Light management in photovoltaics using nanotechnology

Albert Polman

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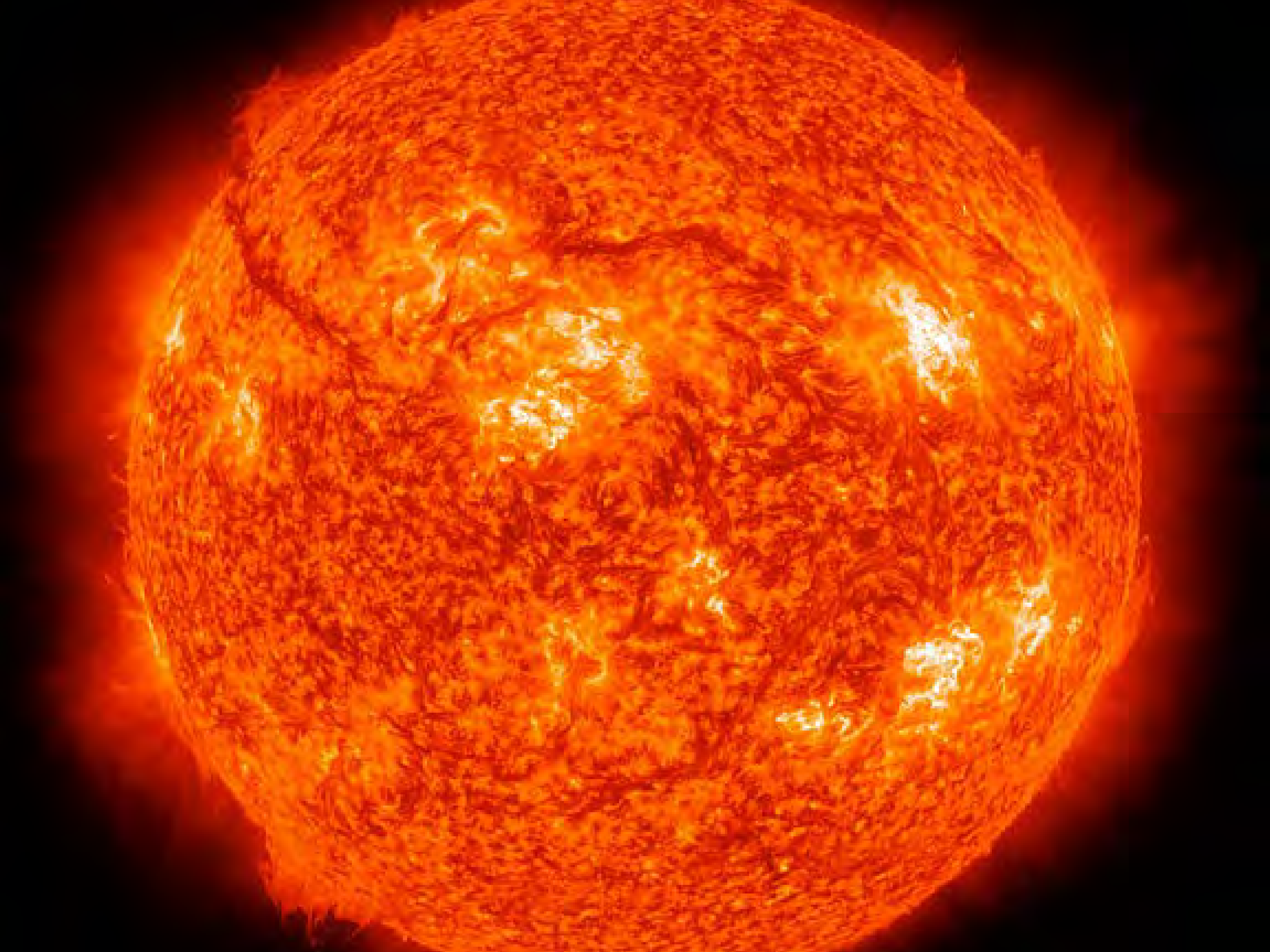
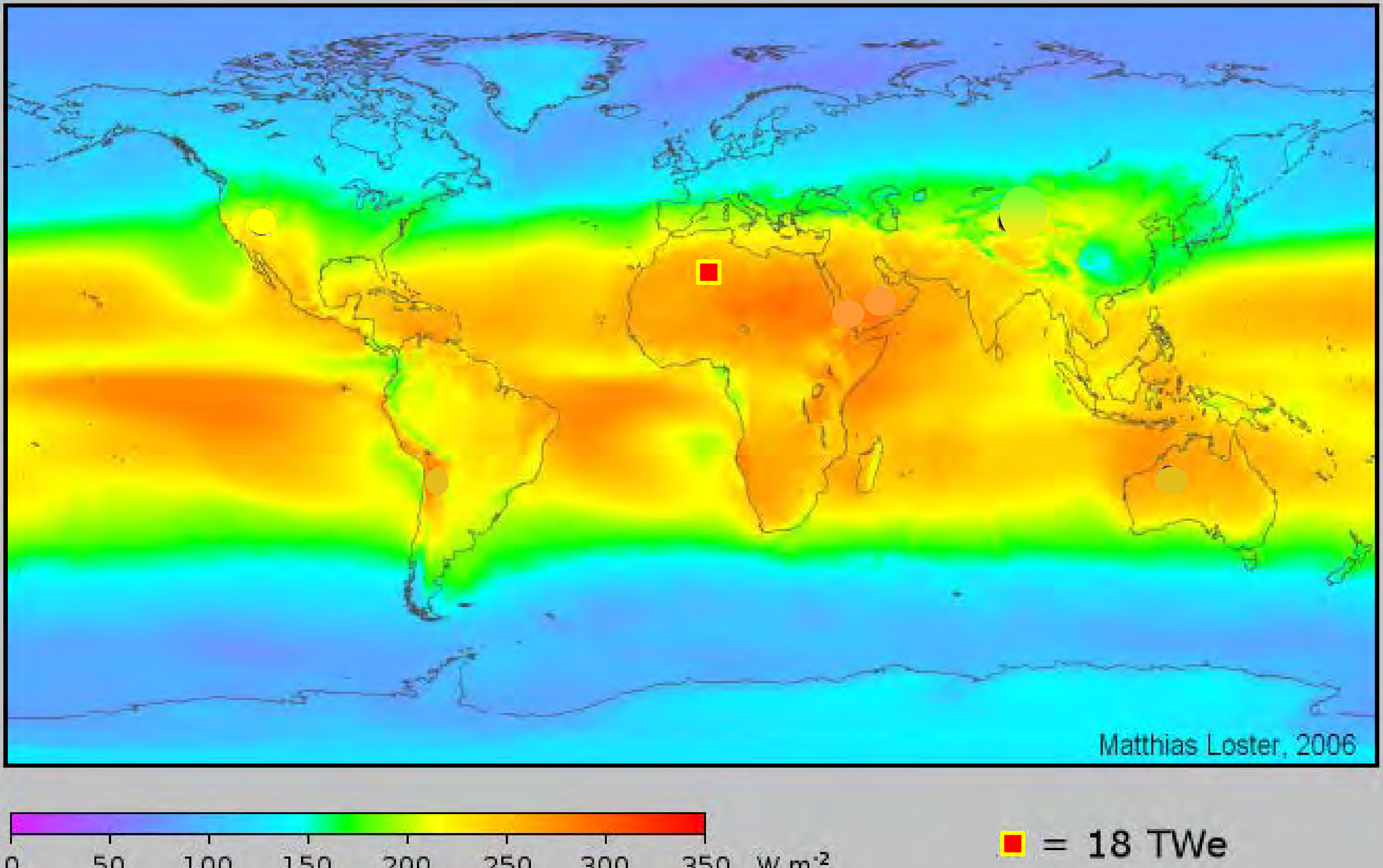


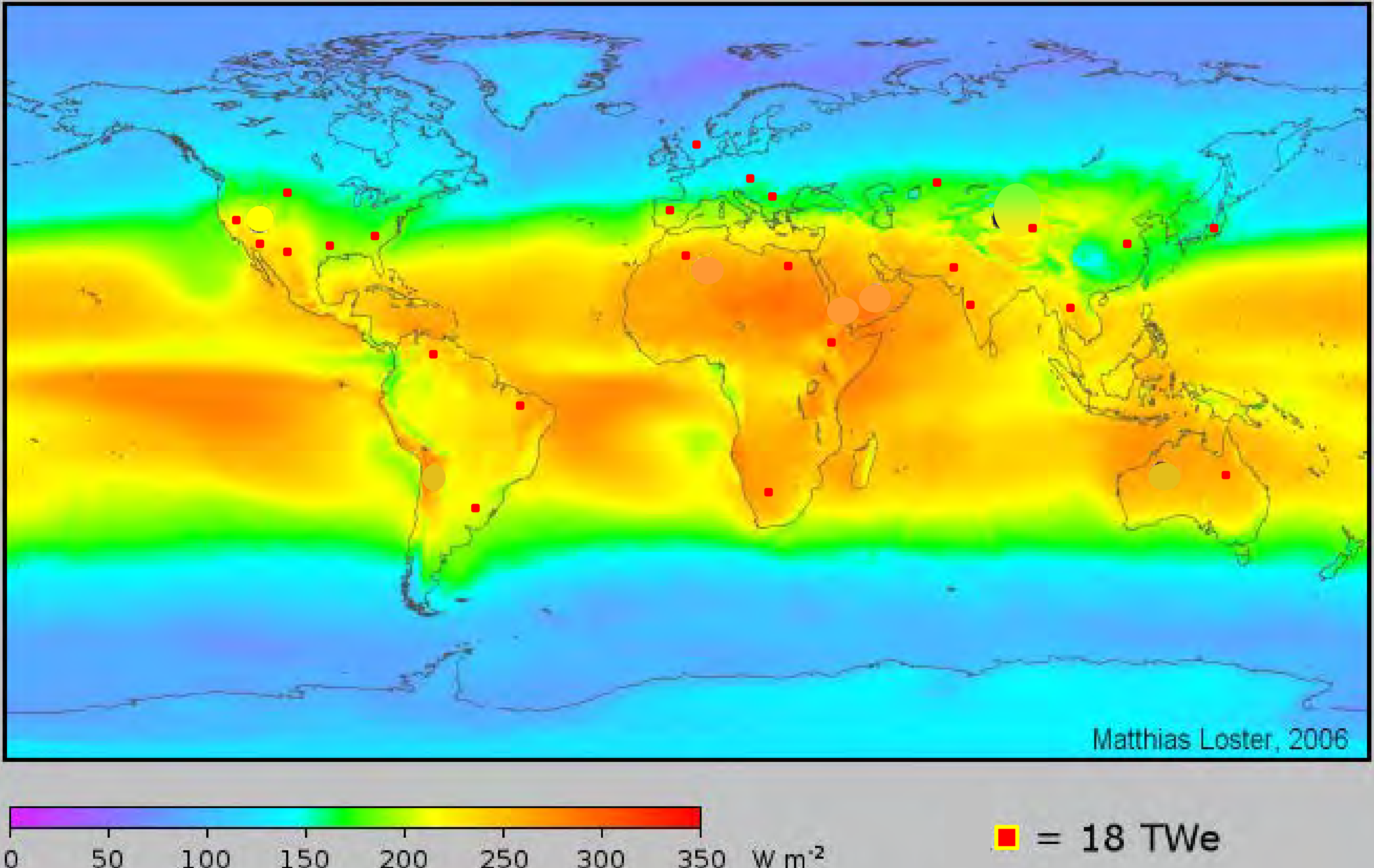
Solar irradiance on earth



■ = 18 TWe

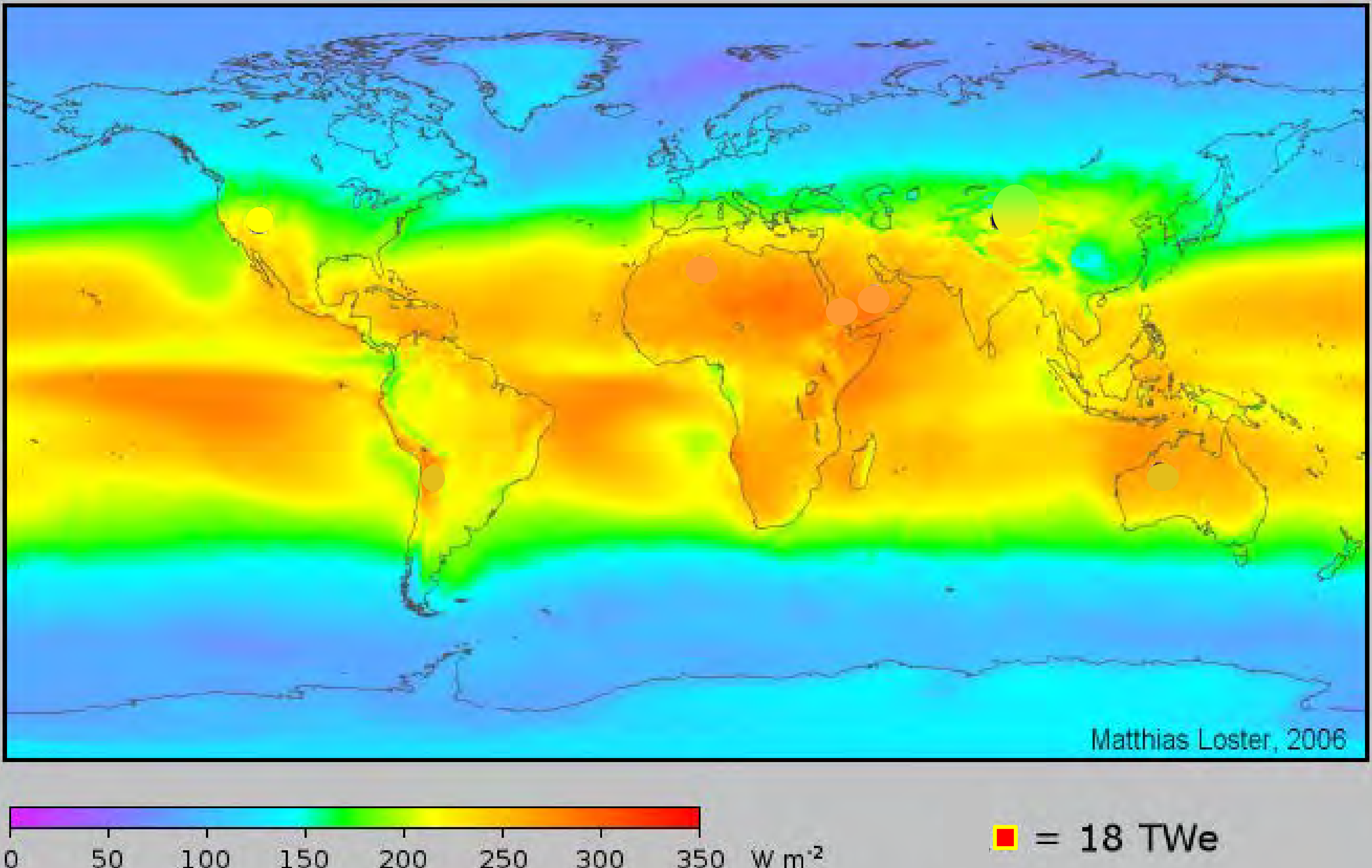
assuming 30% PV, 175 W/m^2

Solar irradiance on earth



assuming 30% PV, 175 W/m^2

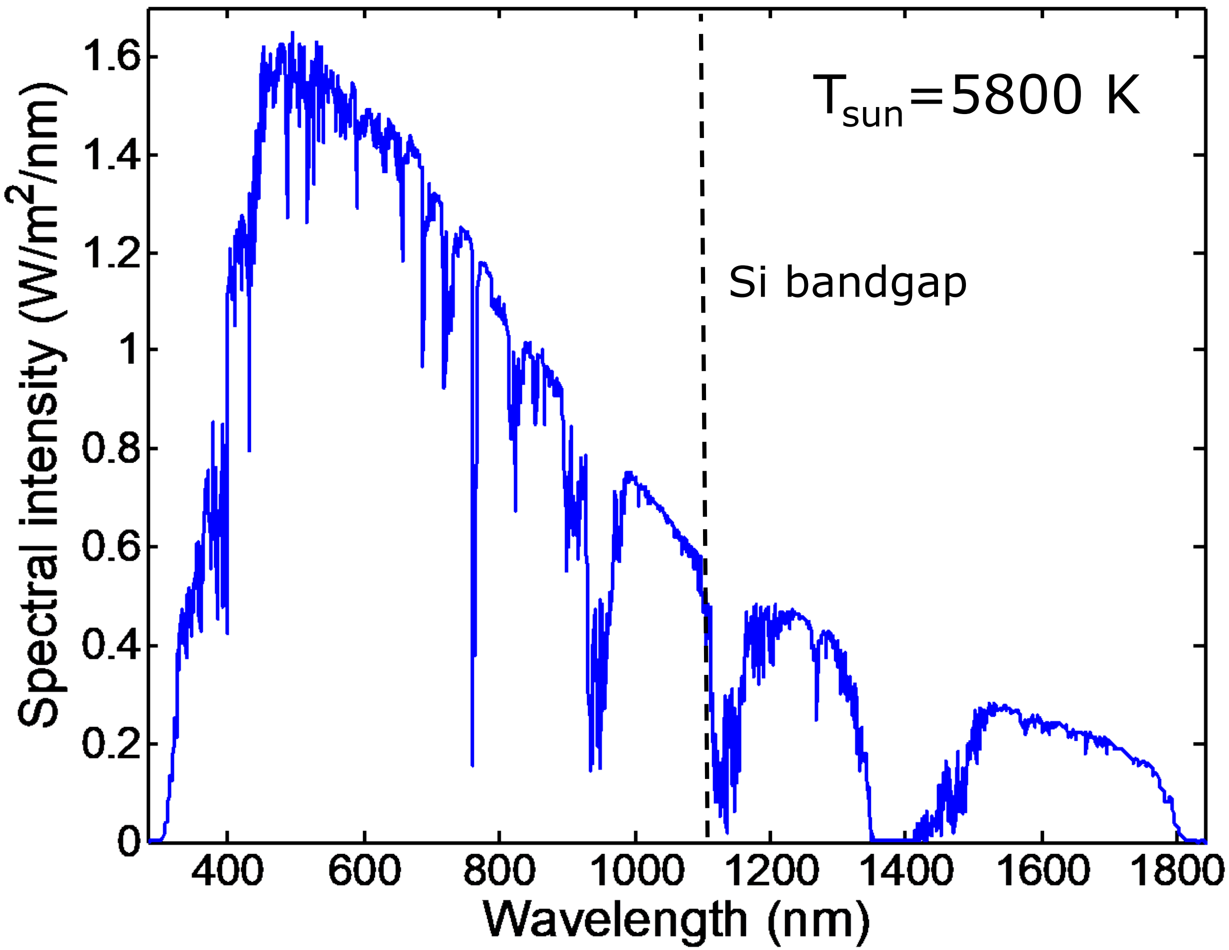
Solar irradiance on earth



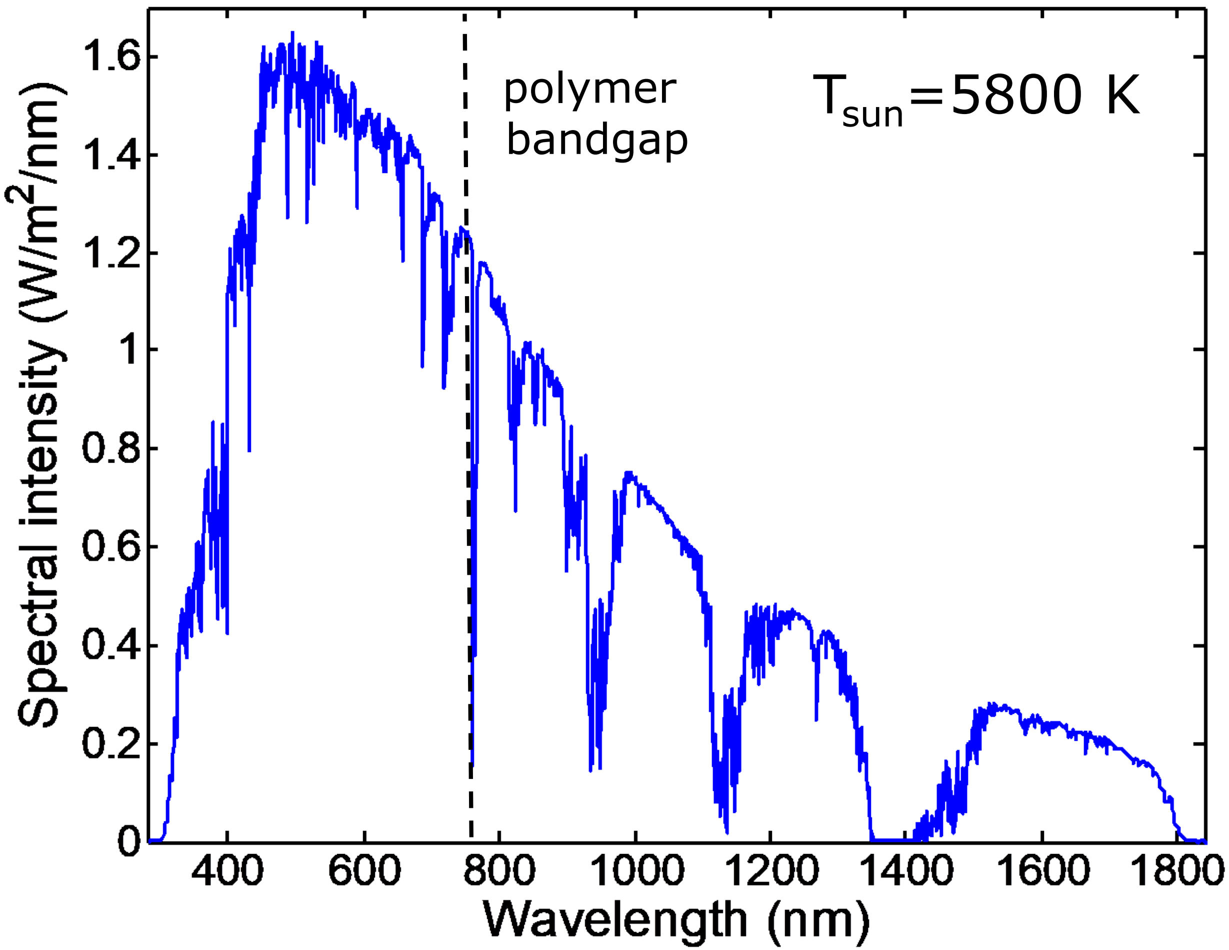
= 18 TWe

assuming 30% PV, 175 W/m²

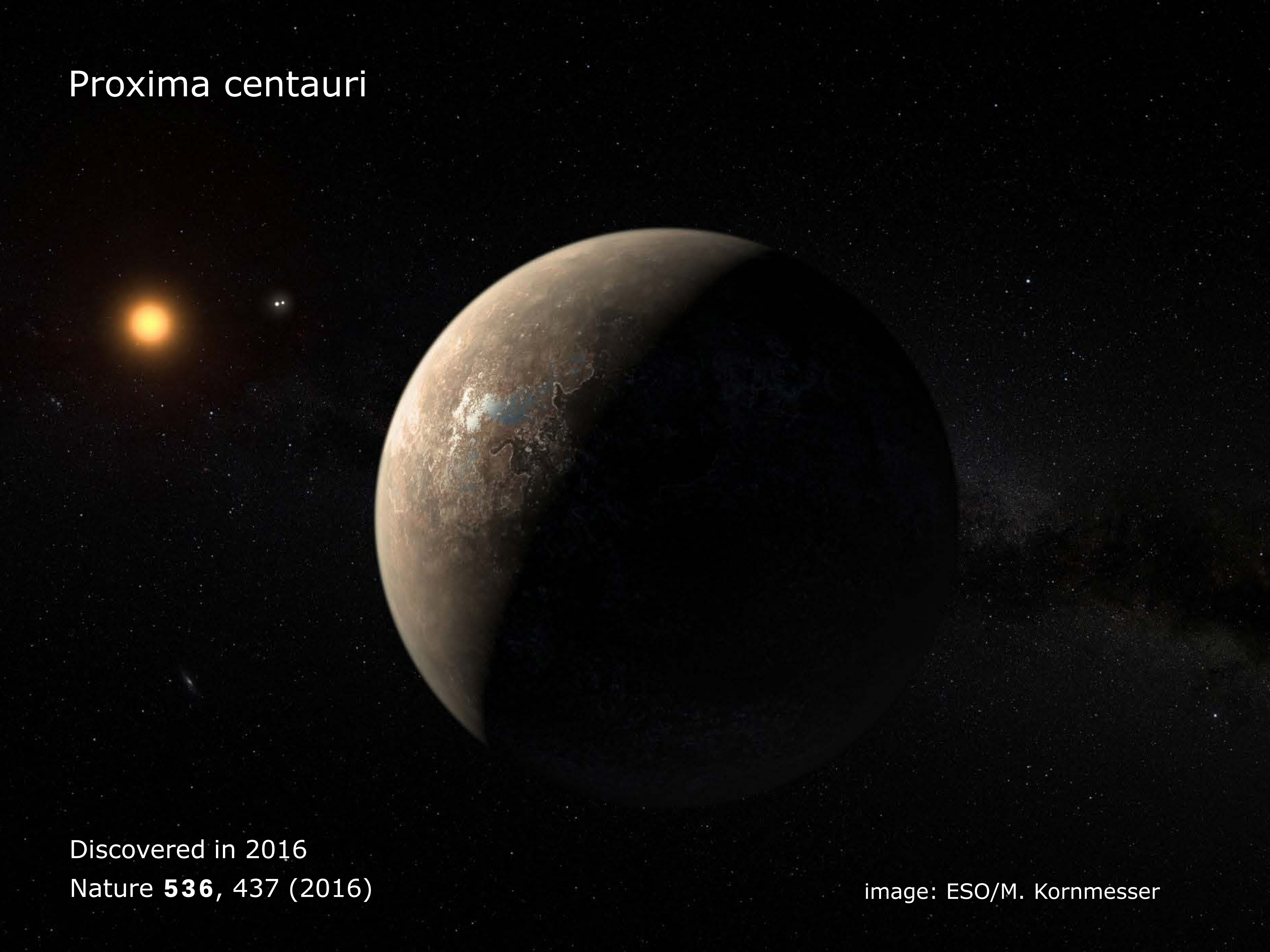
The solar spectrum



The solar spectrum



Proxima centauri

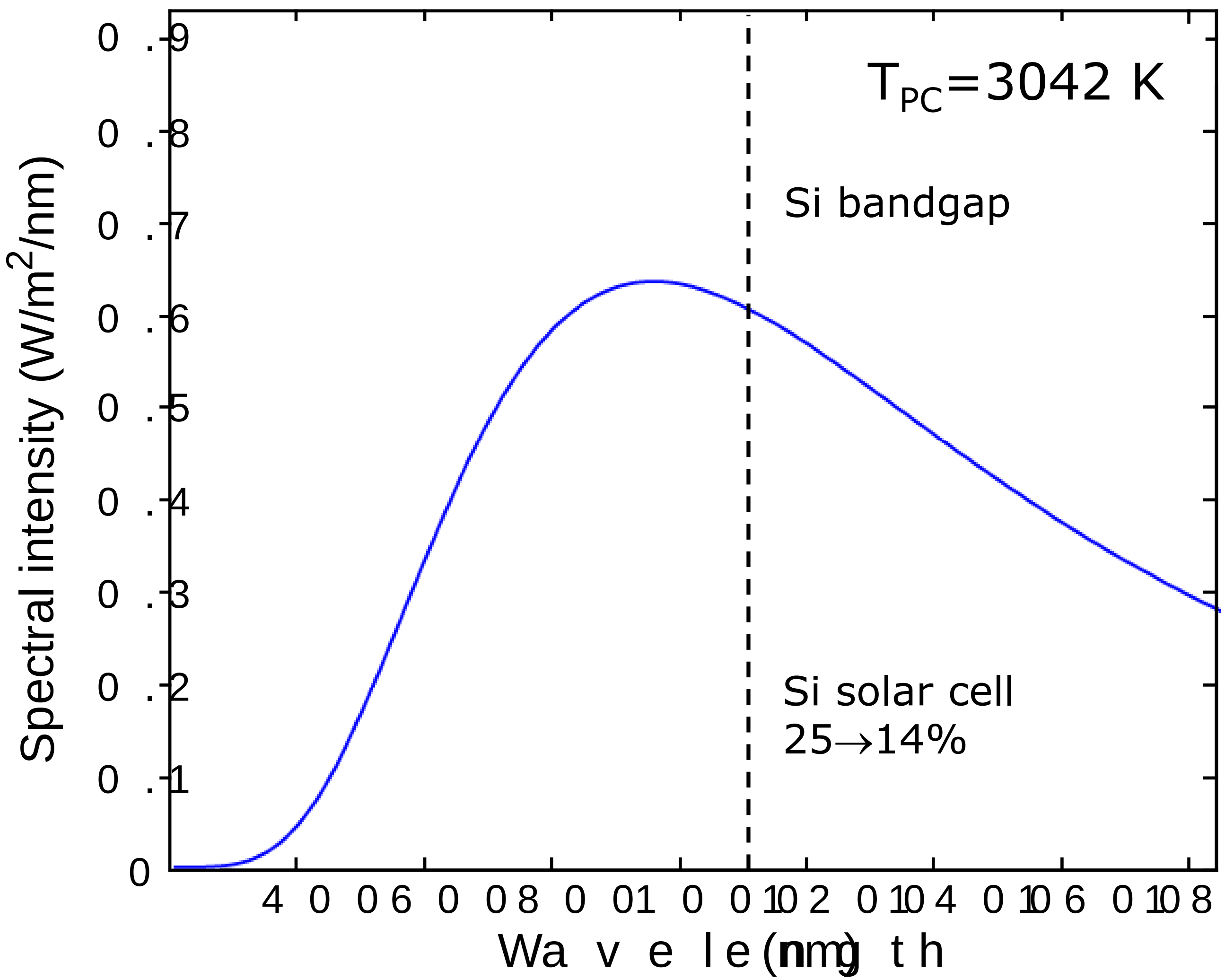


Discovered in 2016

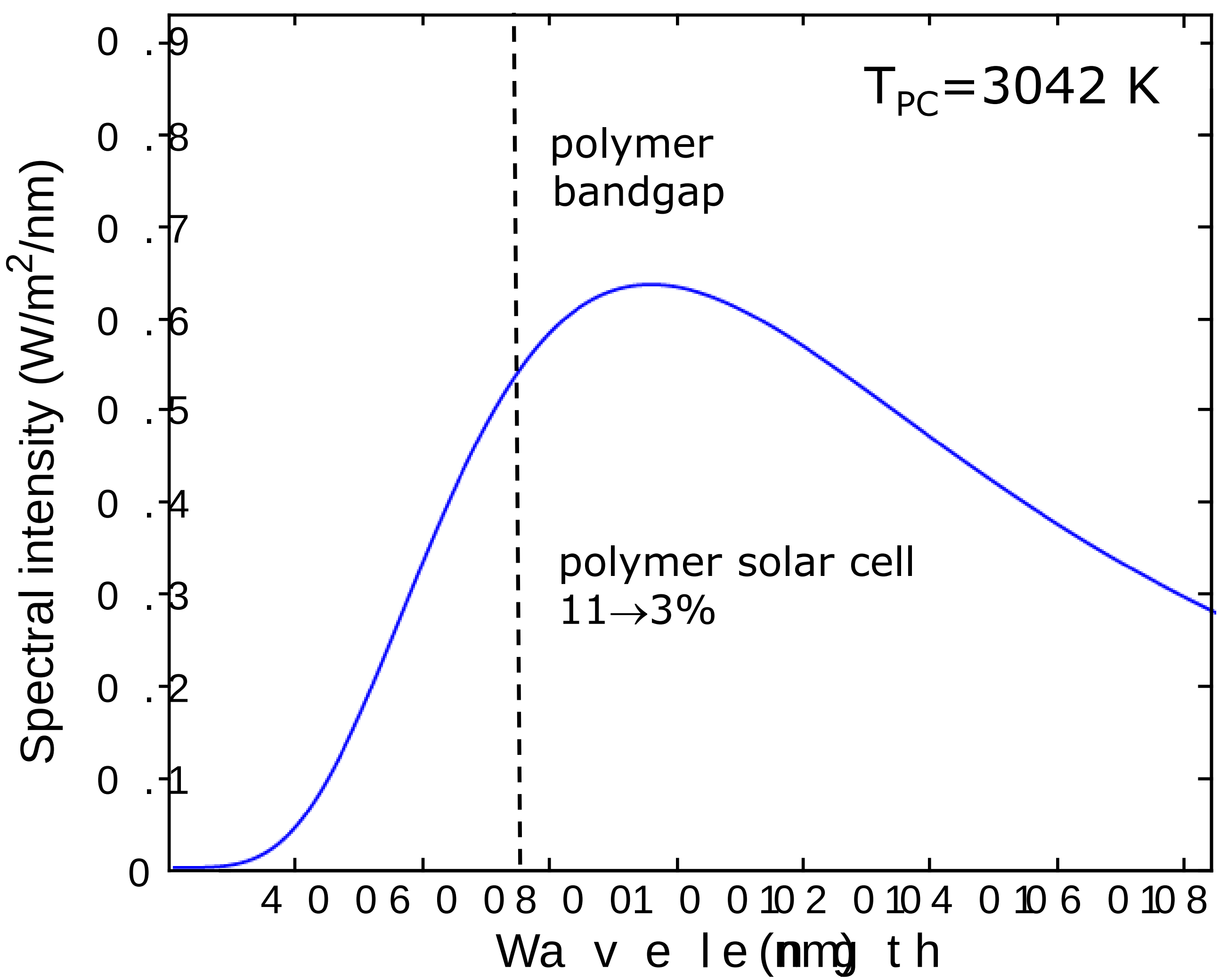
Nature **536**, 437 (2016)

image: ESO/M. Kornmesser

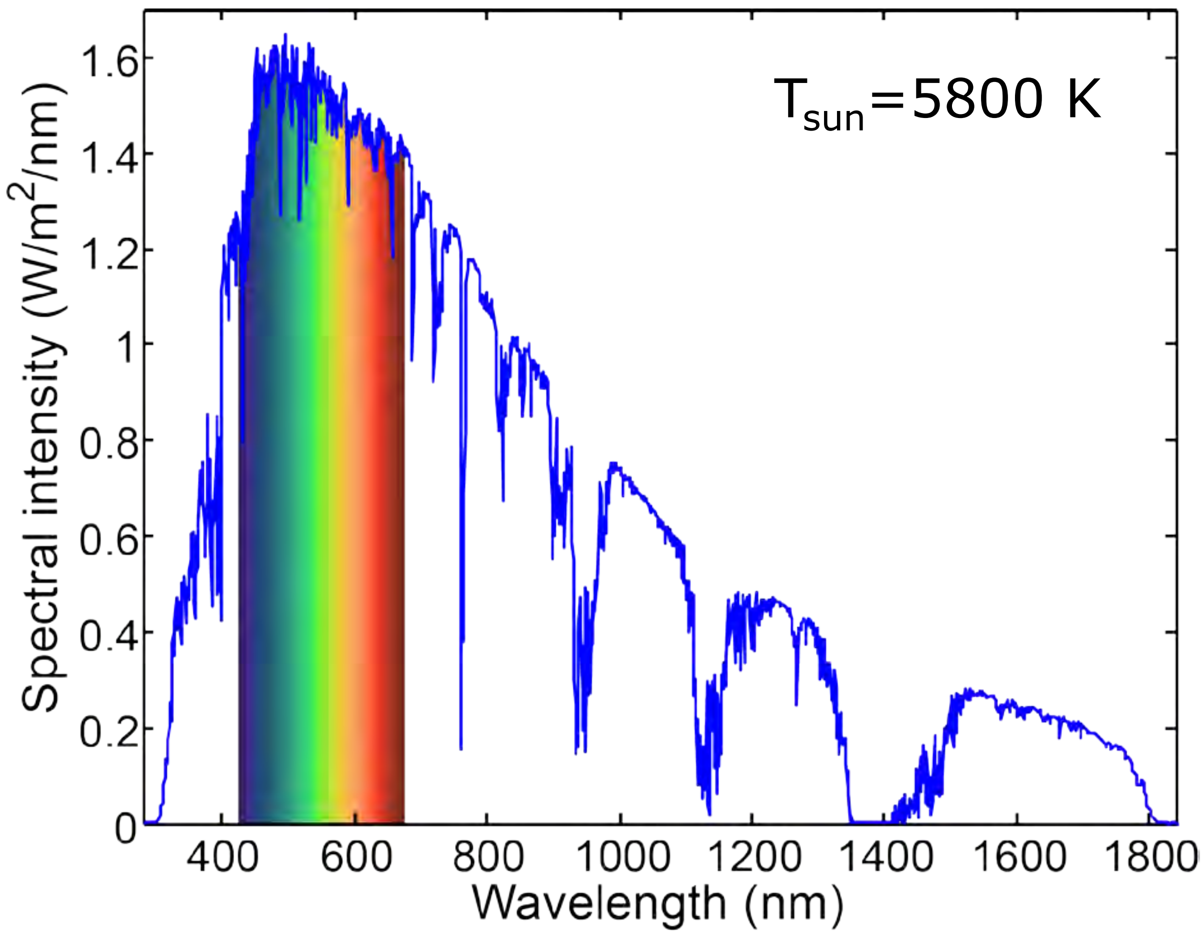
Proxima centauri spectrum



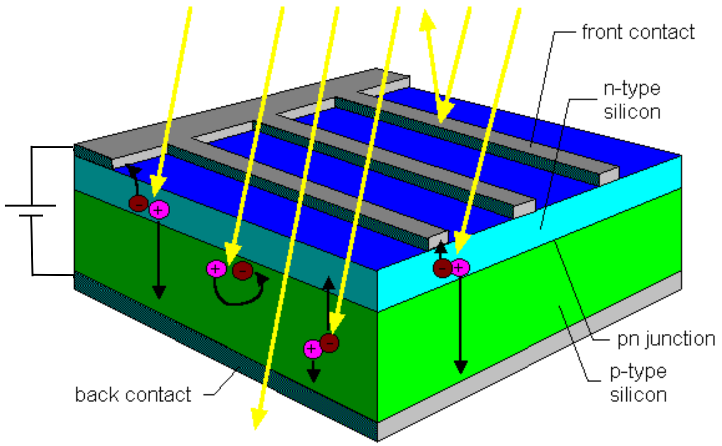
Proxima centauri spectrum

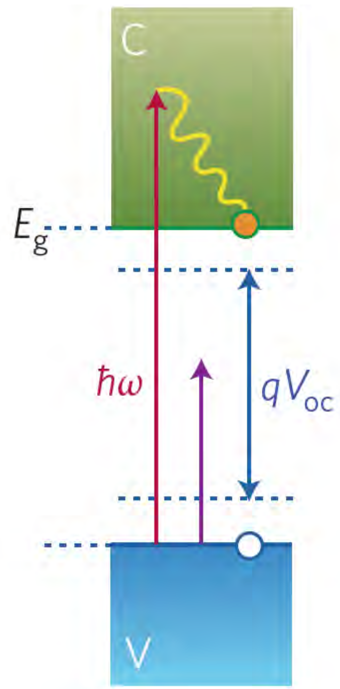


Our solar spectrum - visible spectrum

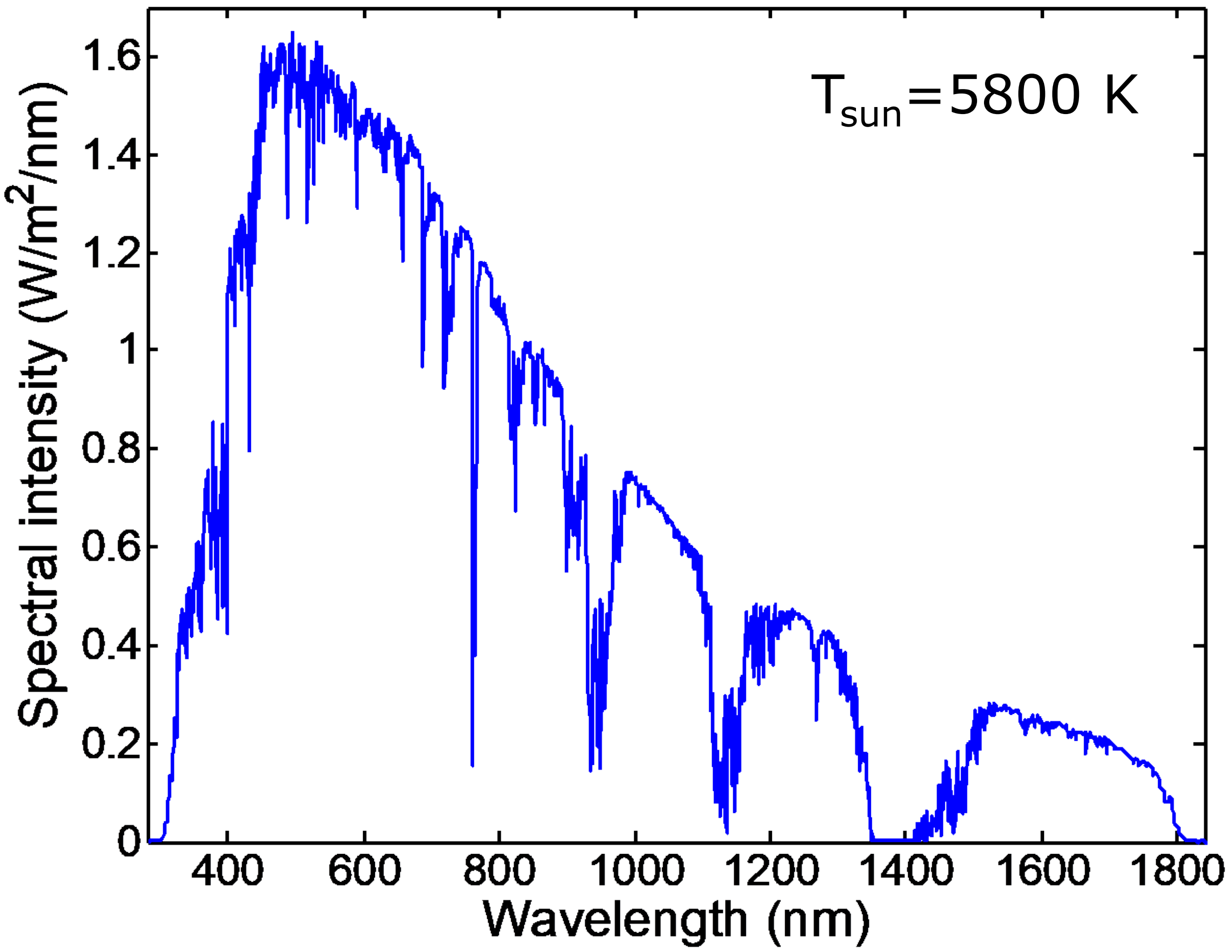


Solar cell basic design

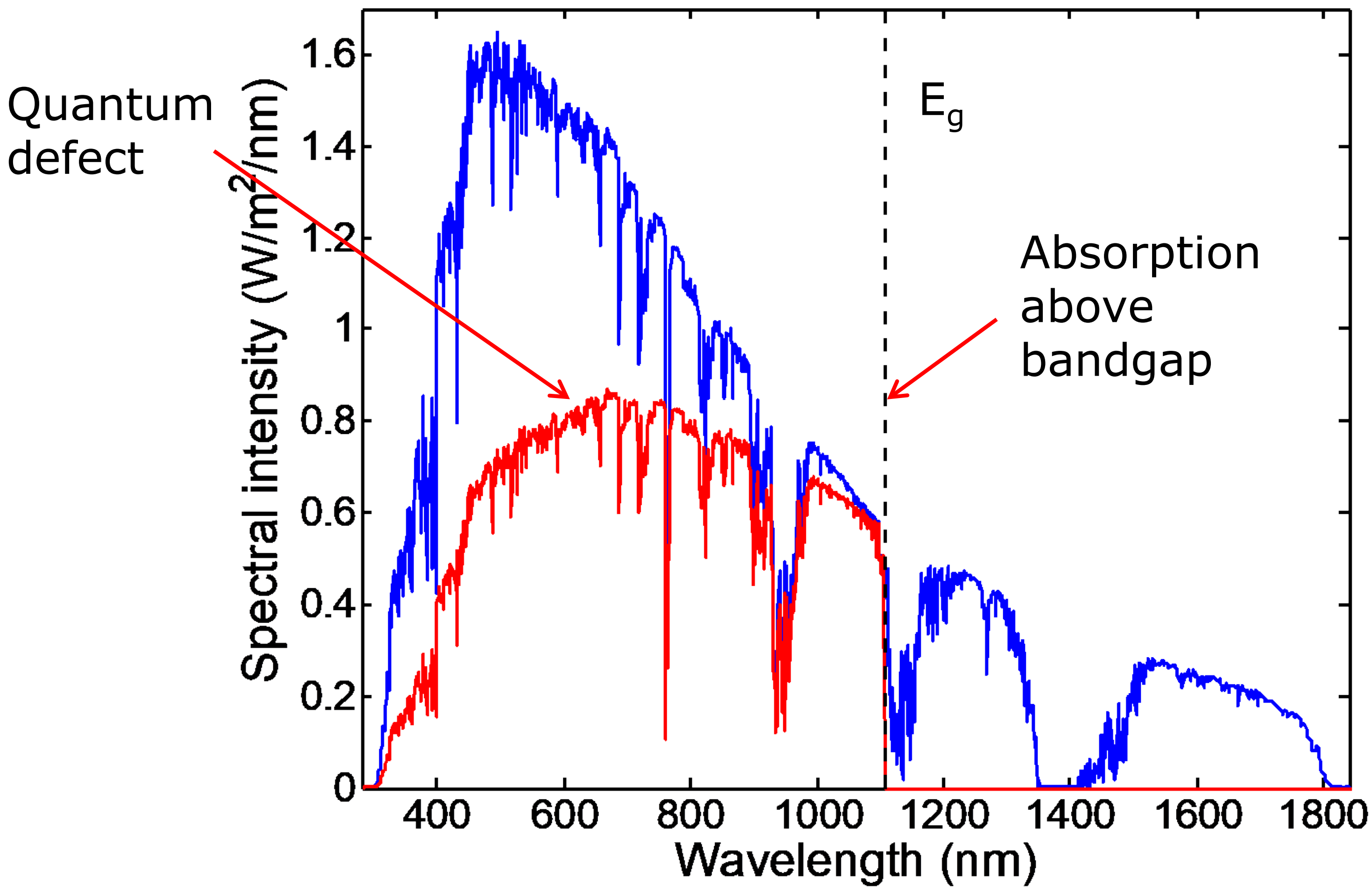




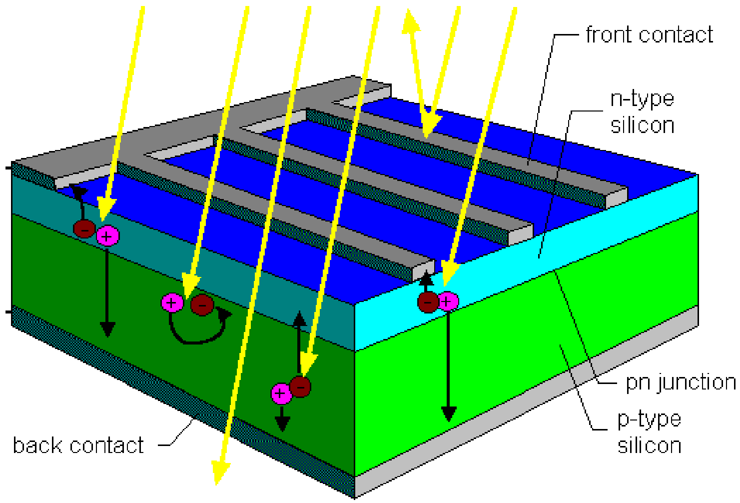
The solar spectrum

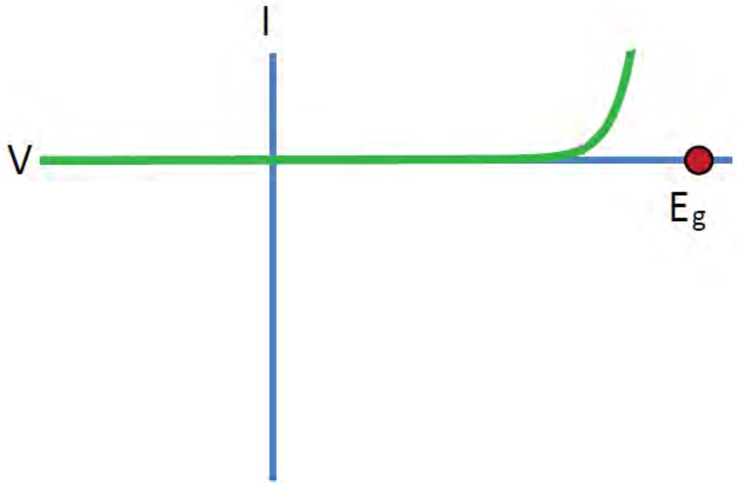


Absorption edge and quantum defect



Voltage is lower than bandgap energy





$$I_{ext} = I_0 \exp(V/kT)\cdot$$

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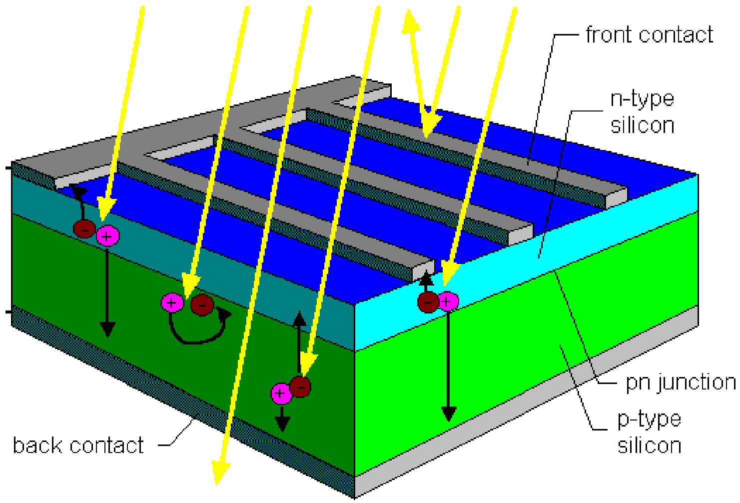
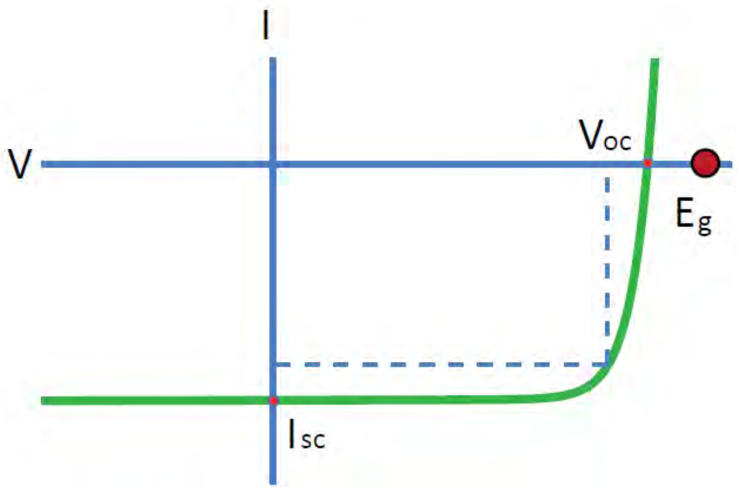
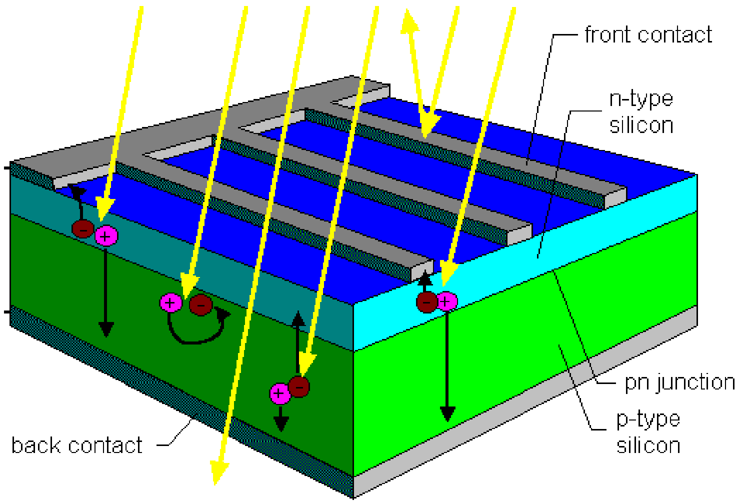
Voltage is lower than bandgap energy

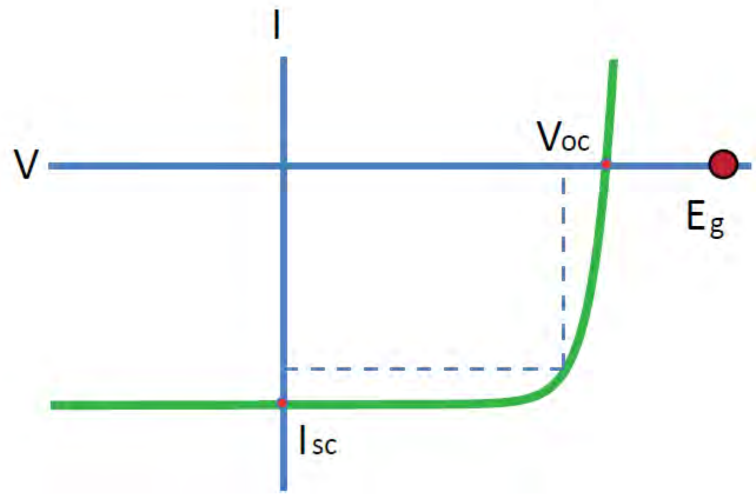




$$I_{ext} = I_0 \exp(V/kT) - I_{SC}$$

Voltage is lower than bandgap energy





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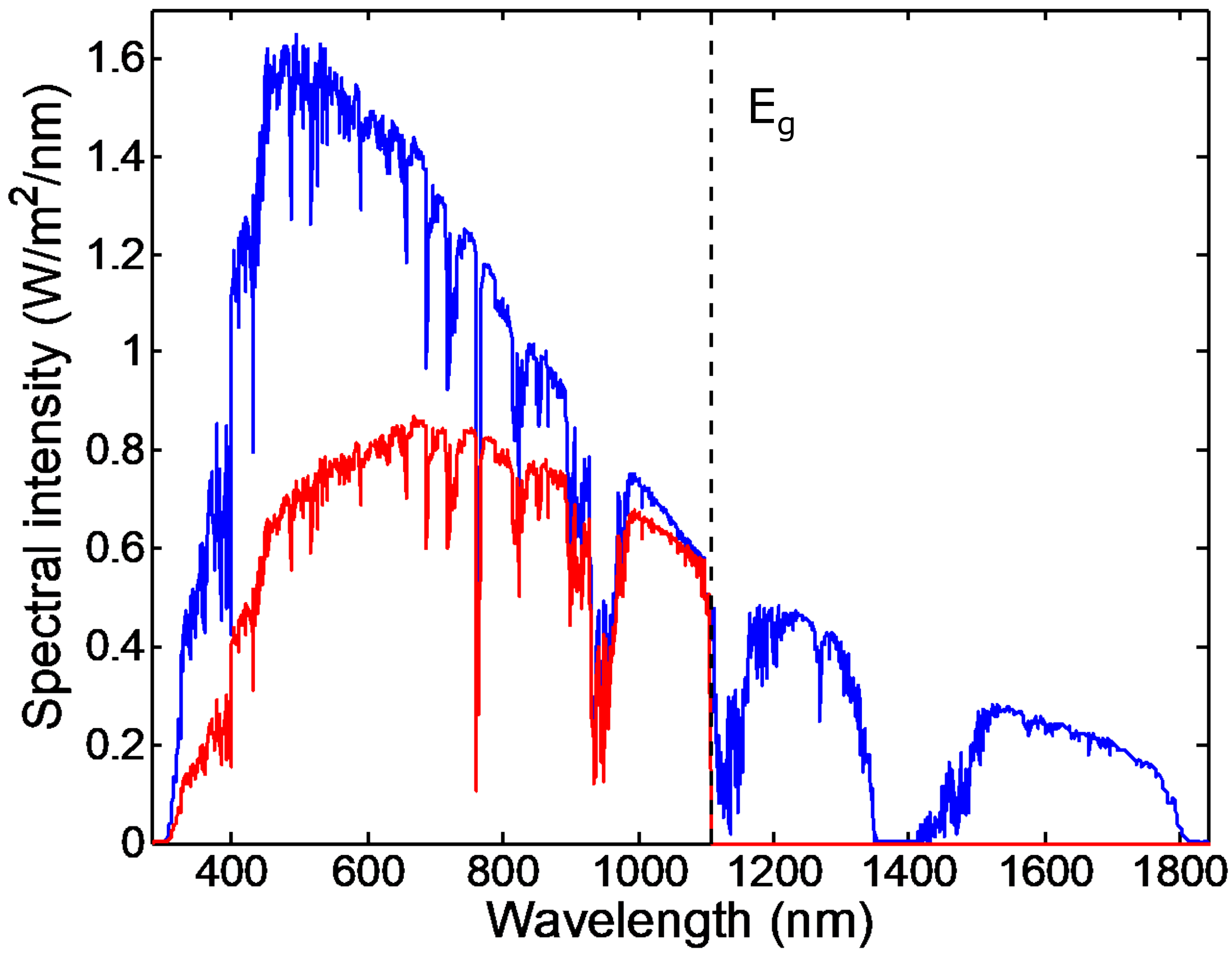
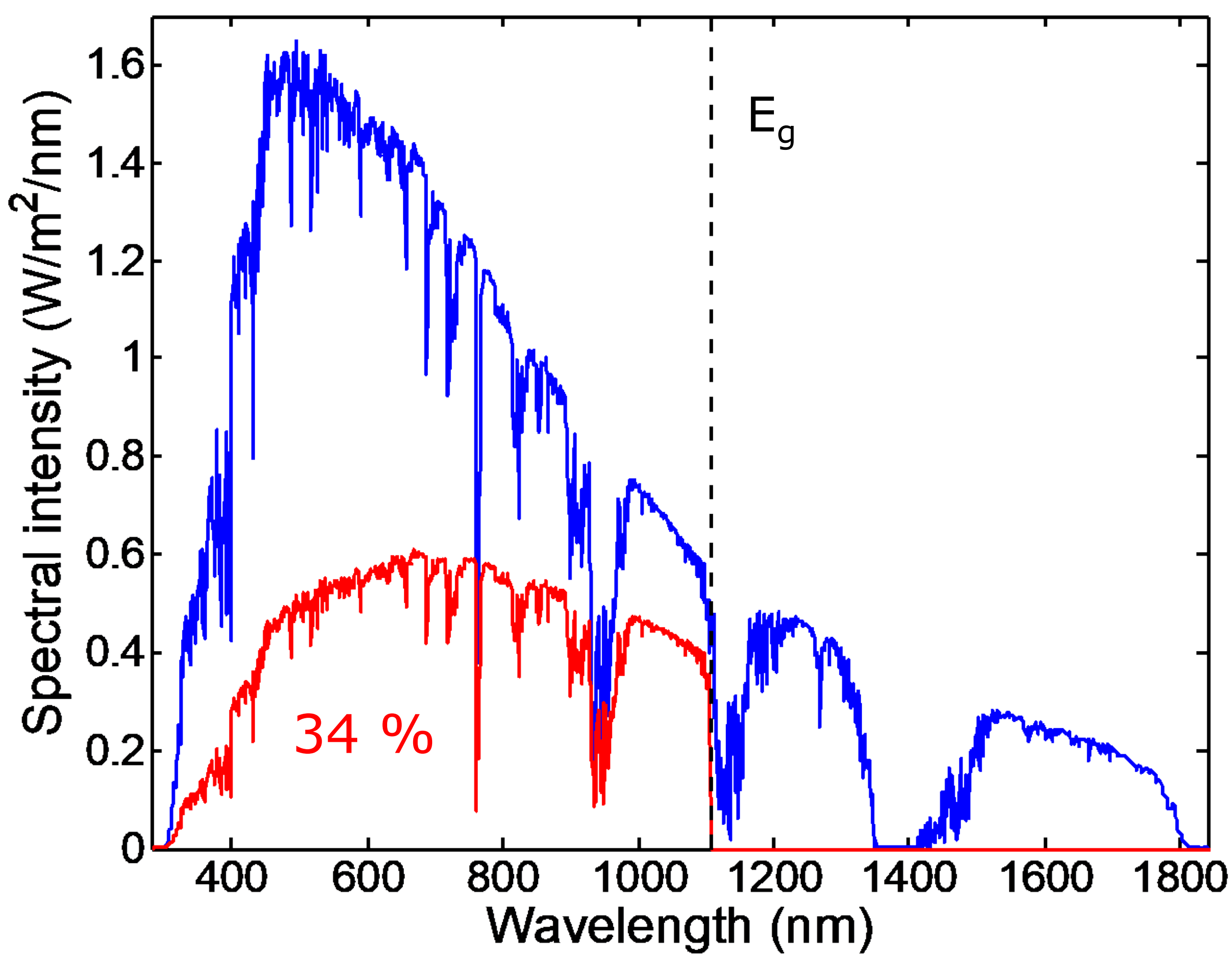
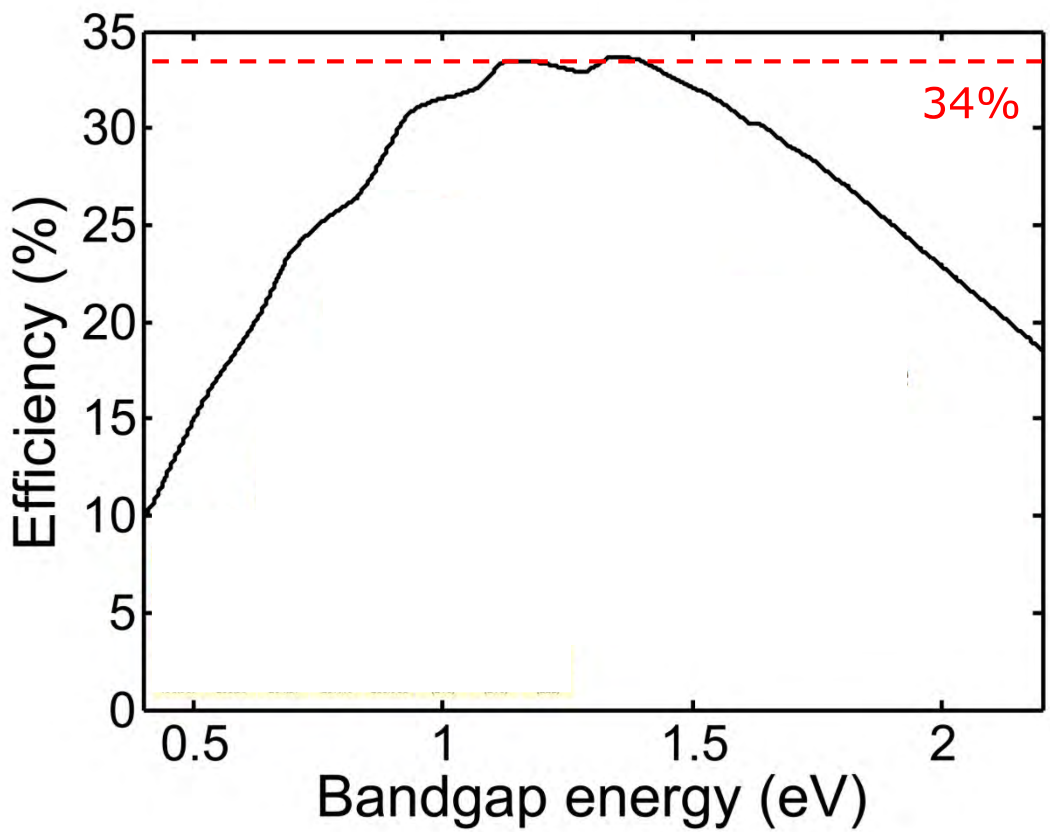
Voltage is lower than bandgap energy

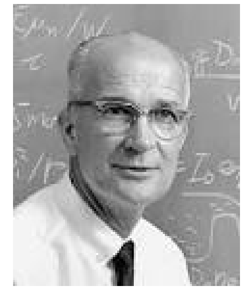


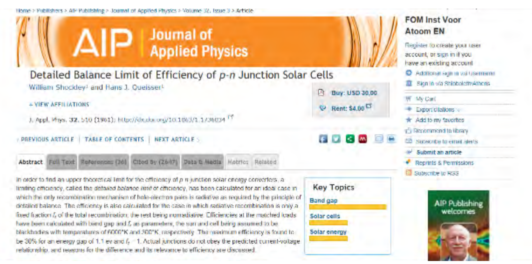
Voltage is lower than bandgap energy



Shockley-Queisser efficiency limit: 34%

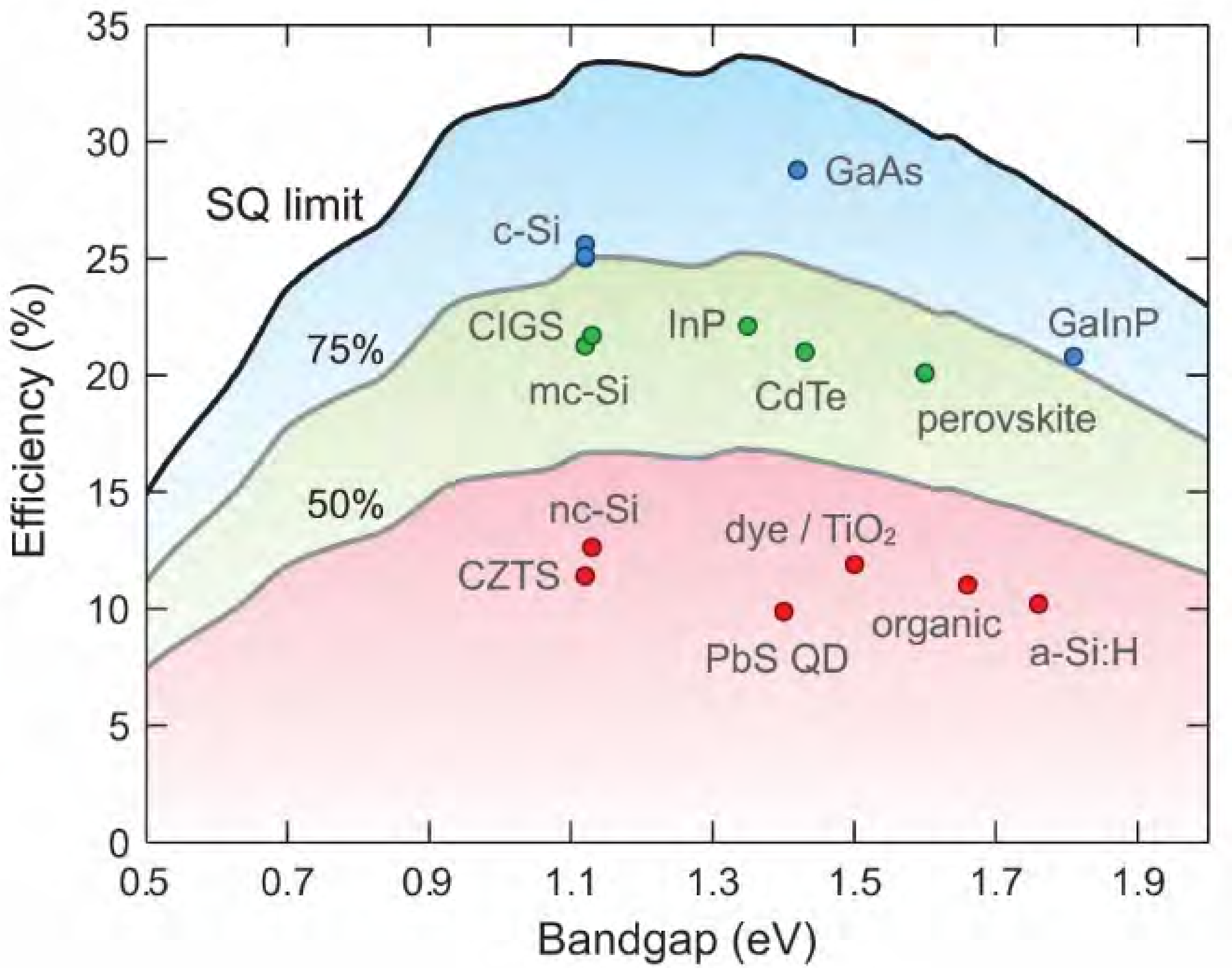






W. Shockley, H. J. Queisser
Detailed balance limit of efficiency of p-n junction solar cells
J. Appl. Phys **32**, 510-519 (1961)

Record solar cell efficiencies



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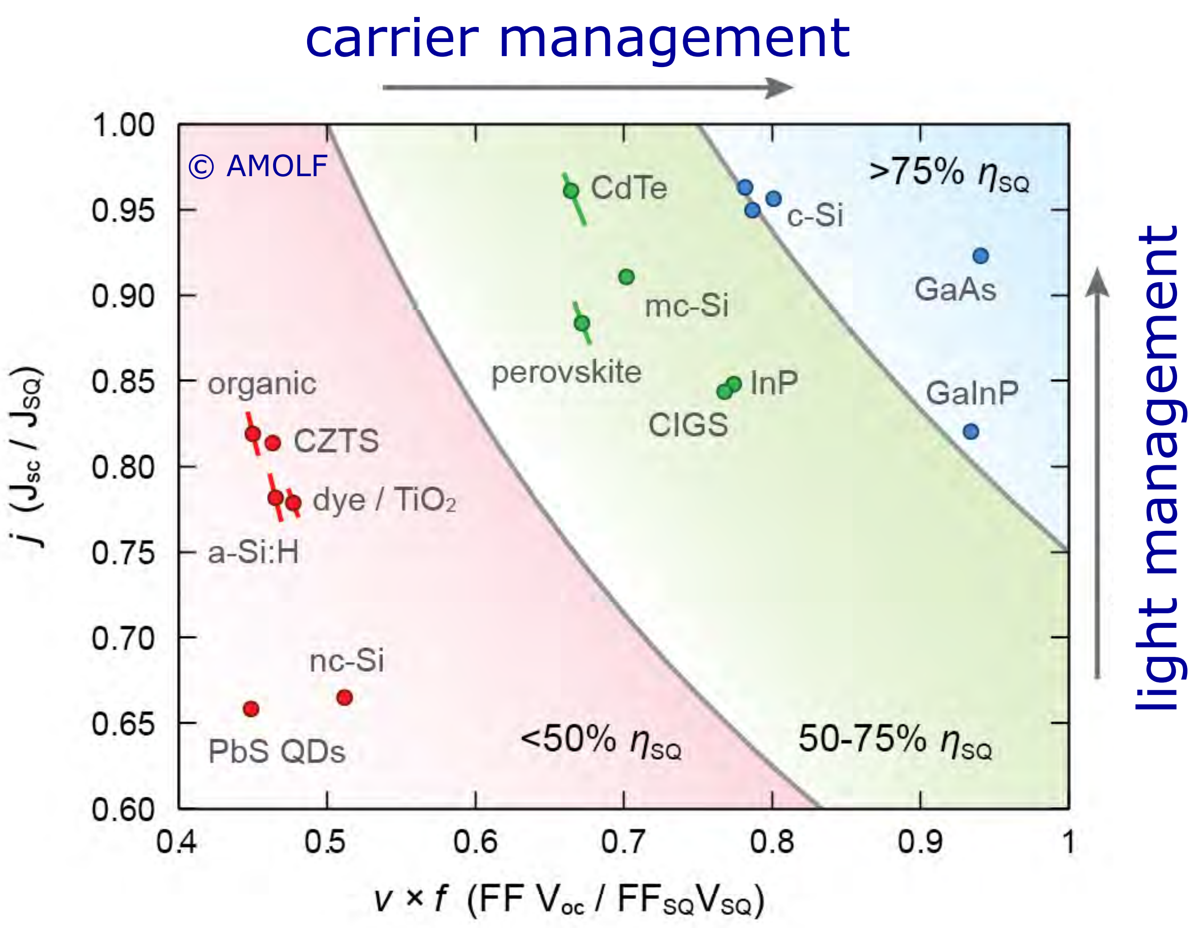
Science **352**, 207 (2016)

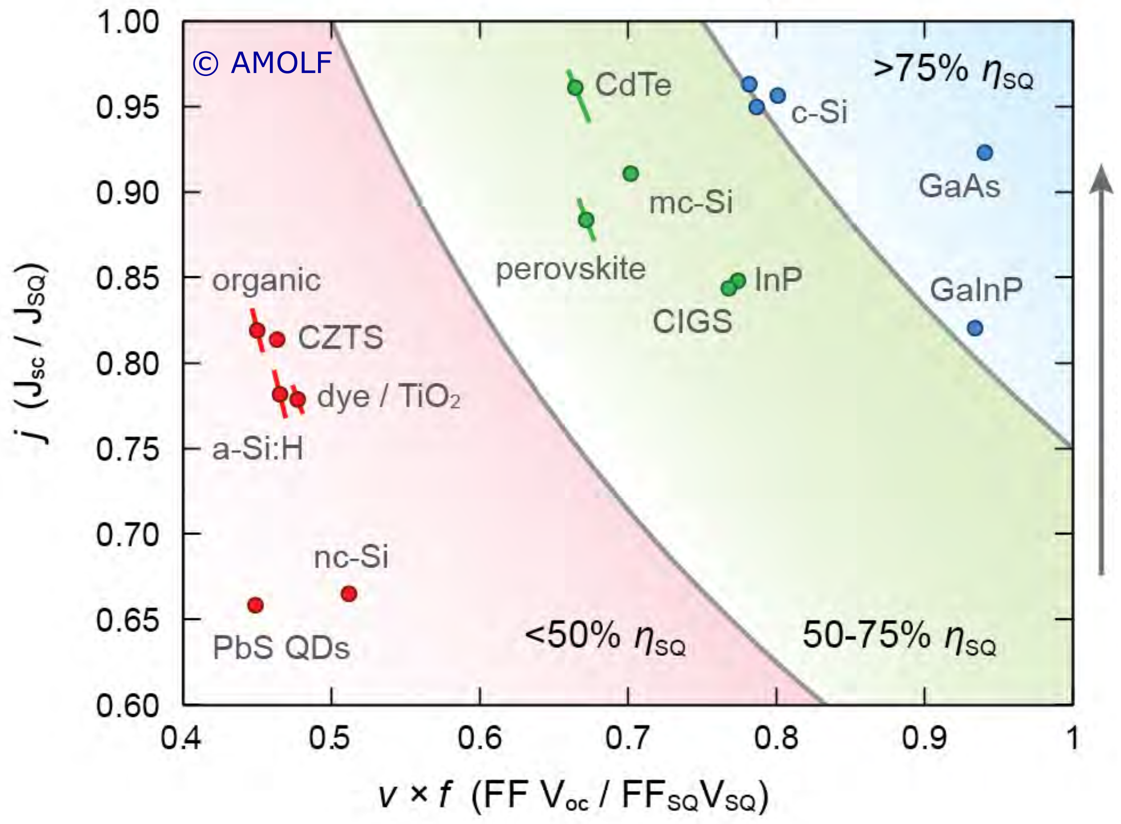
J_{sc} and V_{oc} relative to SQ limit for each material



Science **352**, 207 (2016)

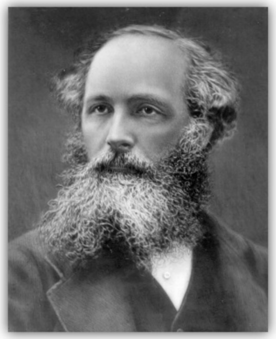
J_{sc} and V_{oc} relative to SQ limit for each material

carrier management



light management

Schrődinger

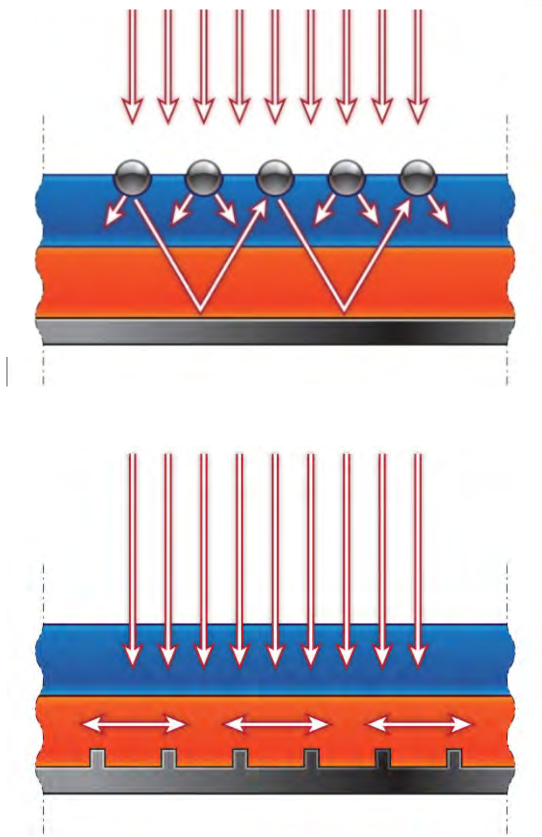


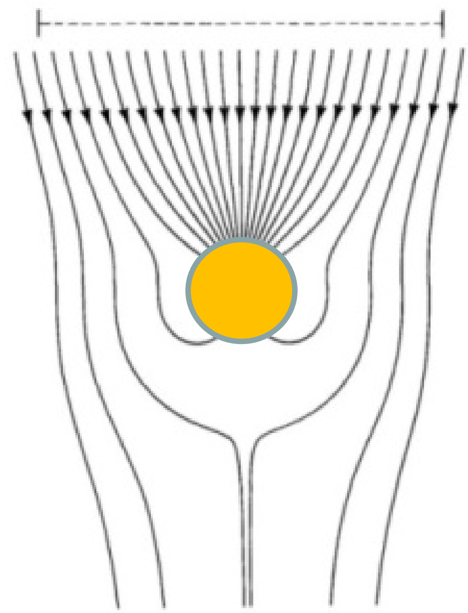
Maxwell

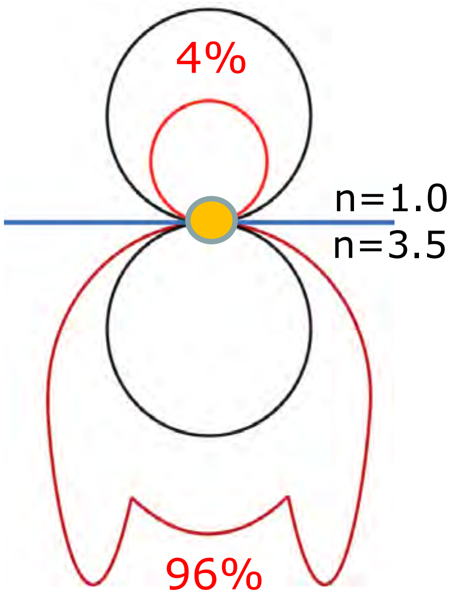
Science **352**, 207 (2016)

The light scattering solar cell

Light coupling and trapping by resonant light scatterers

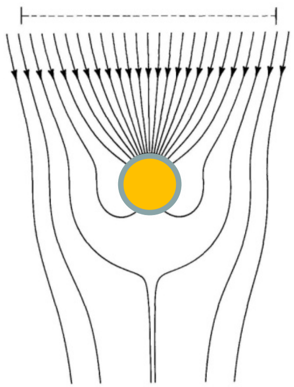


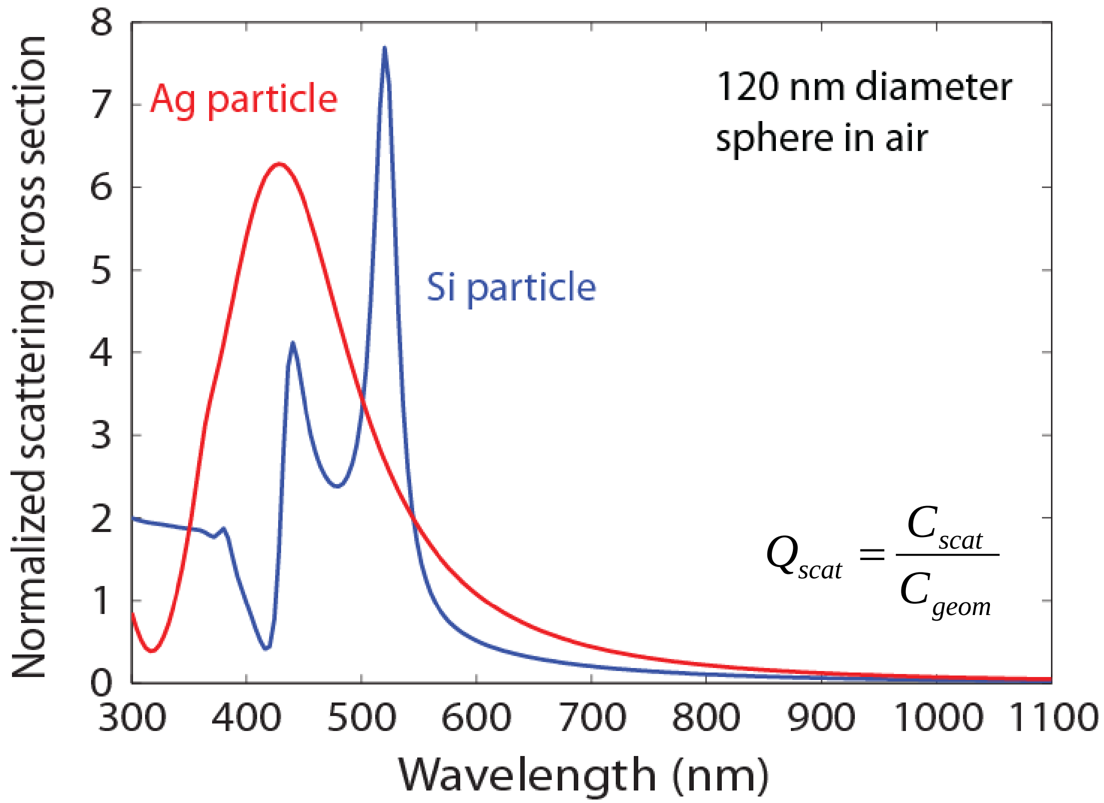




H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010), Nature Mater. **11**, 174 (2012)

Plasmonic vs. dielectric particles



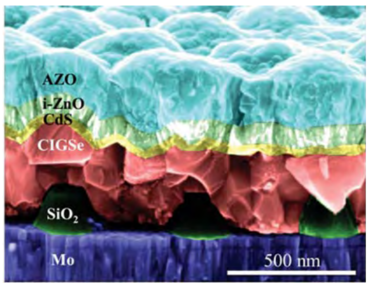


- Metal nanoparticle: plasmonic resonance
- Dielectric nanoparticle: geometrical (Mie) resonance

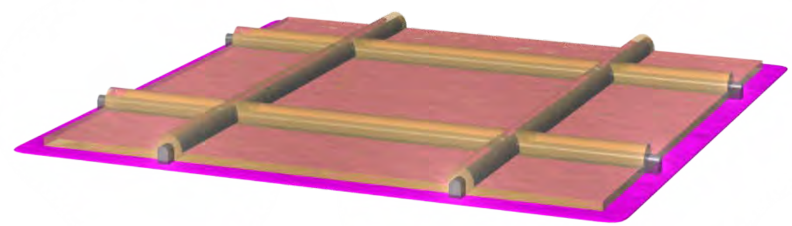
H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010)

Three nanoscale light management architectures

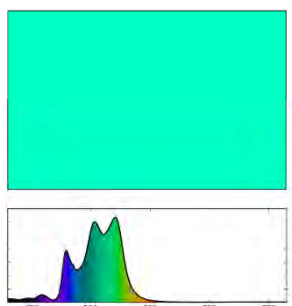
Light trapping in ultra-thin CIGS solar cells

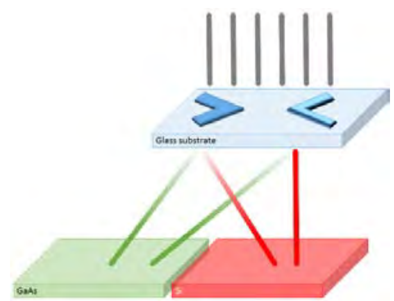


Transparent conducting silver nanowire contacts



Mie scattering coloured solar panels, spectral splitters





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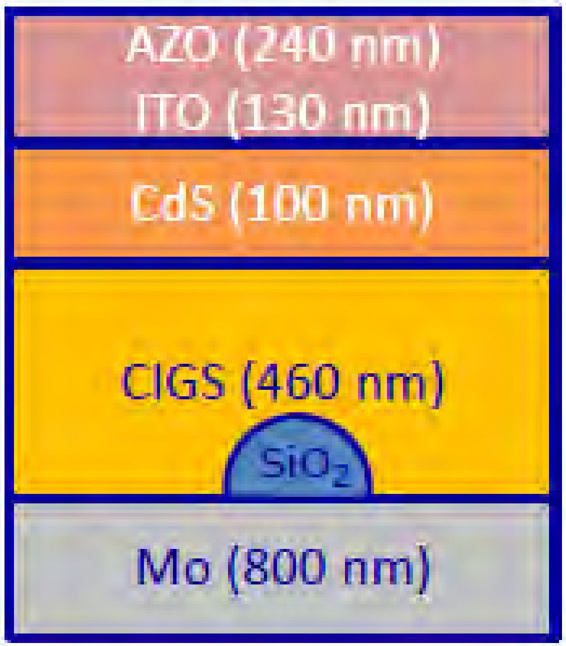
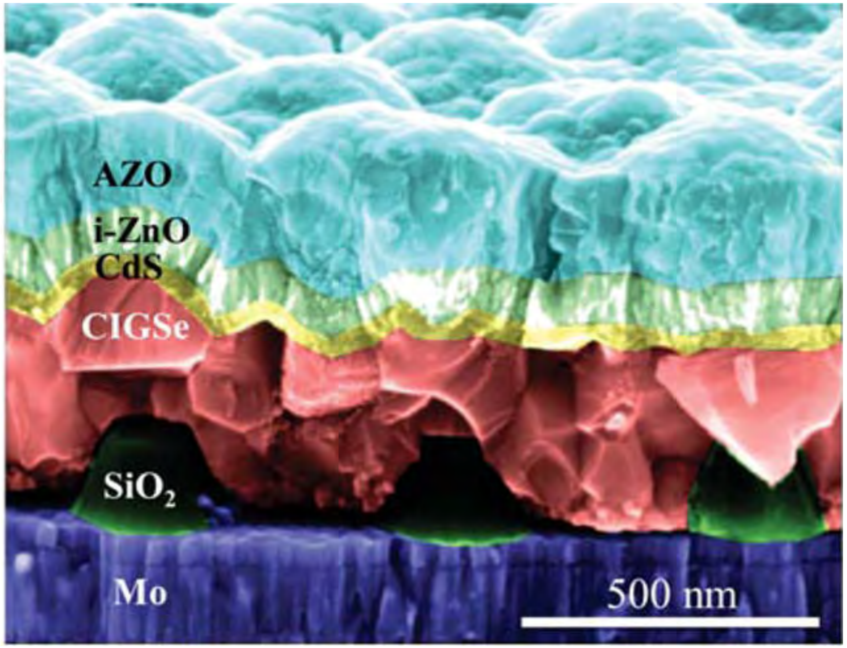
Nanopatterned ultrathin CIGS solar cells





CIGS world record: 22%
ZSW Stuttgart
Thickness: 2.5-3.0 μm

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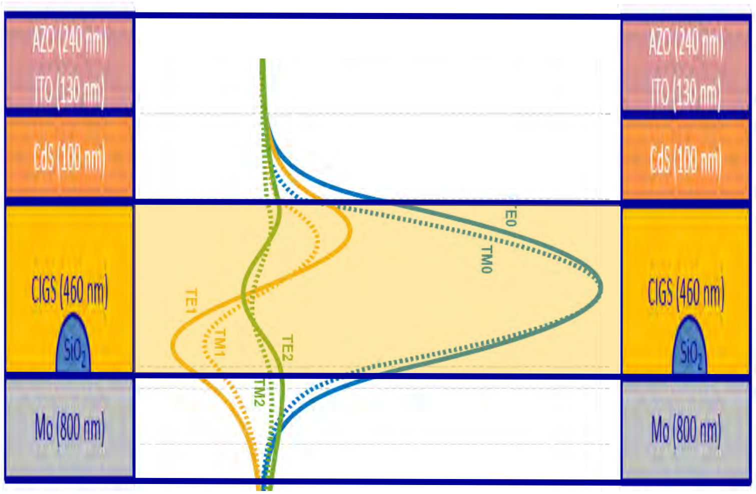
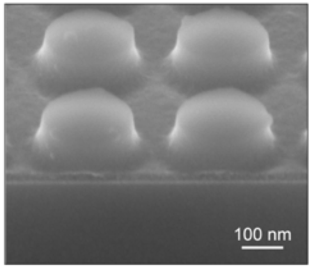
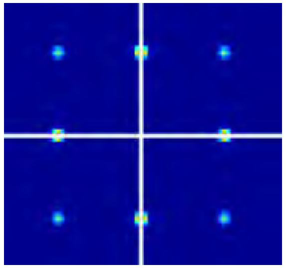
Mark Knight, Claire van Lare, Guanchao Yin
ACS Nano **9**, 9603 (2015)

Optical waveguide modes in ultrathin CIGS solar cells

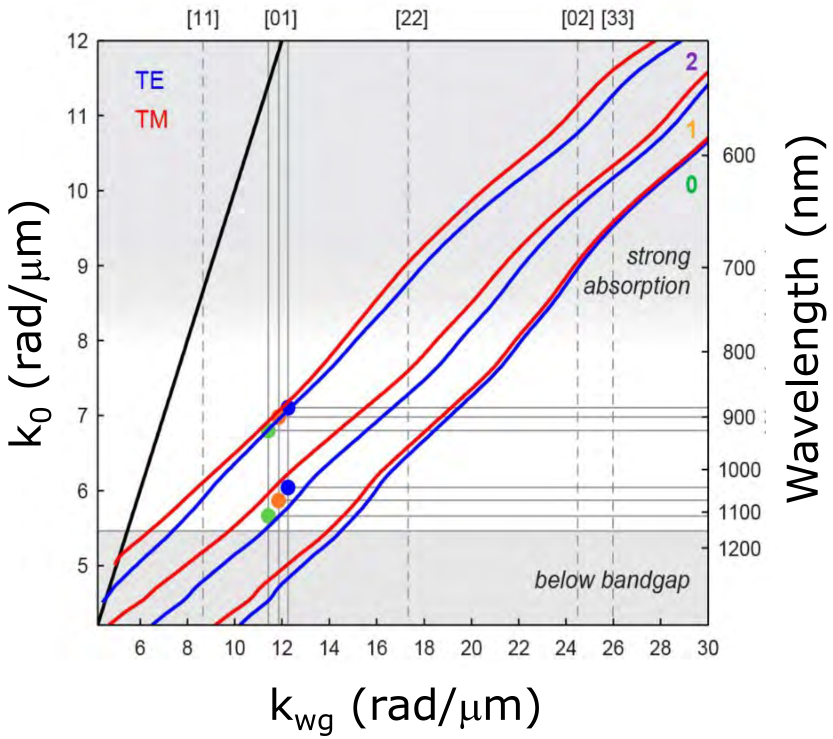




SEM



Fourier space



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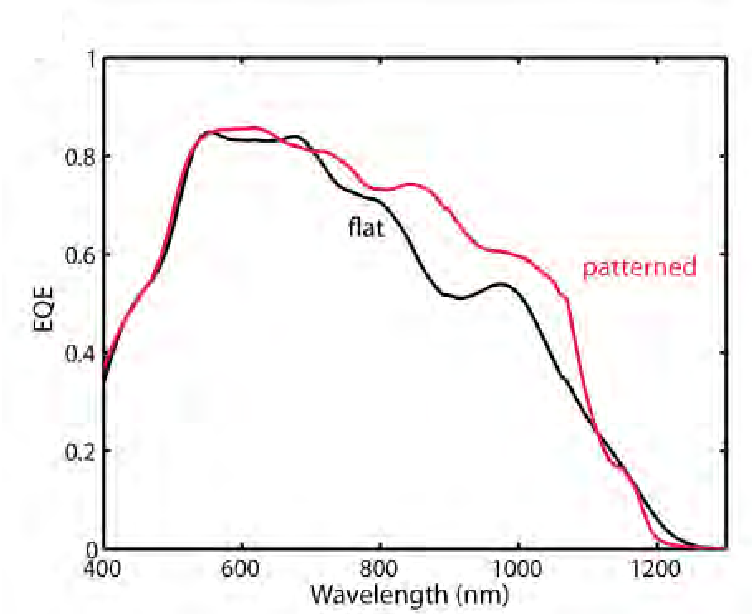
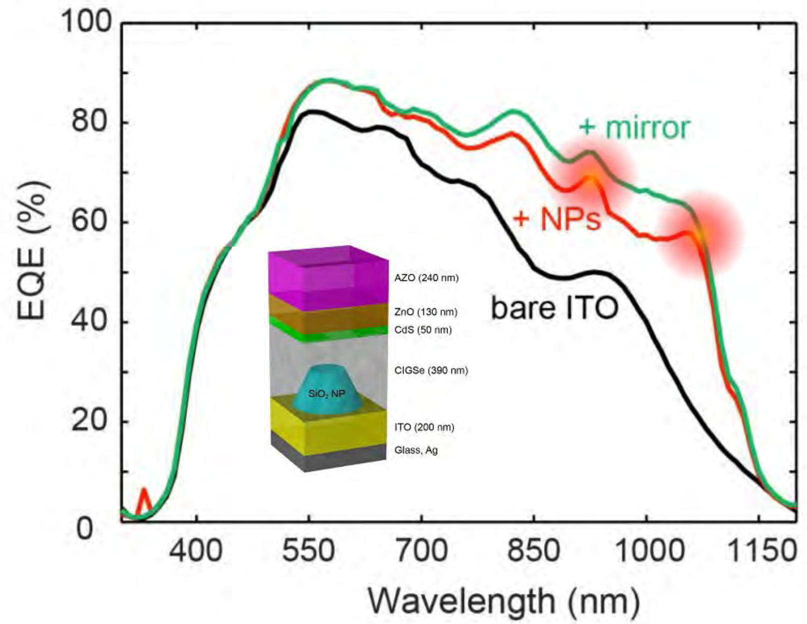
Mark Knight, Magda Sola Garcia, Guanchao Yin
Adv. Opt. Mater. **4**, in press (2016)

Nanopatterned ultrathin CIGS solar cells





Better light trapping

J_{sc} 28.6 → 30.6 mA/cm^2

Lower recombination

V_{oc} 583 → 592 mV

J_{sc} = 34.0 mA/cm^2

93% of world record

for 1/7th of the thickness

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Mark Knight, Guanchao Yin, Magda Sola Garcia, Claire van Lare

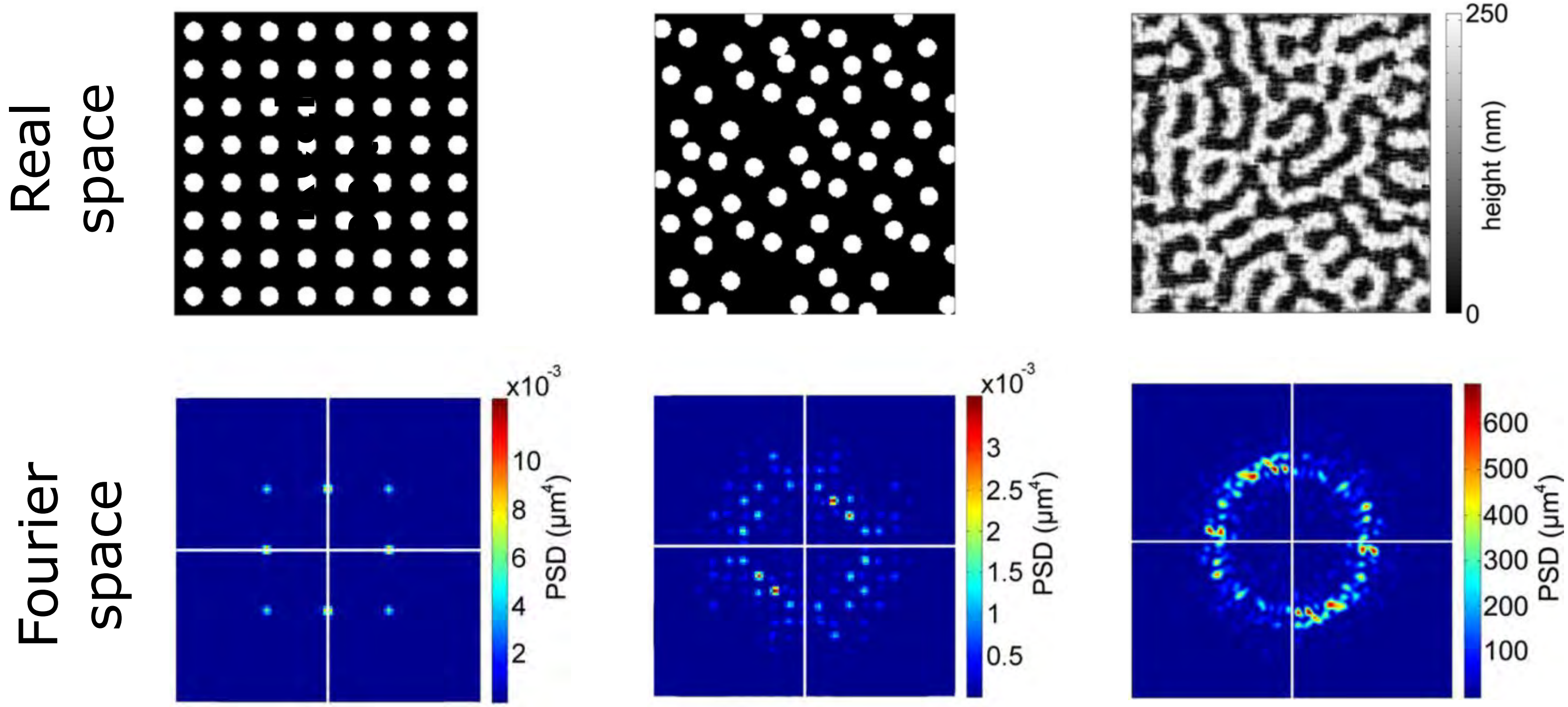
ACS Nano **9**, 9603 (2015), Adv. Opt. Mater. **4**, in press (2016)

Tailoring spatial frequencies for waveguide mode coupling

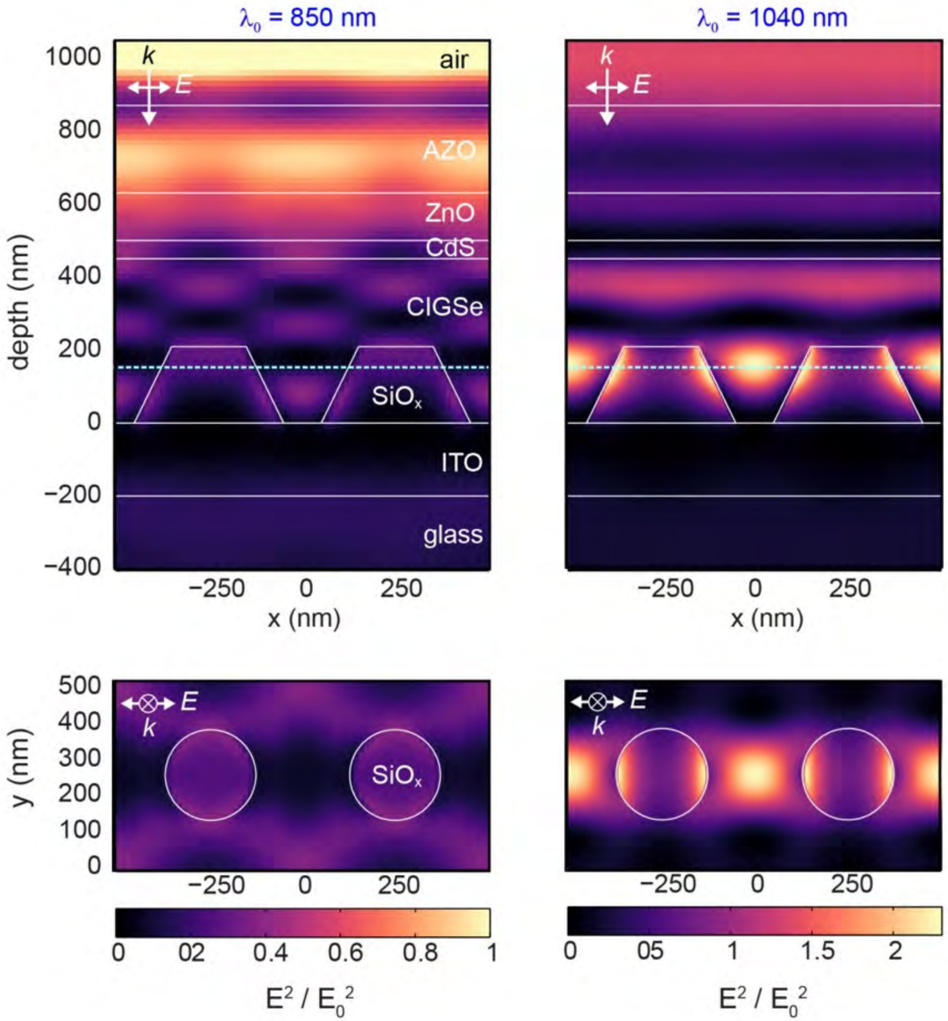
Periodic cylinder pattern

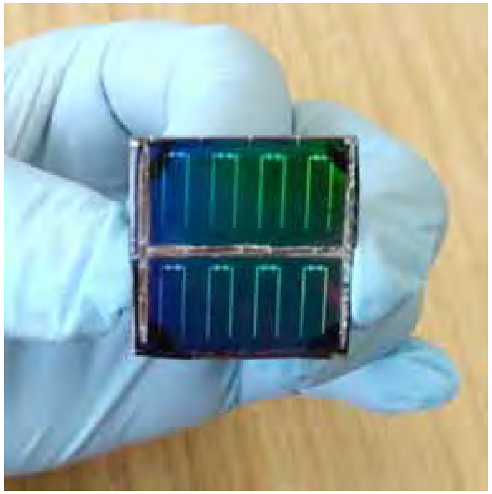
Optimized random cylinders

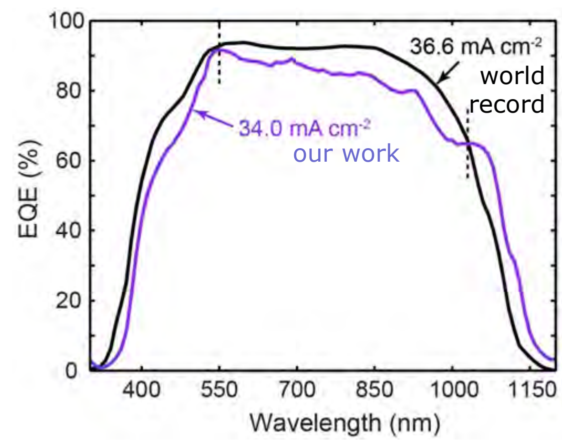
Optimized random geometry



The solar cell as an optical integrated circuit







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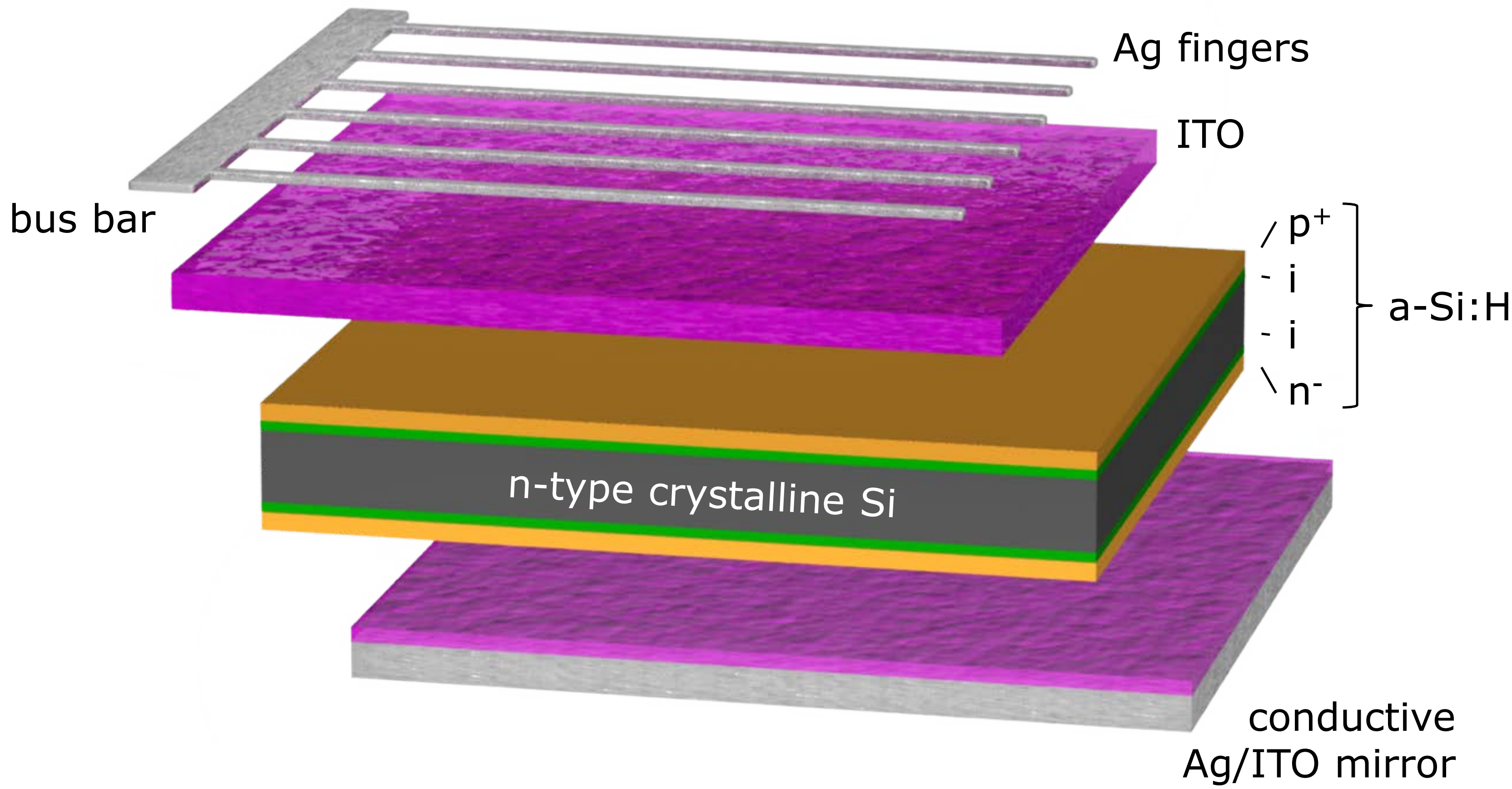
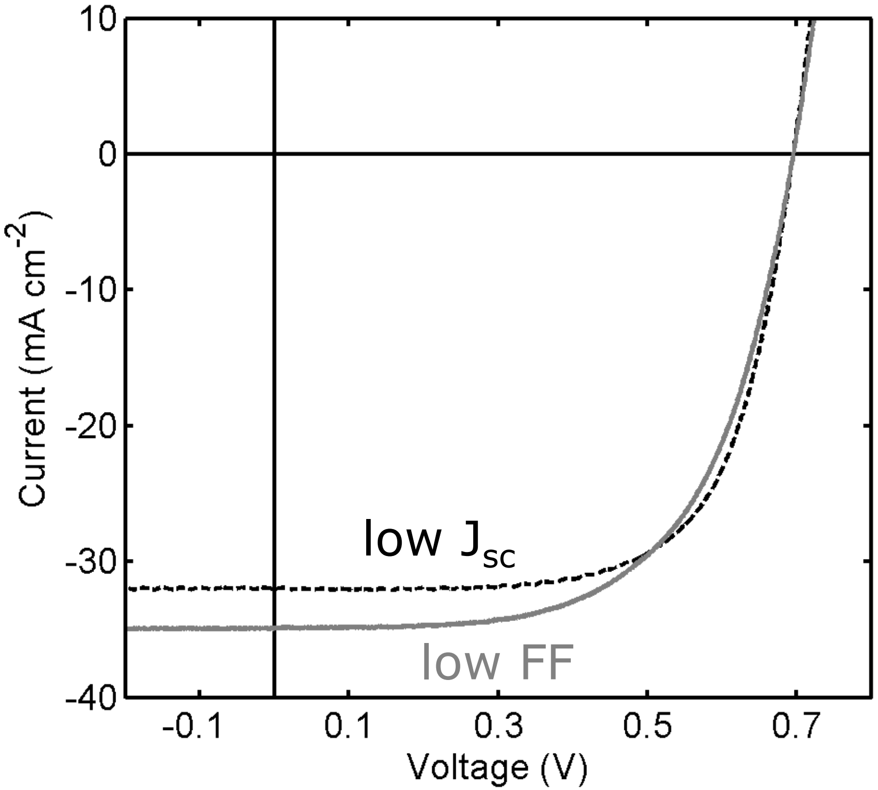
Mark Knight, Guanchao Yin, Claire van Lare
Adv. Opt. Mater. **4**, in press (2016)

Si heterojunction solar cell with front contacts



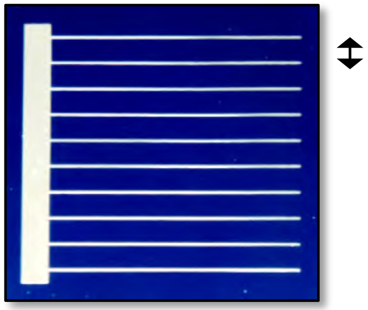
Mark Knight, Paula Bronsveld
Nano Energy **30**, 398 (2016)

Problem: shading by Ag fingers

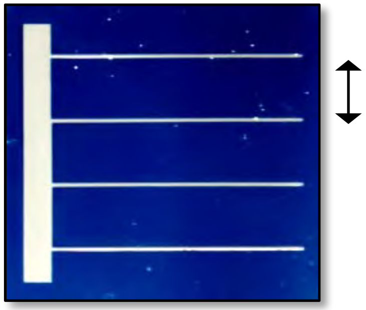


	V_{oc} mV	J_{sc} mA cm^{-2}	FF	Eff %
ITO, 2 mm	696	32.0	0.676	15.0

2 mm



5 mm



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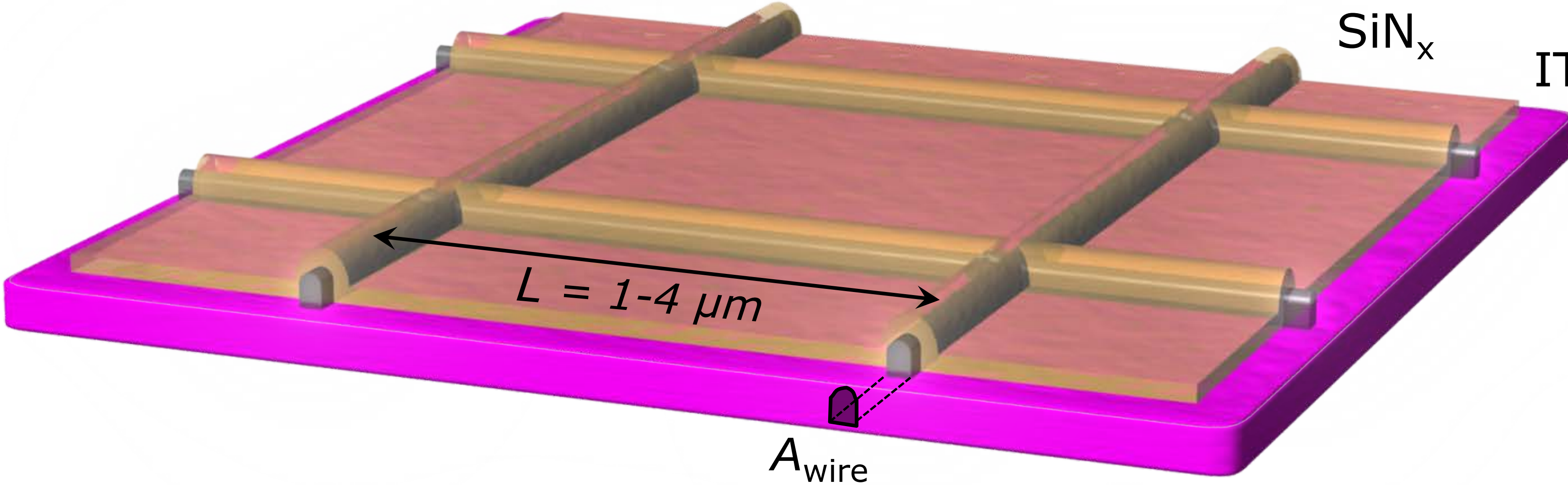
Nano Energy **30**, 398 (2016)

Nanowire hybrid electrode design



- Thin ITO protect passivating a-Si
- Ag NWs engineered conductivity, plasmonic resonators
- SiN_x antireflection, protect NWs

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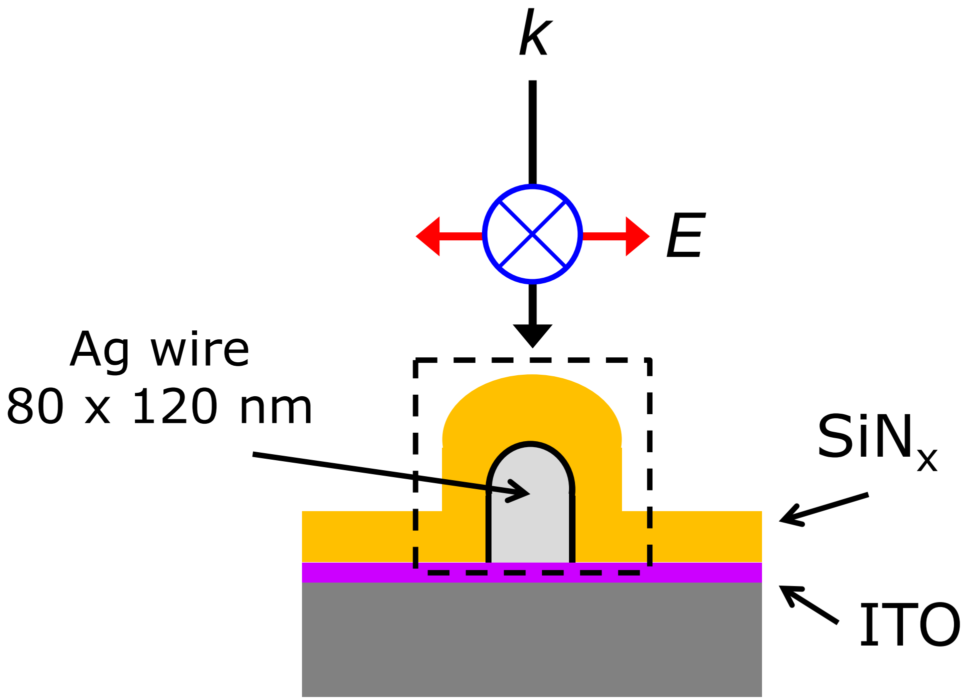
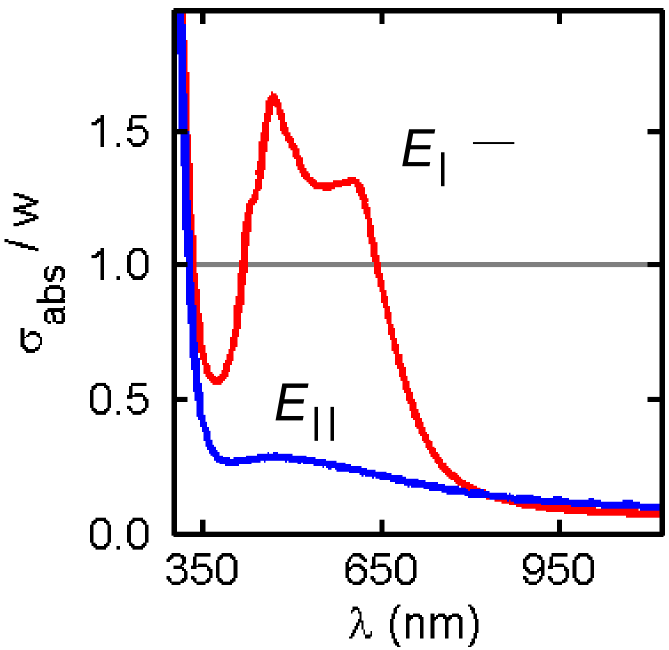
Nano Energy **30**, 398 (2016)

Plasmonic nanowire resonances





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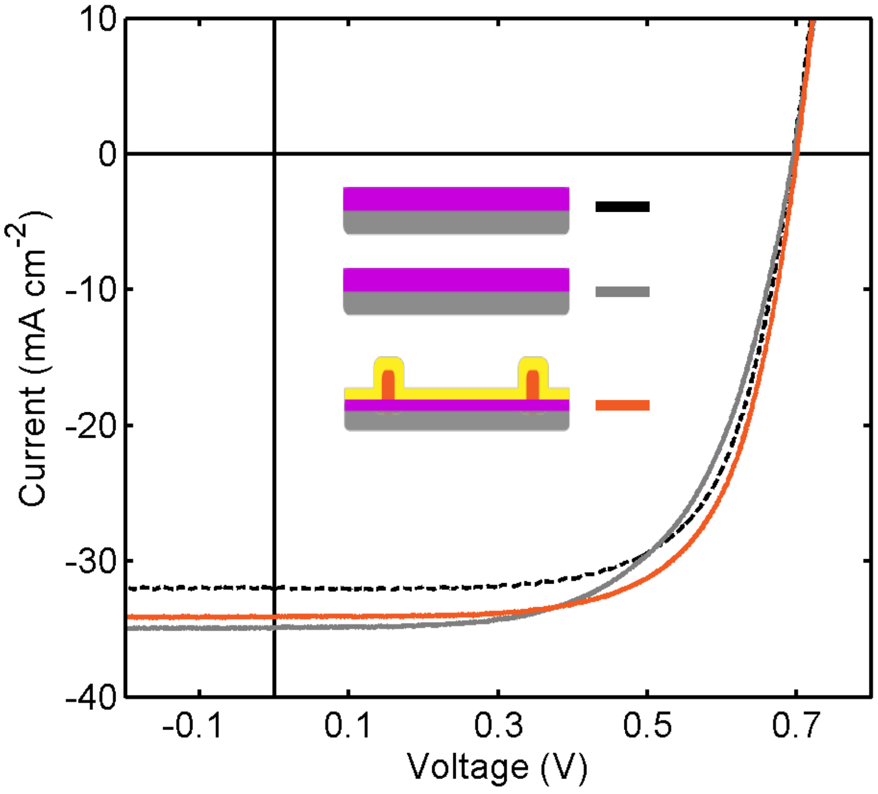
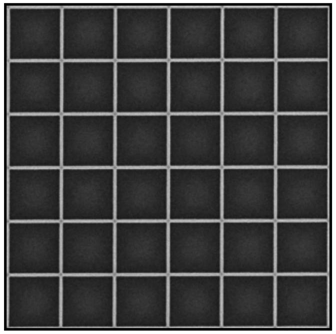
Current-voltage response

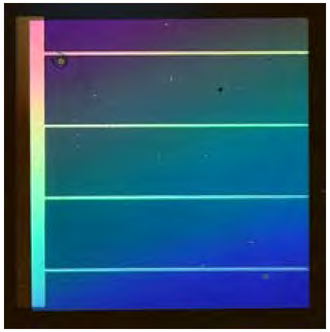


	V_{oc} mV	J_{sc} mA cm^{-2}	FF	Eff %
ITO, 2 mm	696	32.0	0.676	15.0
ITO, 5 mm	683	34.7	0.604	14.3
NW hybrid	701	**34.1**	**0.670**	**16.0**



2 µm

width: 80 nm
height: 120 nm



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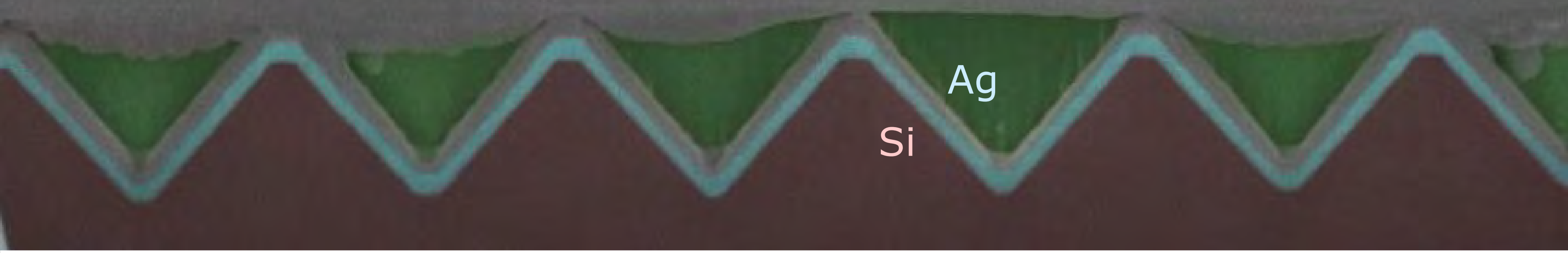
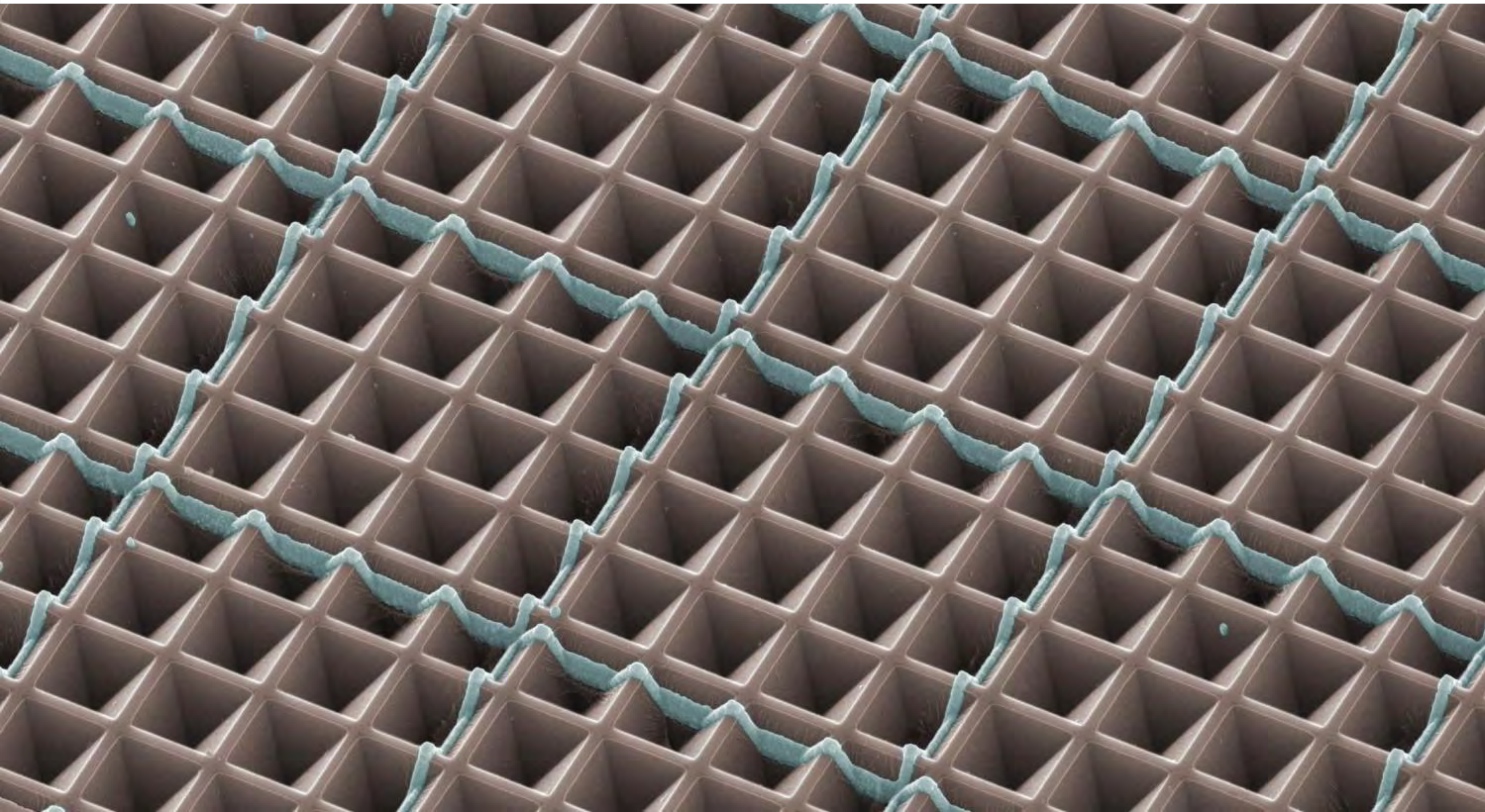
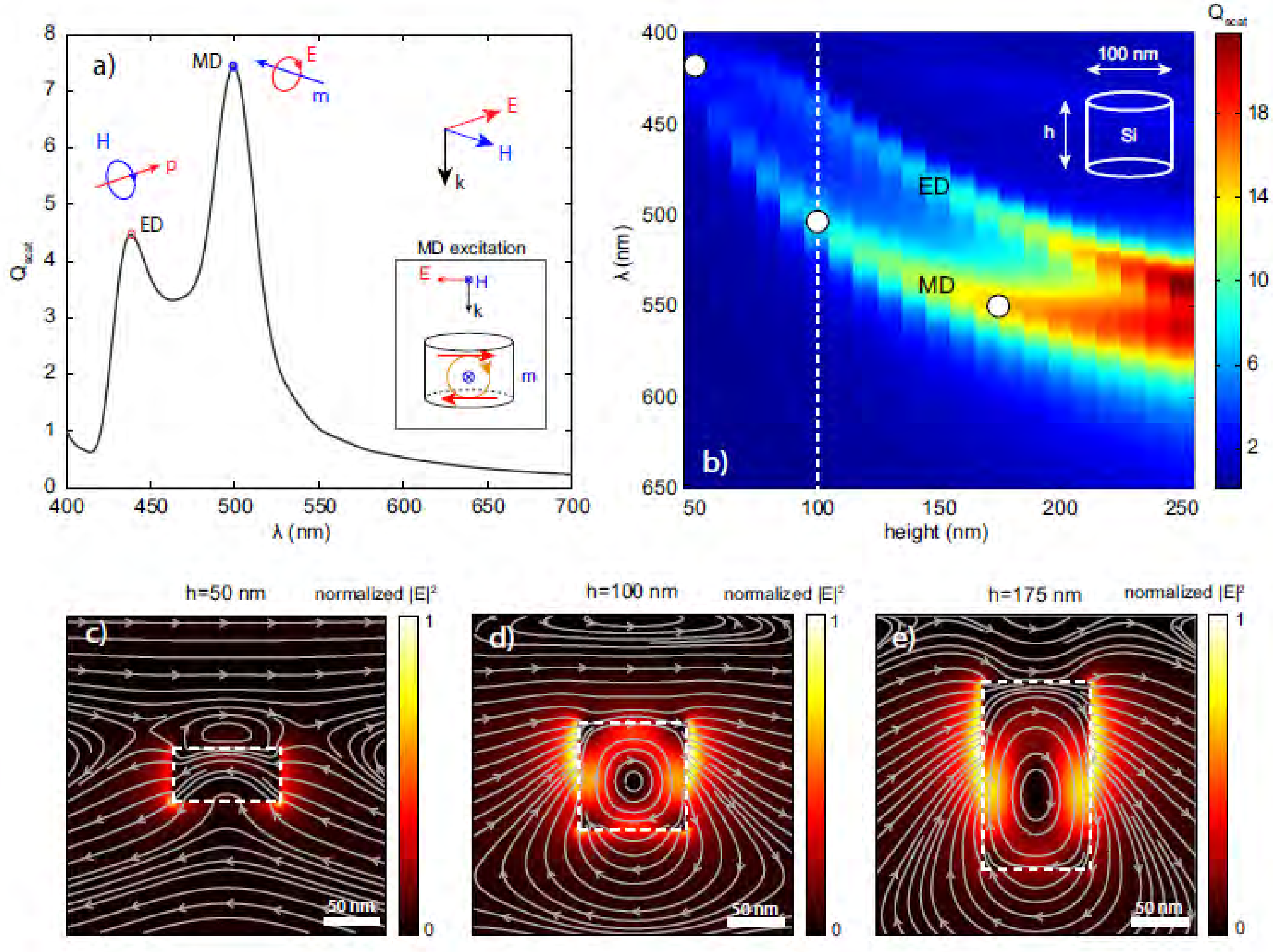
Mark Knight, Paula Bronsveld
Nano Energy **30**, 398 (2016)

Nanowires on μ-textured Si



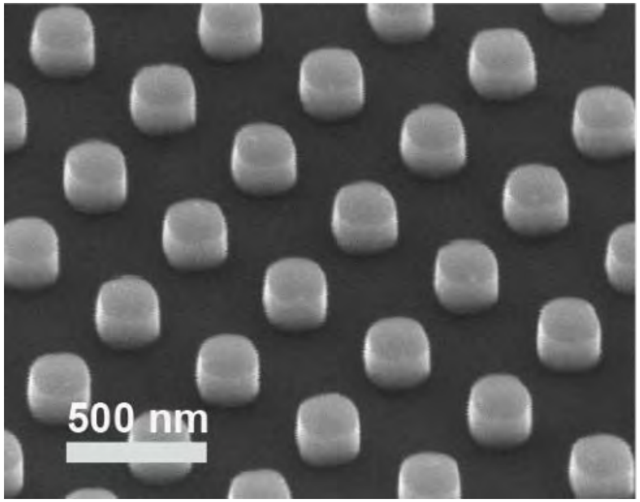


Resonant light scattering from Mie cylinders

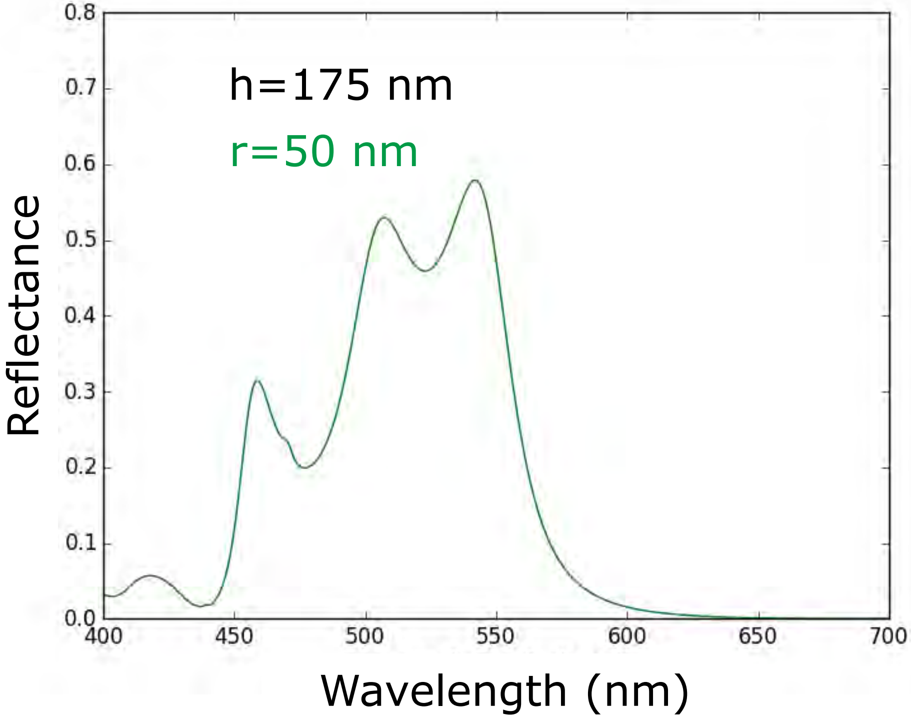


Jorik van de Groep
Optics Express. **21**, 26296 (2013)

Resonant light scattering for colored PV

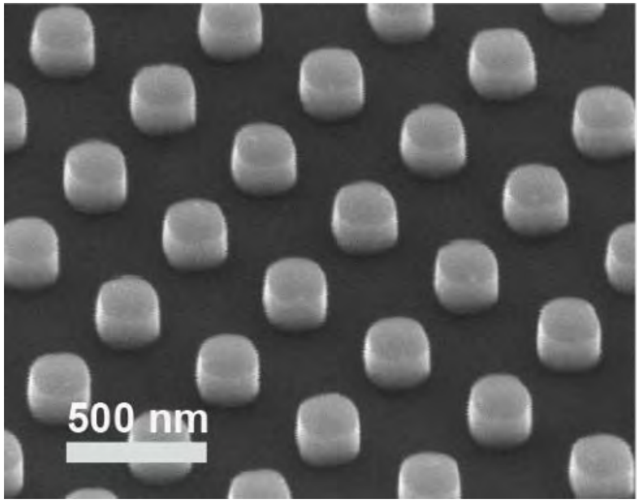


Back reflection from
Si nanocylinders in glass

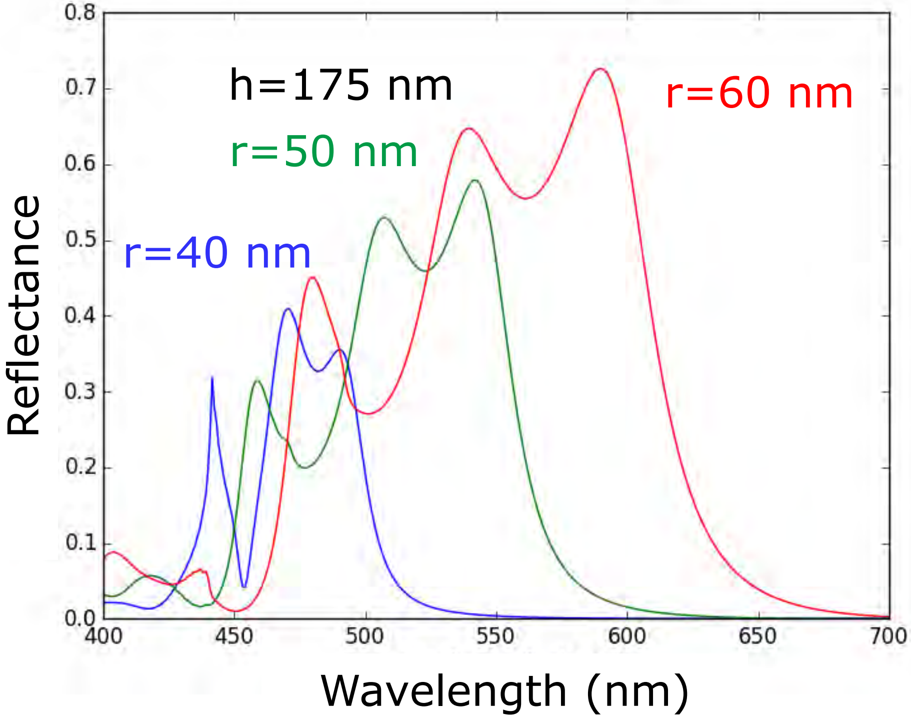


Verena Neder, Piero Spinelli
Nature Comm. **3**, 692 (2012)

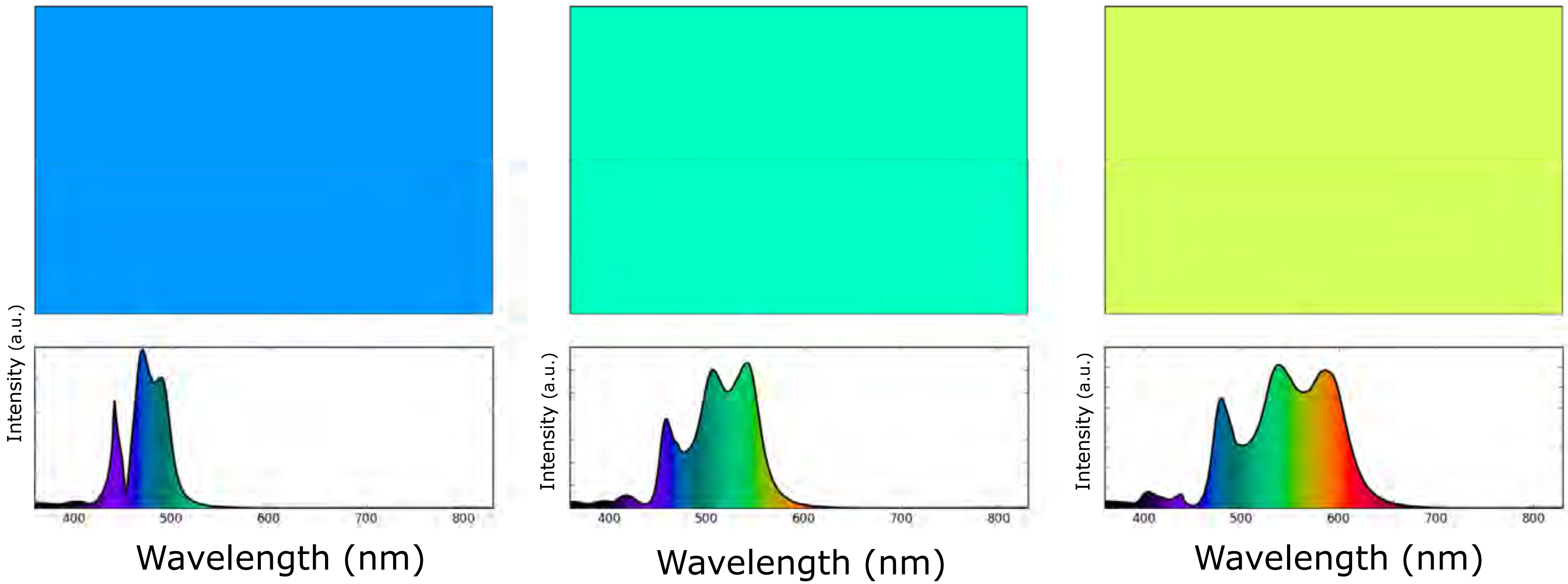
Resonant light scattering for colored PV



Back reflection from
Si nanocylinders in glass



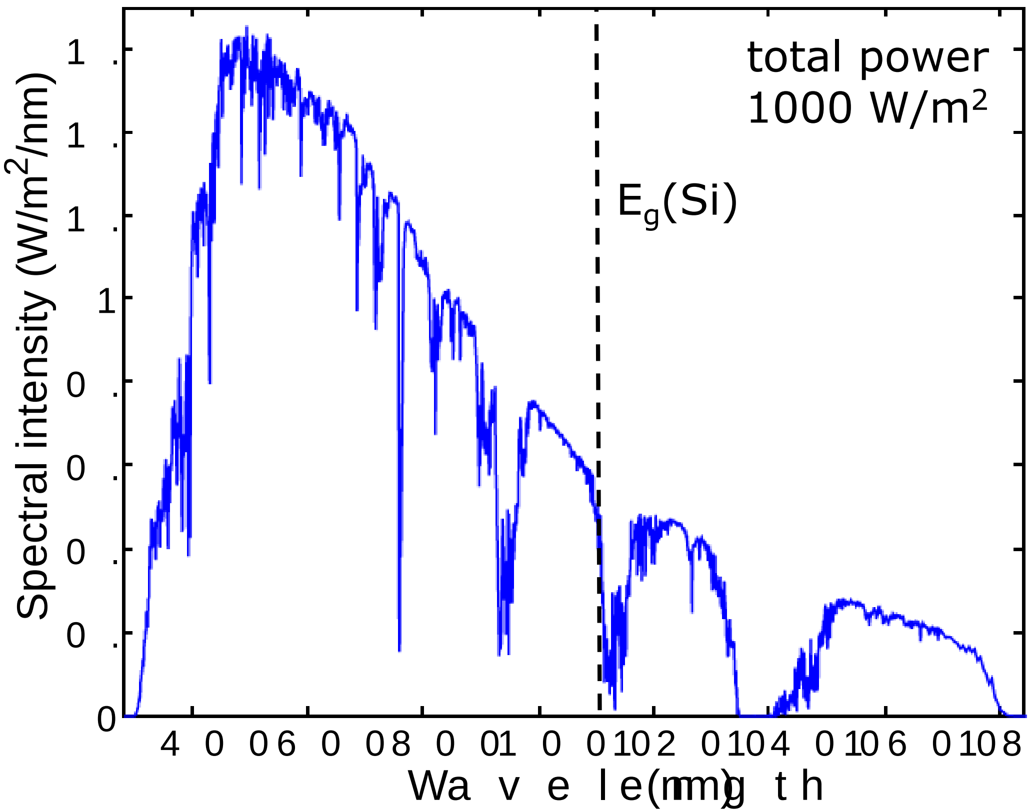
Resonant light scattering for colored PV



Python color code:
markkness.net/colorpy/ColorPy.html

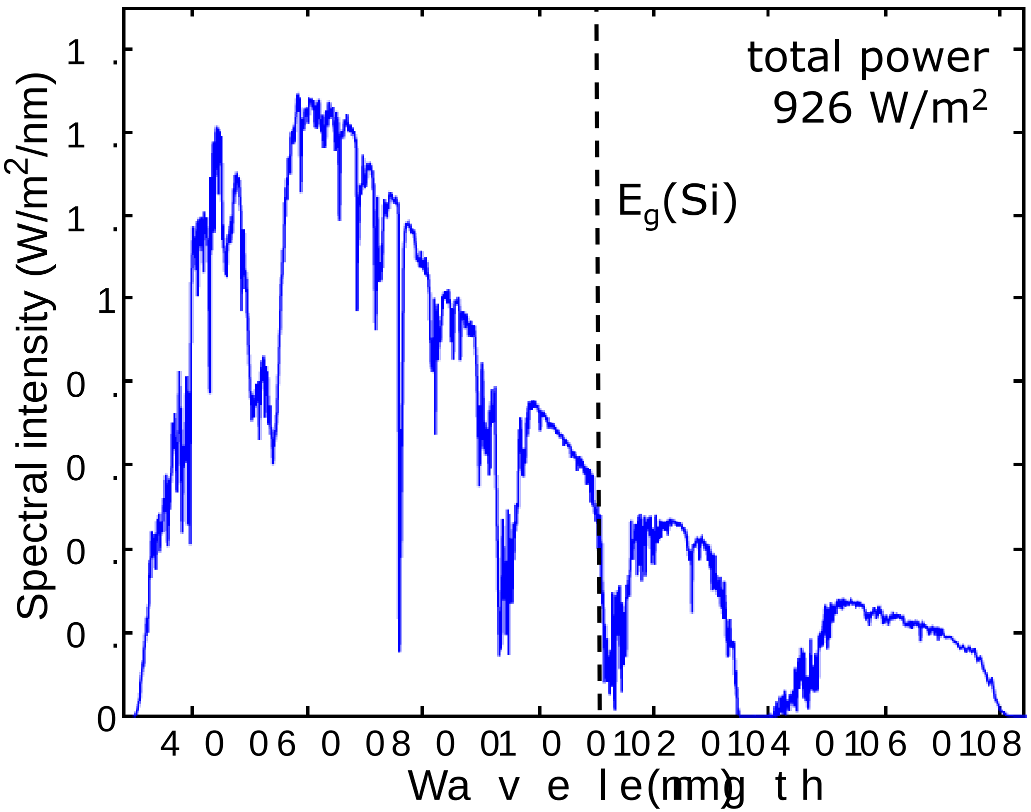
Verena Neder

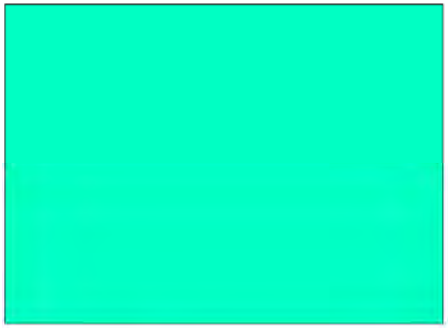
Solar spectrum

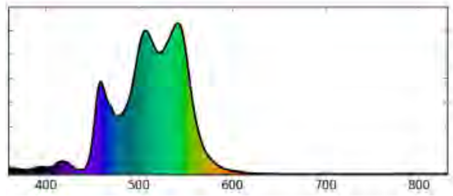


SQ limit=33.7%
at E_g=1.34 eV

Modified solar spectrum

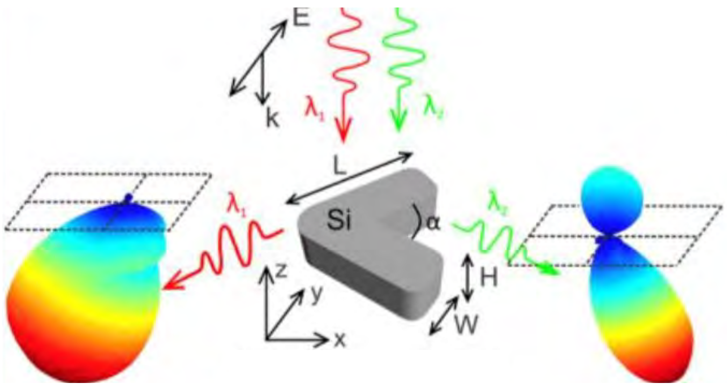




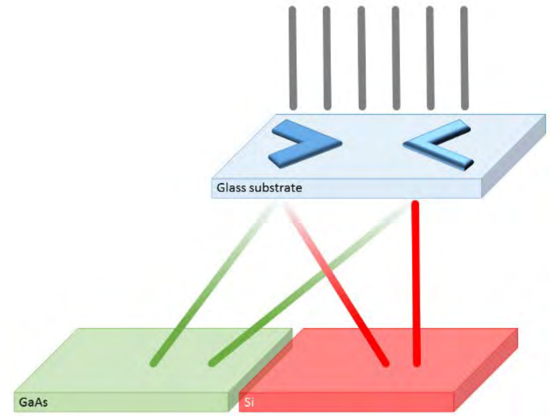


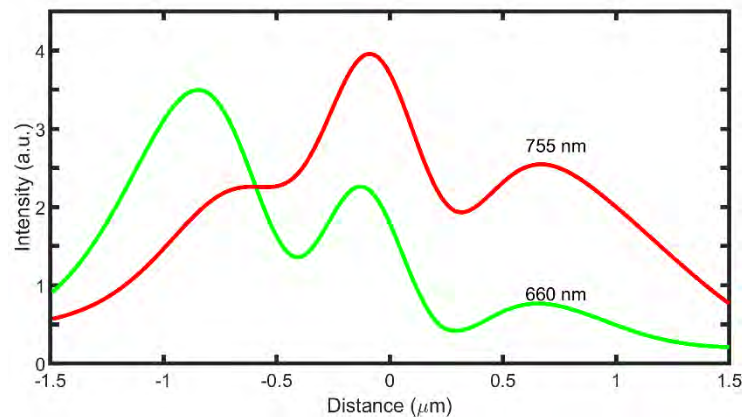
SQ limit (eff) =31.5%
at E_g=1.13 eV

Spectrum splitting dielectric metasurface

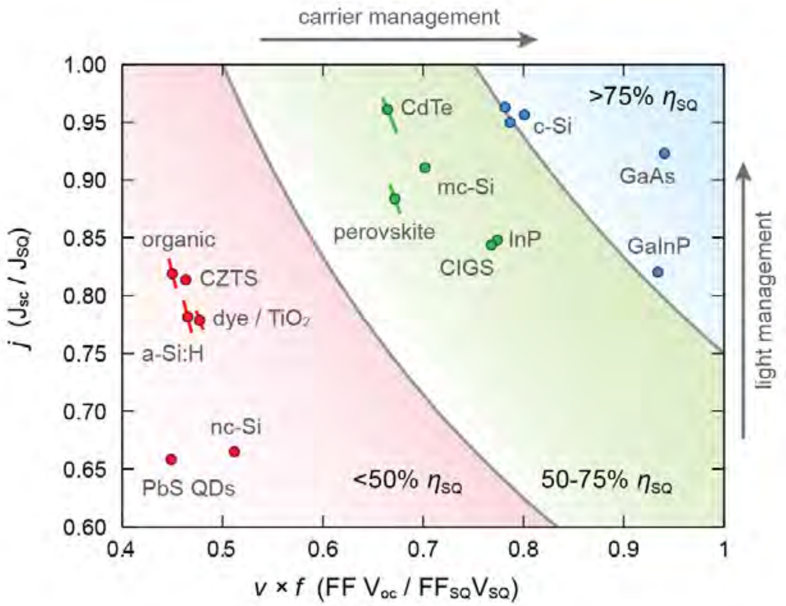


from: Li et al., Nano Lett. **16**, 4396 (2016)

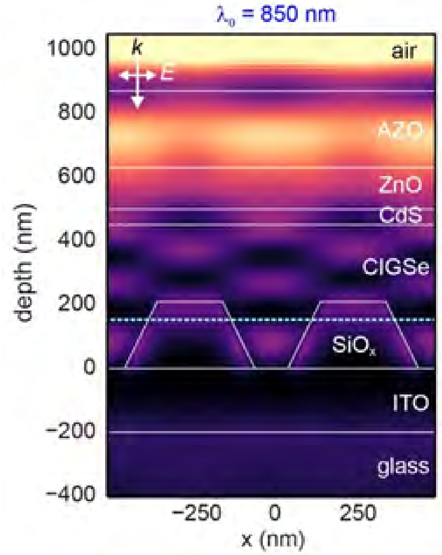




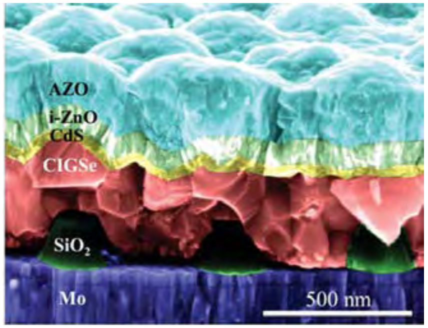
Summary



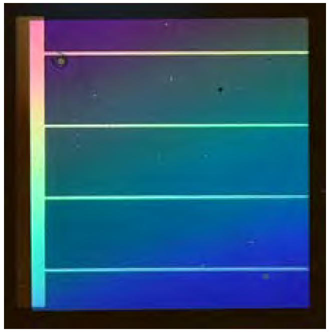
carrier management
light management
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.4
0.5
0.6
0.7
0.8
0.9
1
j (Jsc / JSQ)
v × f (FF Voc / FFSQVSQ)
CdTe
c-Si
GaAs
mc-Si
perovskite
InP
CIGS
GaInP
organic
CZTS
dye / TiO2
a-Si:H
nc-Si
PbS QDs
>75% ηSQ
50-75% ηSQ
<50% ηSQ

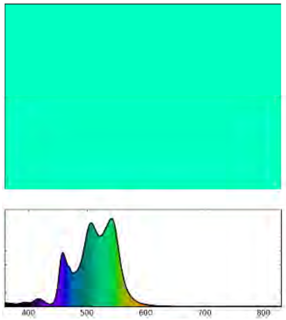


λ0 = 850 nm
k
E
air
AZO
ZnO
CdS
CIGSe
SiOx
ITO
glass
1000
800
600
400
200
0
−200
−400
depth (nm)
−250
0
250
x (nm)



AZO
i-ZnO
CdS
CIGSe
SiO2
Mo
500 nm





Collaborators

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Light management LMPV in new photovoltaic materials

Light Management
in new Photovoltaic
Materials (LMPV) program

Esther Alarcon Llado, Albert Polman, Bruno Ehrler, Erik Garnett

FOM Institute AMOLF

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