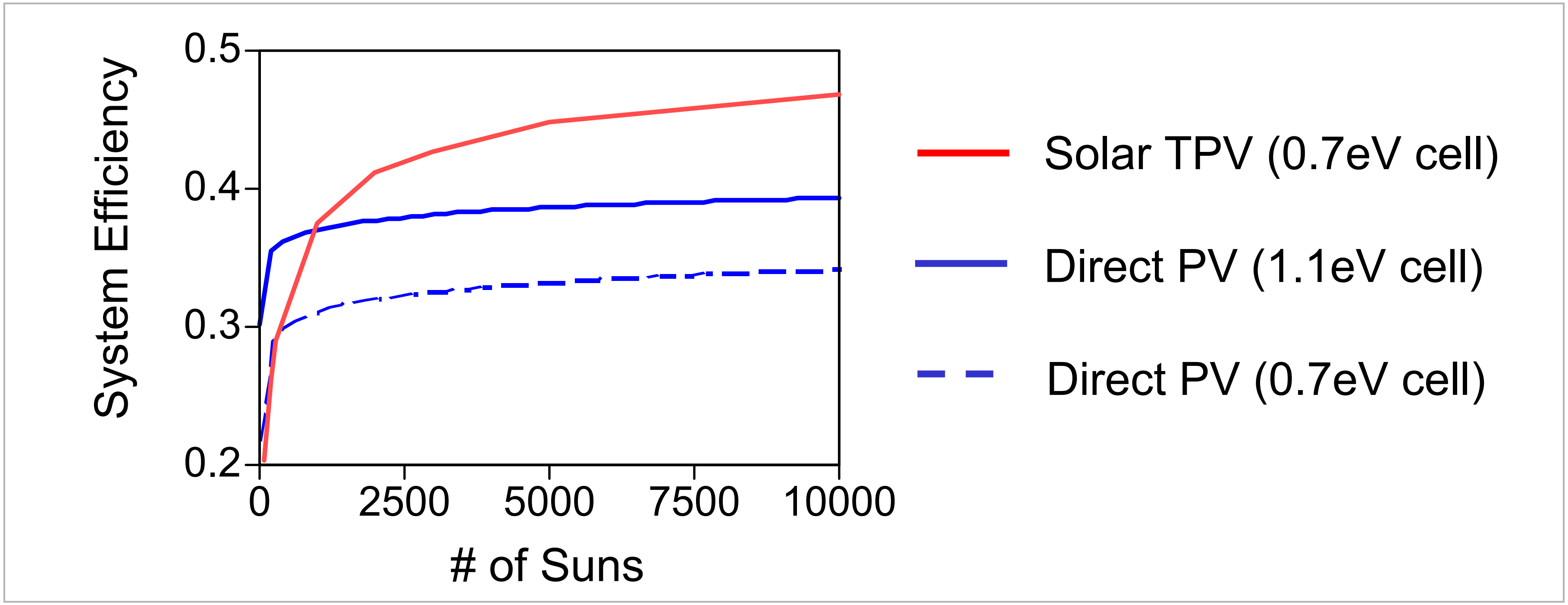
6000K

~2000K

0.7eV cell

P

N



E. Rephaeli and S. Fan, Optics Express 17, 15415 (2009).

Low-Cost Fabrication Techniques

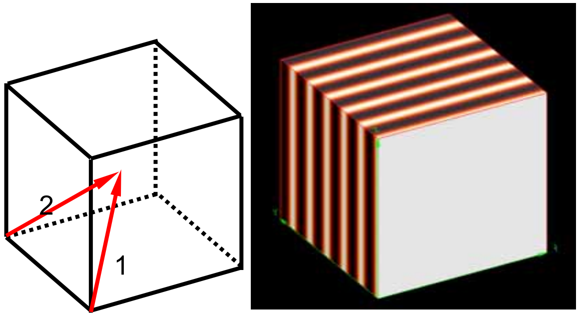
- Interference Lithography to create complex 2D and 3D structures in photo-resist.

- Covert the photo-resist to high-temperature-stable oxide photonic crystal template.

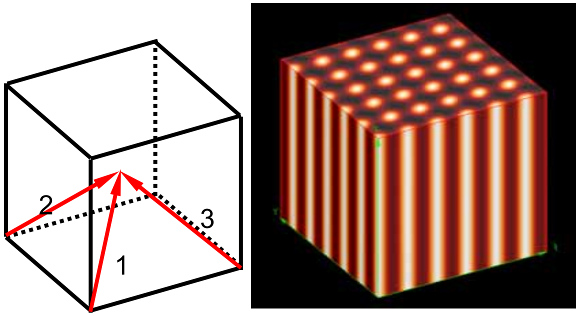
- Electro-deposit metal into the oxide photonic crystal template.

Multi-beam lithography

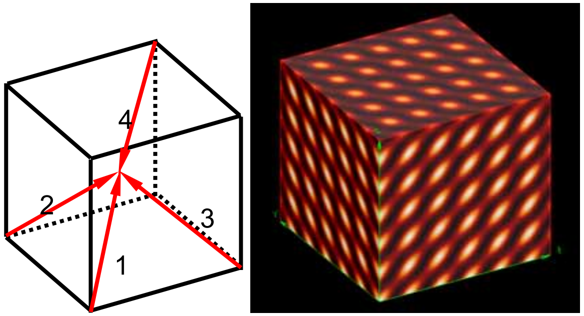
2 beams (1D)



3 beams (2D)



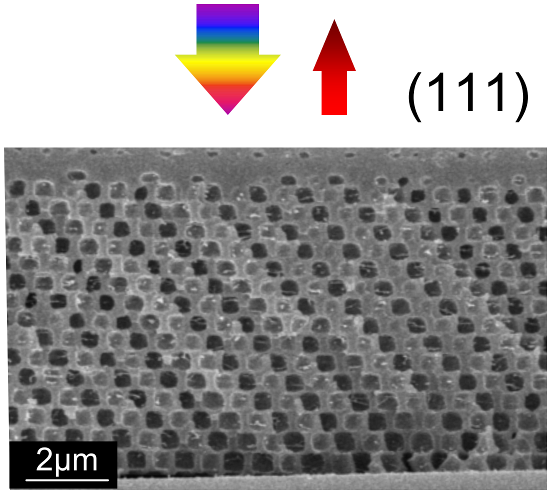
4 beams (3D)



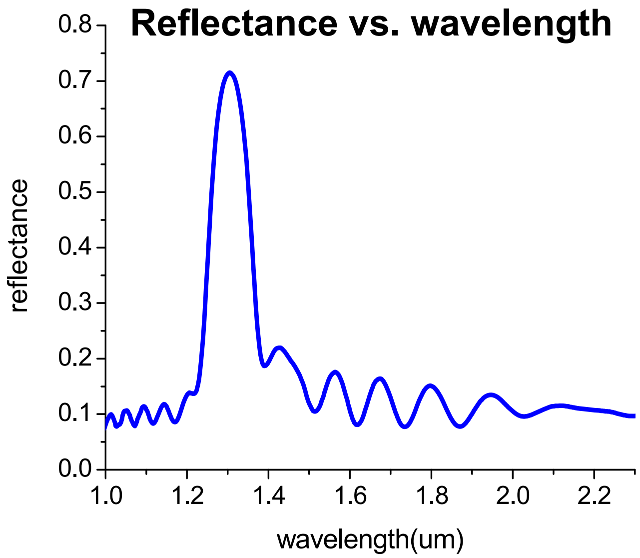
$$I = \underbrace{\sum_j {E_j}^2 + \sum_{i<j} 2E_iE_j}_{\text{power}} \; \underbrace{\cos\theta_{ij}}_{\text{polarization}} \; \cos[\underbrace{(\mathbf{K}_i - \mathbf{K}_j)\mathbf{r}}_{\text{wavevector}} + \underbrace{\varphi_{0i} - \varphi_{0j}}_{\text{phase}}]$$

wavevector

- beam geometry
- wavelength
- refractive index



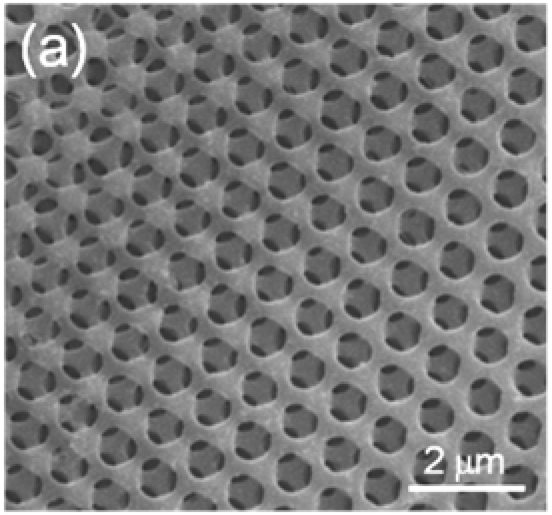
SEM cross-section

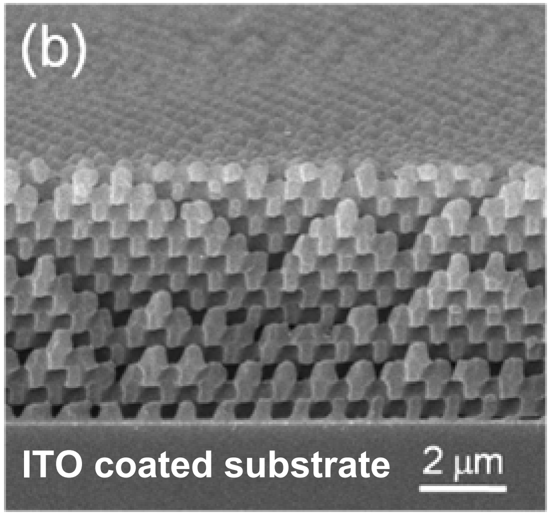


Electrochemical Templating of Cu_2O 3D Photonic Crystals

Cu_2O has a high refractive index (2.6), and is transparent above 600 nm

SU-8 template: Formed via 4-beam interference lithography

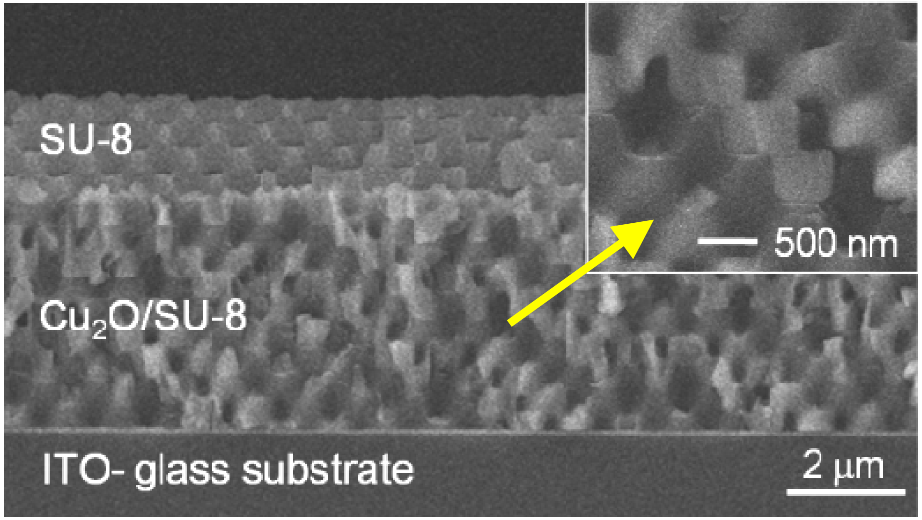




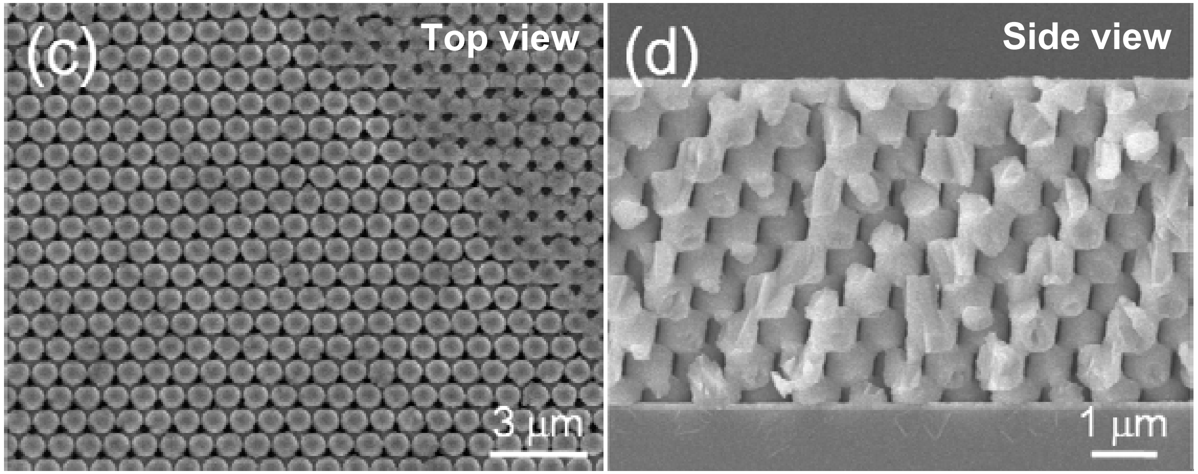
Advanced Materials, 2009

Cu_2O electrodeposition

Top of Cu_2O



1) Polish (remove surface roughness)
2) RIE to remove SU-8 Photoresist



Result: Cu_2O 3D Photonic Crystal

Implications for Solar Thermal Applications

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decompressor
are needed to see this picture.

N. Sergeant, M. Agrawal and P. Peumanns

Summary

- Design for Tungsten-based absorber and emitter for solar thermophotovoltaic applications.

- Interference lithography techniques.

- Solar thermal applications in general.