Ultrahigh-efficiency solar cells based on nanophotonic design

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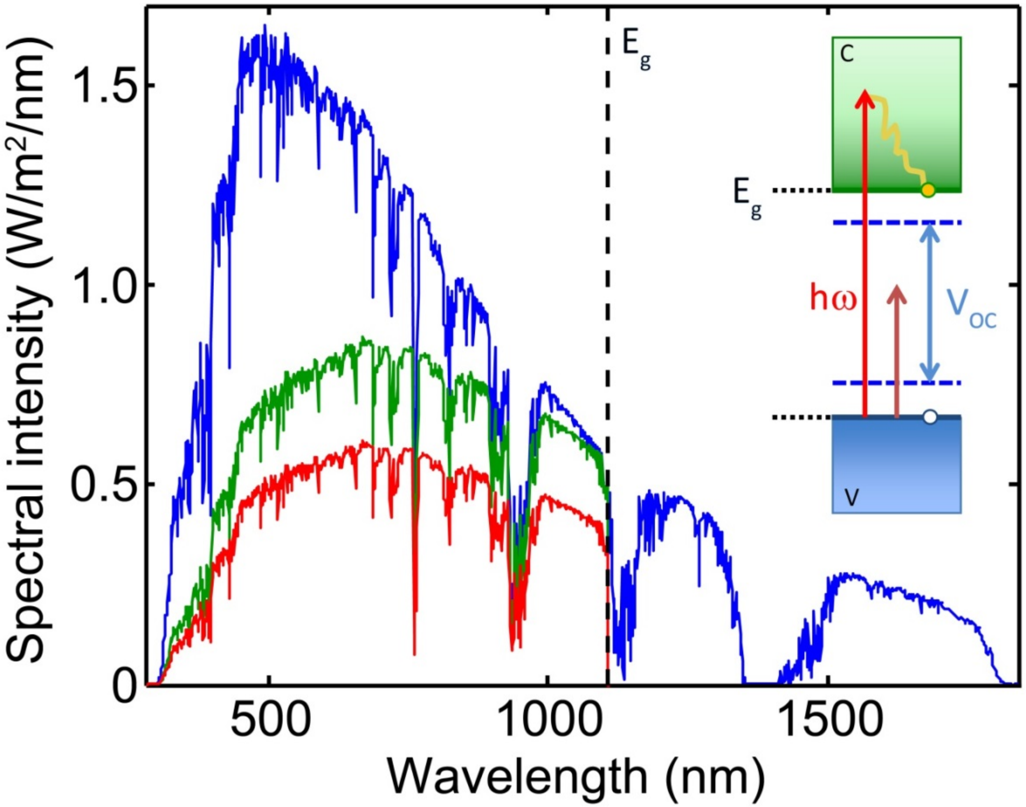
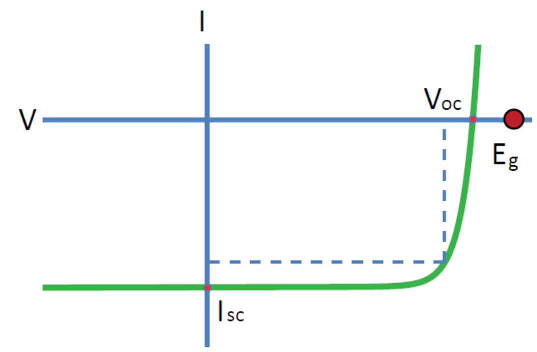
Guanchao Yin
Martina Schmid

California Institute of Technology 1891

Vivian Ferry
Emily Kosten
Harry Atwater

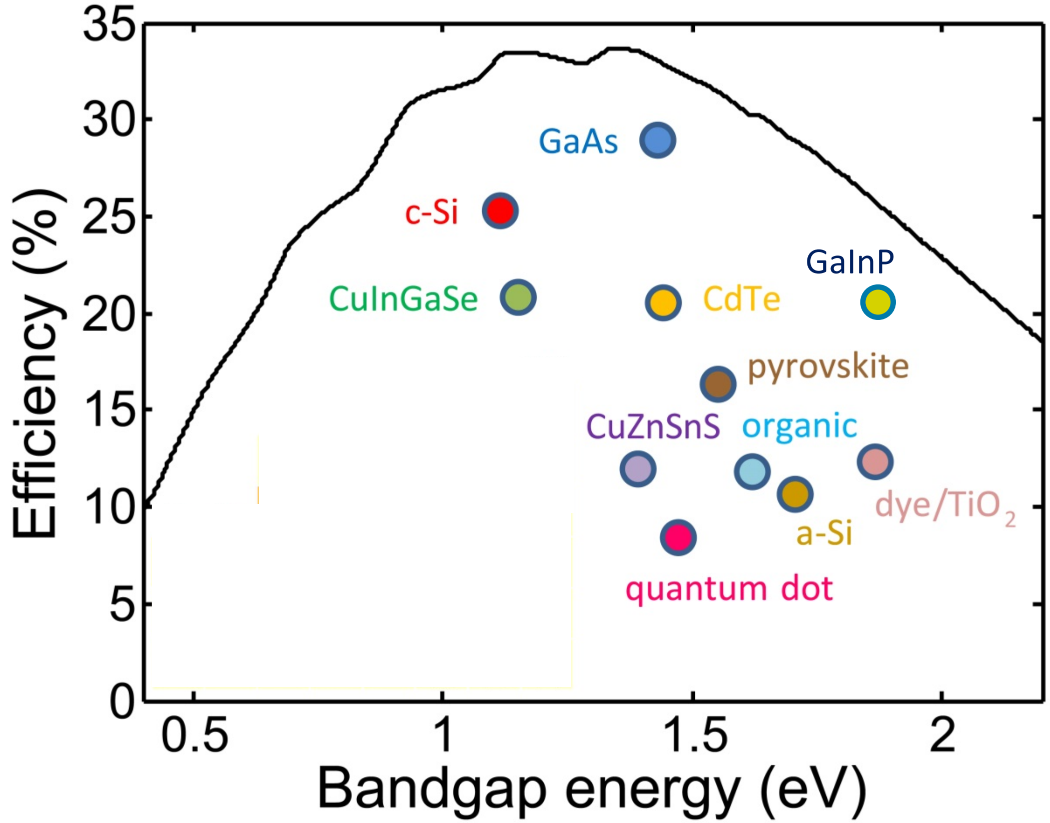
Solar spectrum and Shockley-Queisser limit





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

Record efficiencies of solar cell materials



Strategies towards high efficiency at low costs

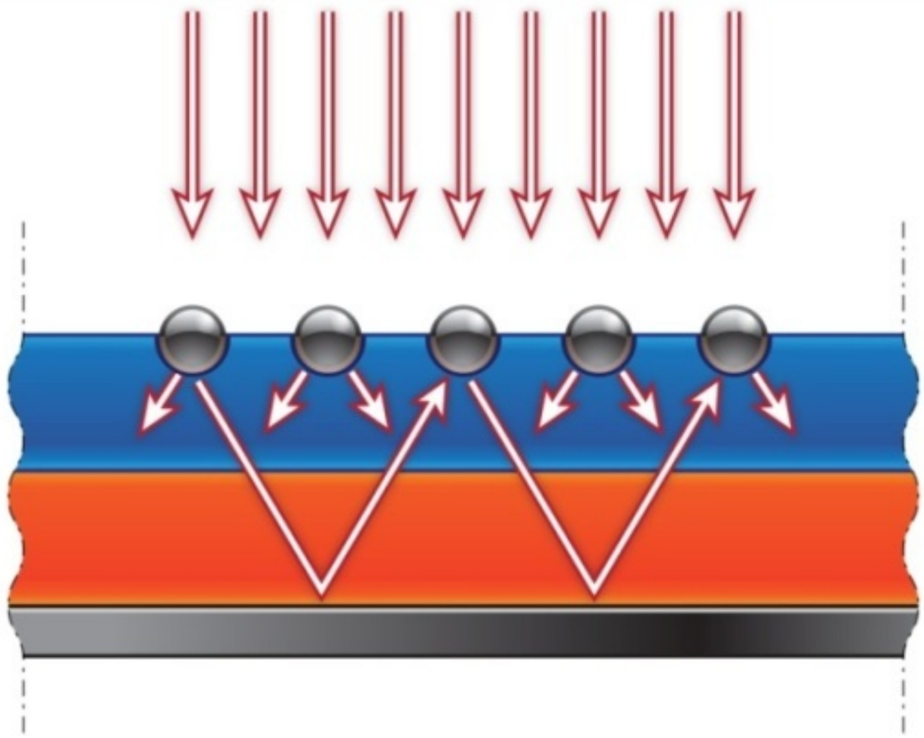
1) Wafer-based Si solar cells (→25-29%)
- Reduce costs (=reduce wafer thickness: 10-20 μm)
- Decrease recombination at surface, junctions, contacts
- Increase light trapping, angular emission restriction,..

2) Thin-film solar cells
- Increase efficiency & reduce costs

3) Dual-junction solar cells on silicon (→30-35%)
- Increase efficiency and bandgap of top cells
- Define spectral splitting architectures

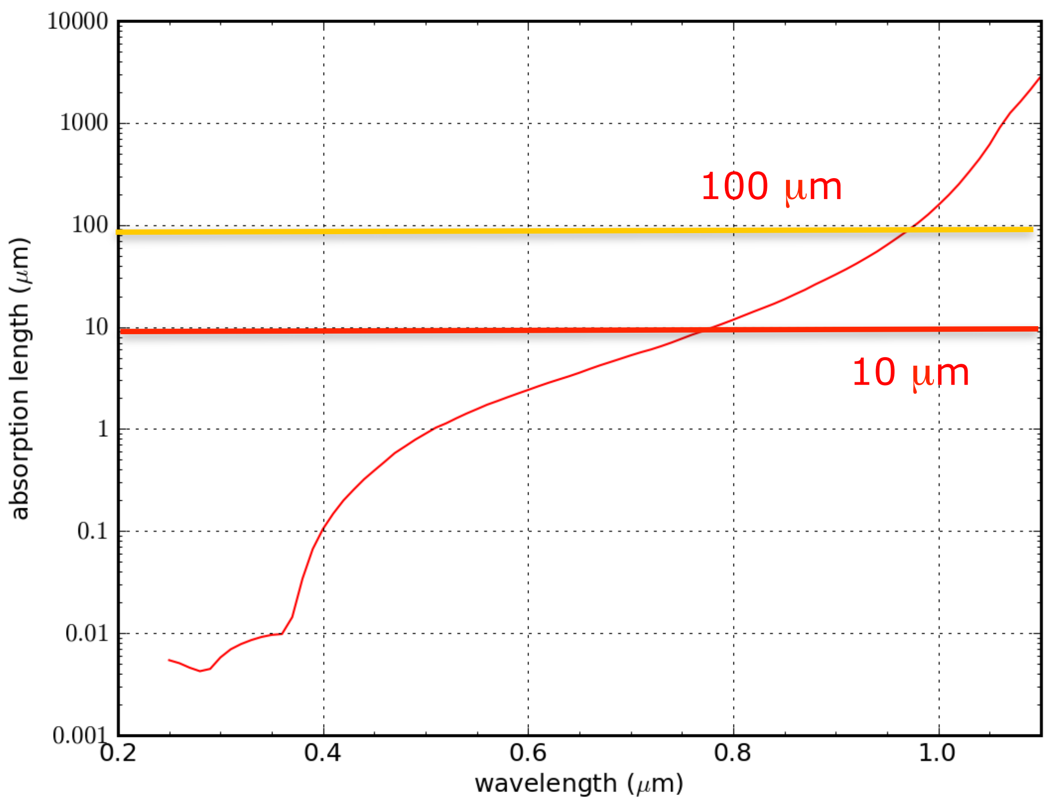
4) New materials and designs (→>40%)
- Novel multijunction cell architectures
- Nanowire solar cells
- ….

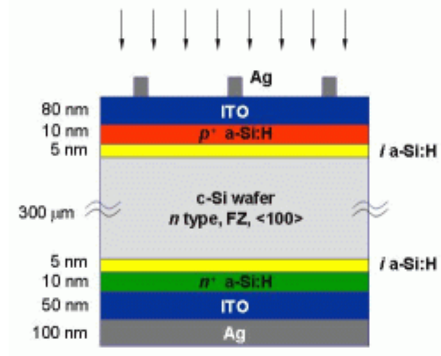
Light coupling and trapping by resonant light scatterers

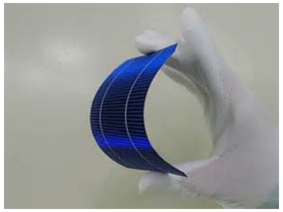


H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010)

Absorption length in silicon

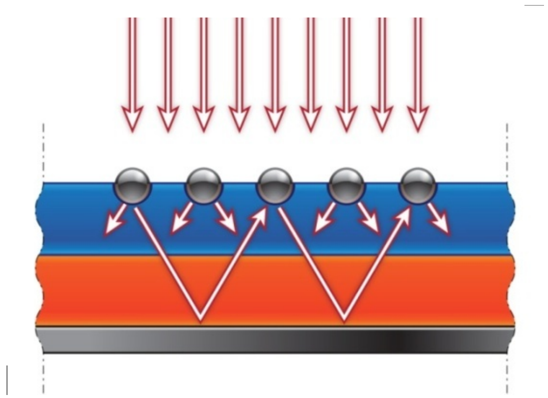


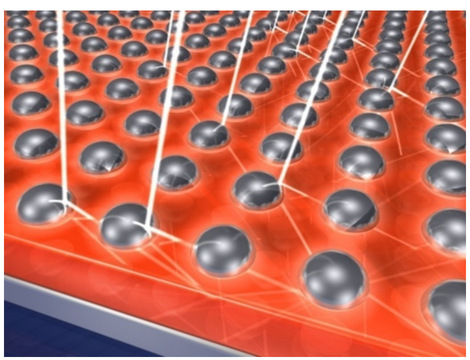


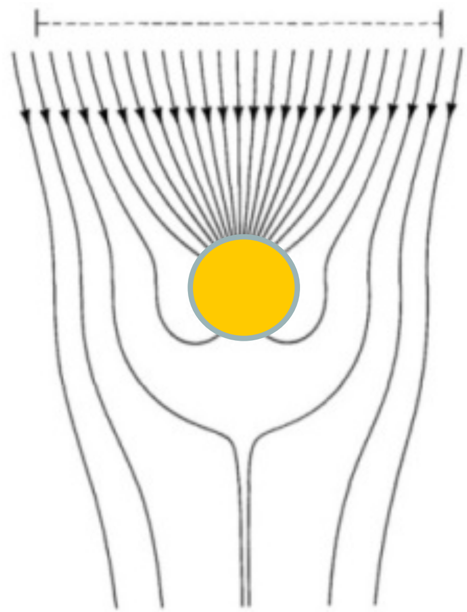


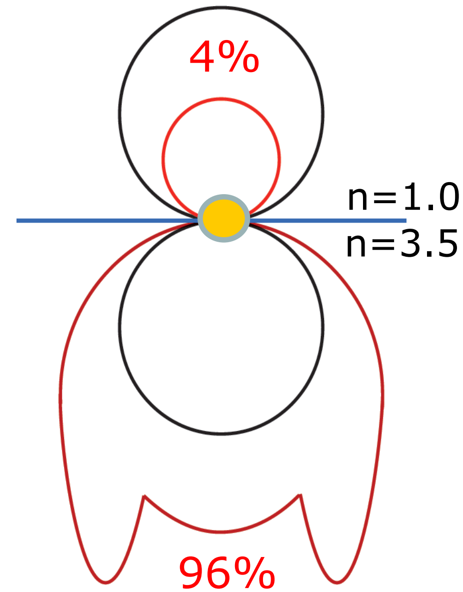
physics.ucsd.edu
japantechniche.com, pvlab.epfl.edu

Light coupling and trapping by resonant light scatterers



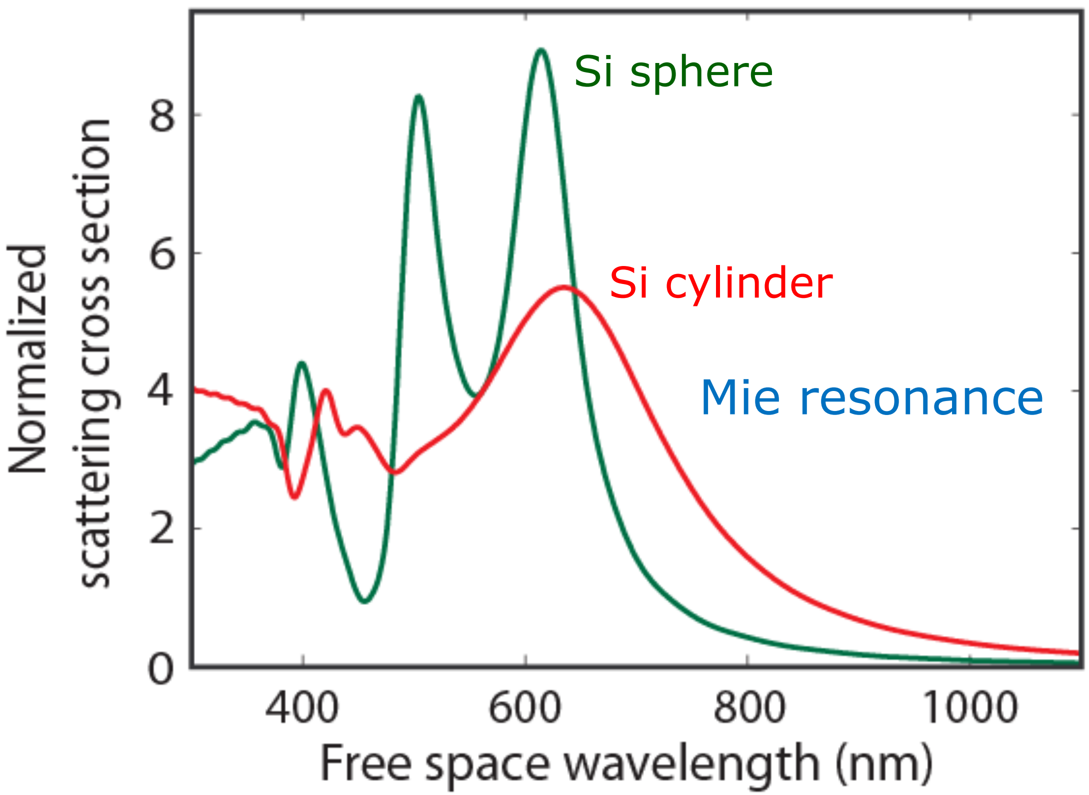


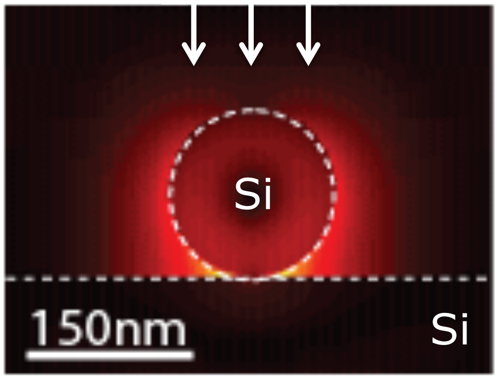


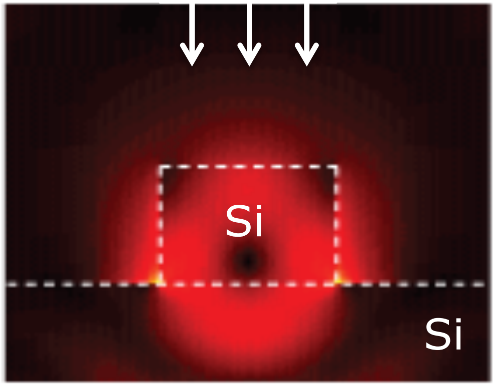


H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010)

Silicon Mie scatterer on a Si substrate



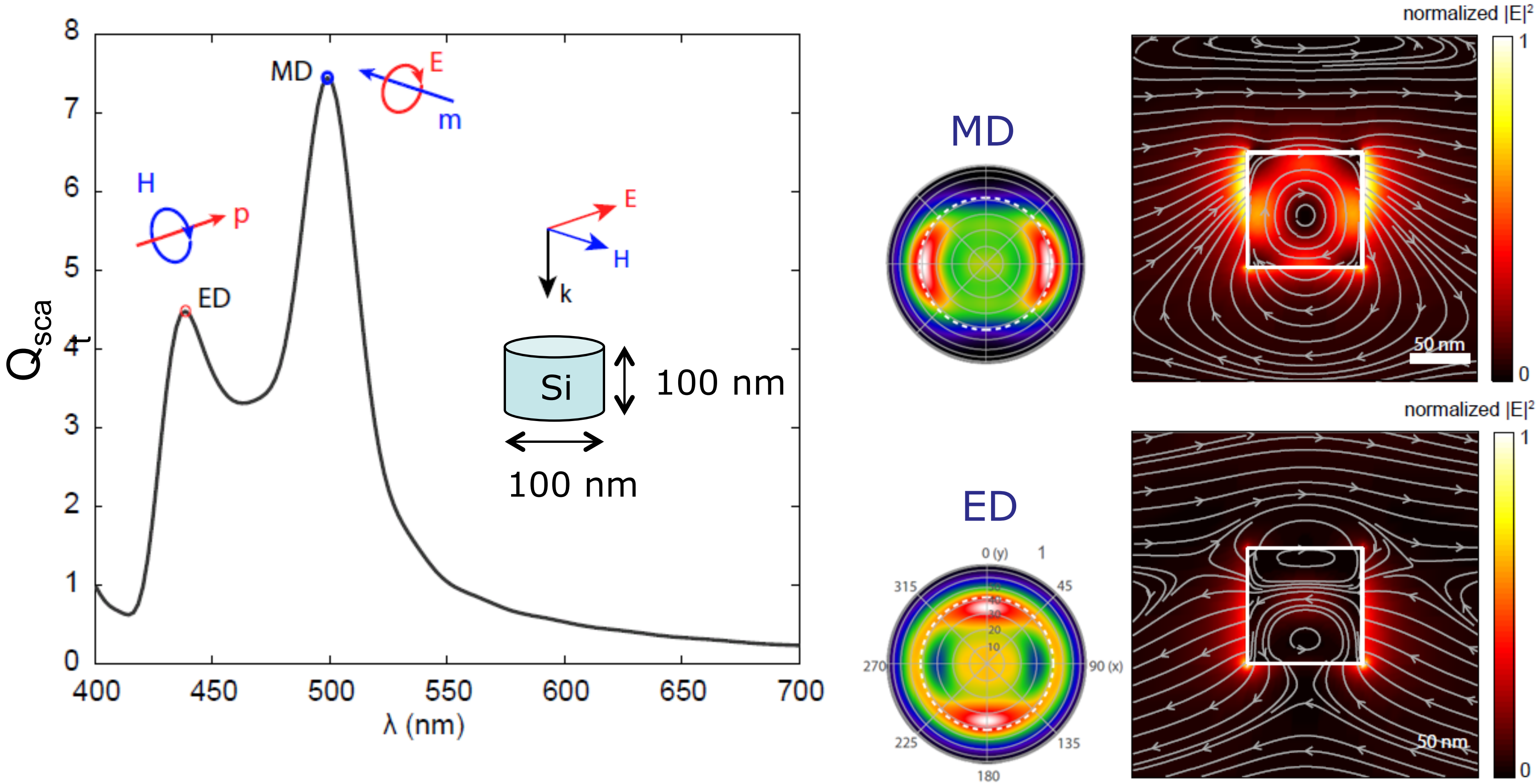




Silicon nano-cylinders act as cavities for light and direct light into the substrate

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

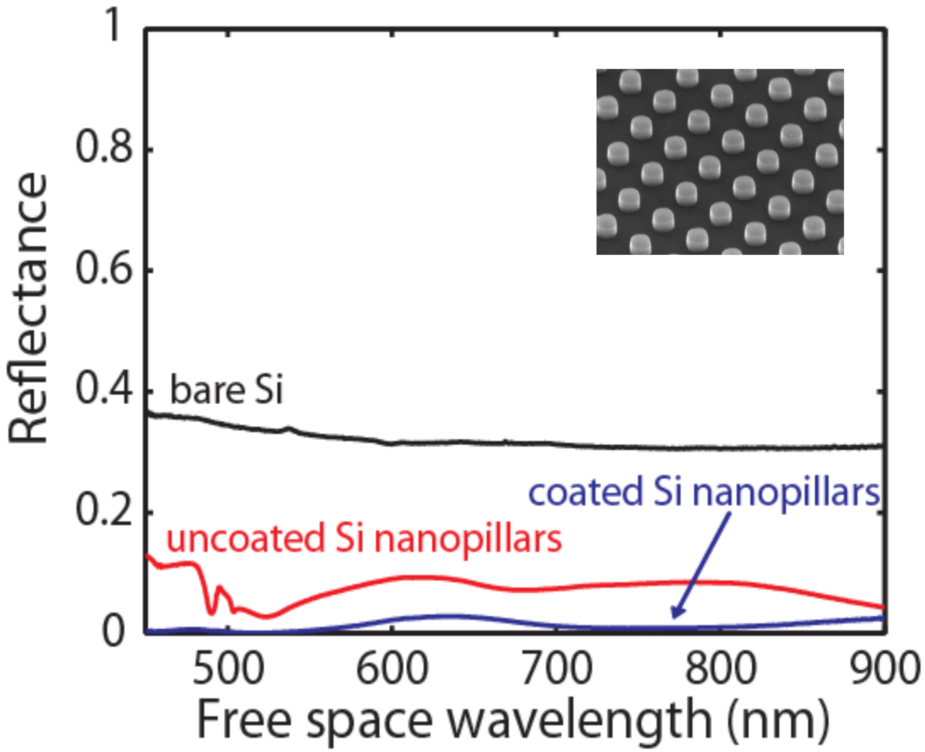
Electric and magnetic Mie modes

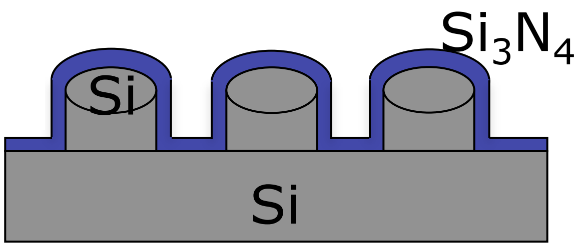


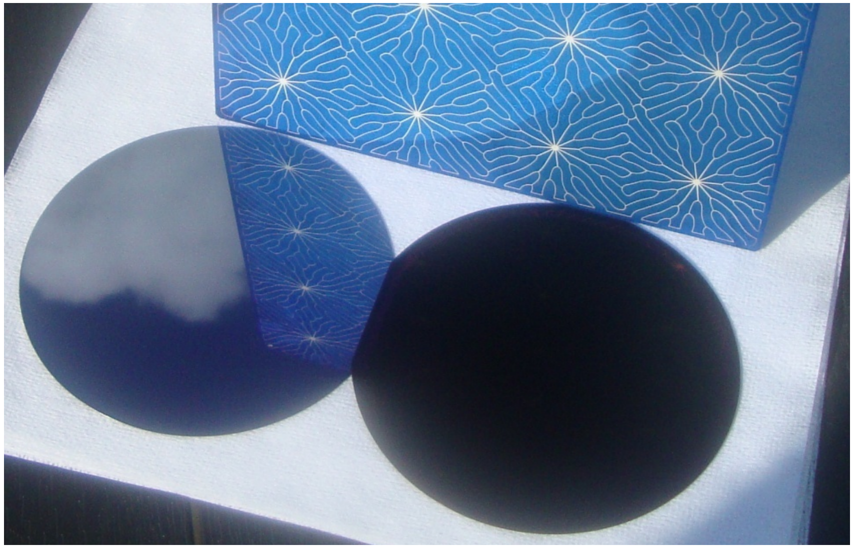
Jorik van de Groep
Optics Express **21**, 26285 (2013)

Black silicon using leaky Mie resonances

Average reflectivity: 1.3%







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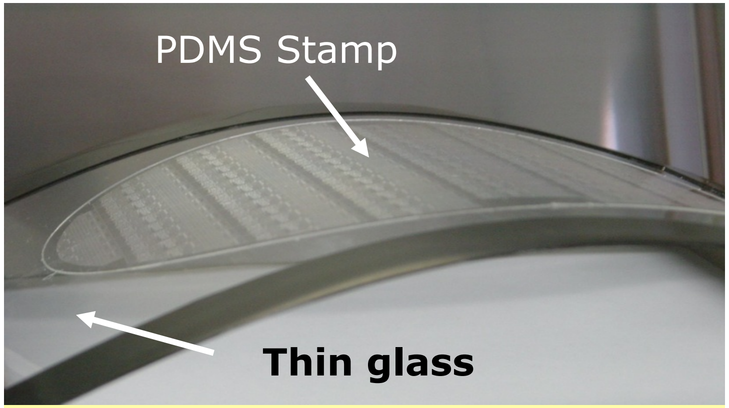
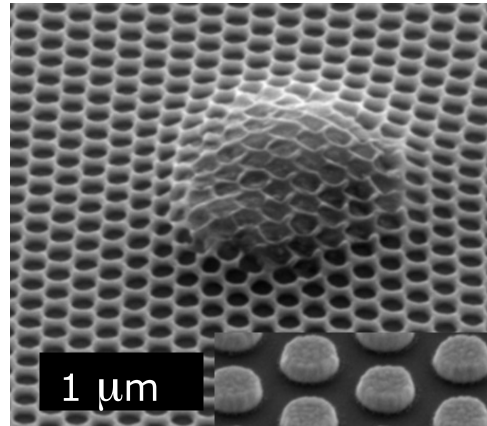
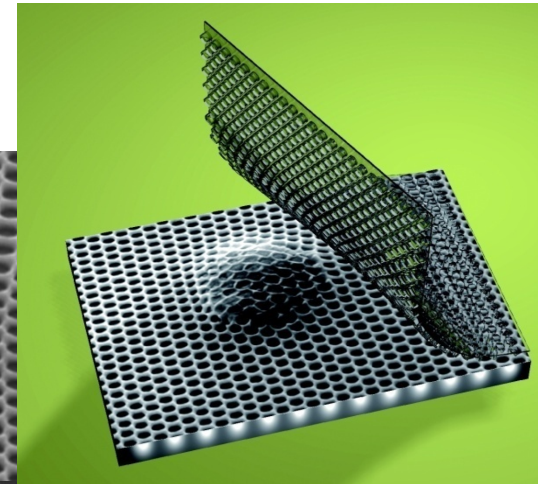
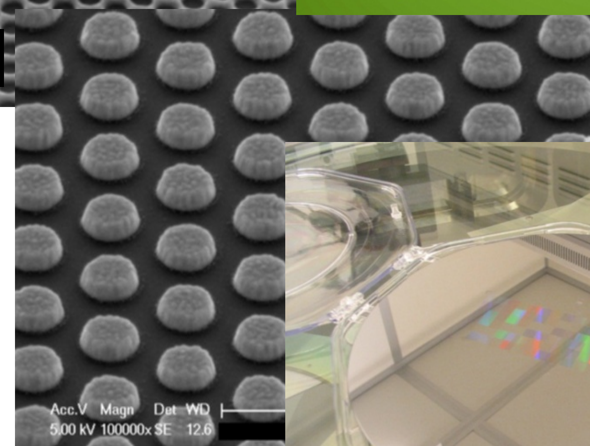
Substrate conformal imprint lithography

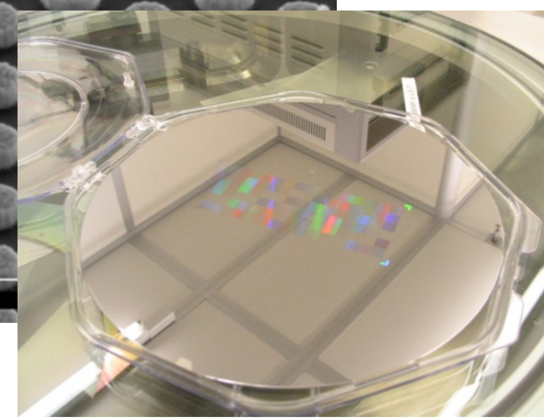


PDMS stamp (6”) on 200 µm AF-45 glass







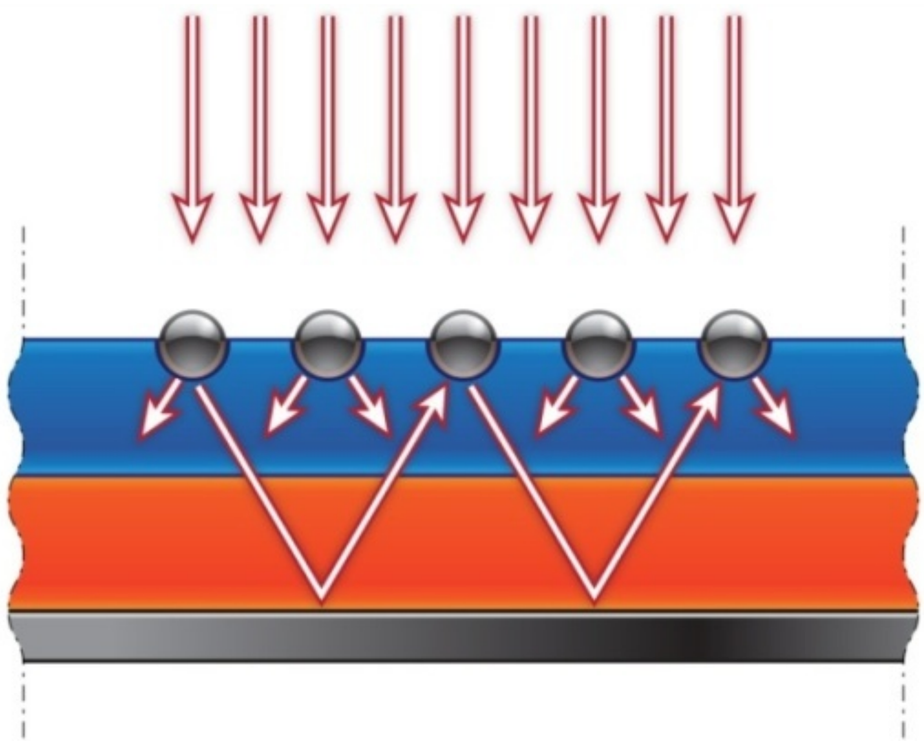


Full-wafer soft nano-imprint

- Flexible rubber on thin glass
- Conform to substrate bow and roughness
- No stamp damage due to particles

Marc Verschuuren
PhD thesis, Utrecht University (2010)

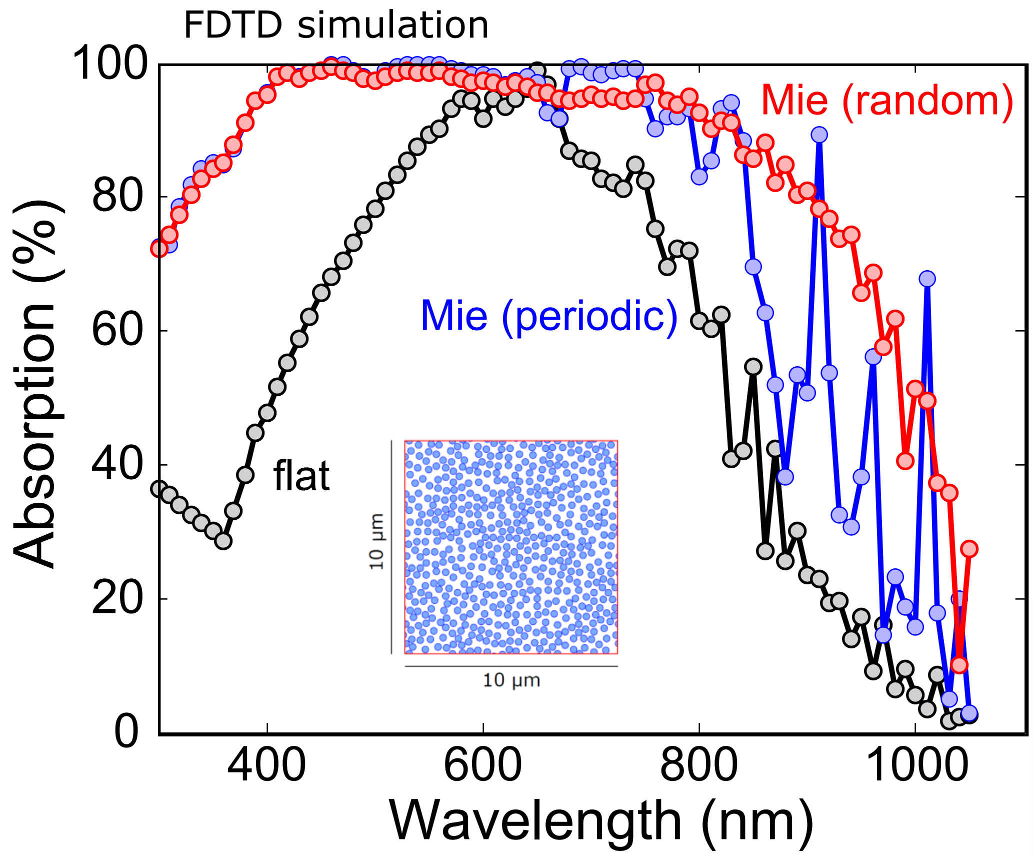
Light coupling and trapping by resonant light scatterers

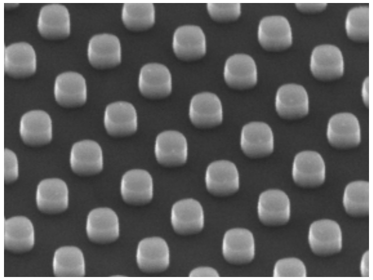


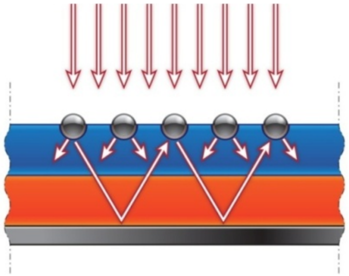
H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010)

Light trapping in 5 μm crystalline Si slab

Goal: higher V_{OC} (reduced bulk recombination)





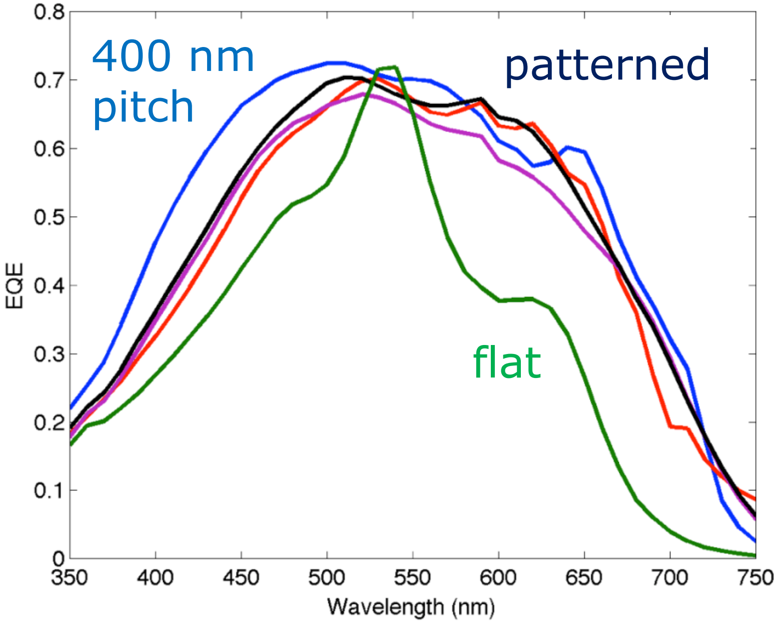


Enables 20 μm thick Si solar cell with efficiency > 23 %

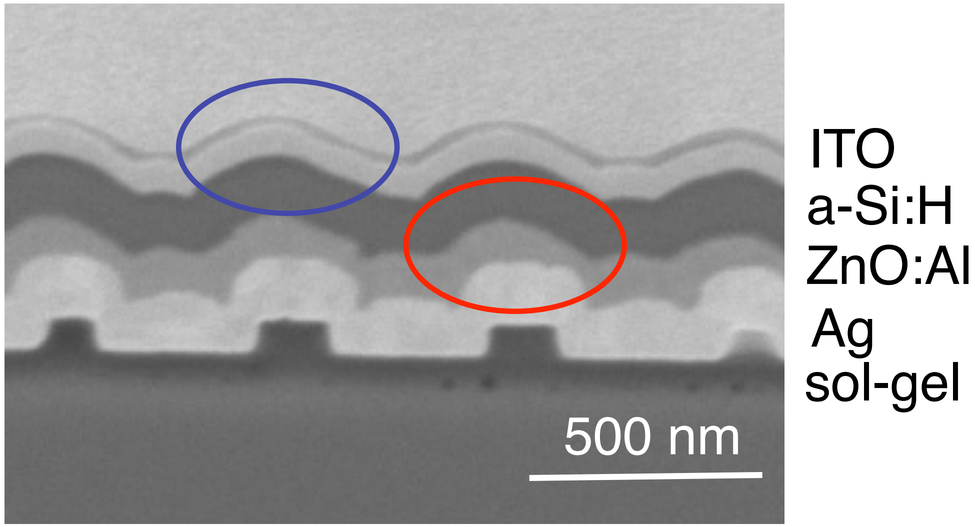
Piero Spinelli
J. Photovolt. **4**, 554 (2014)

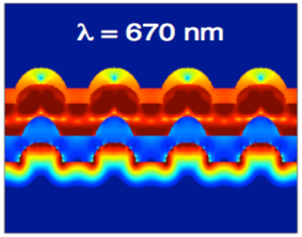
Ultra-thin a-Si:H solar cell: 90 nm *i*–layer

Experiment



enhanced **red** and **blue** response by resonant dielectric scatterers

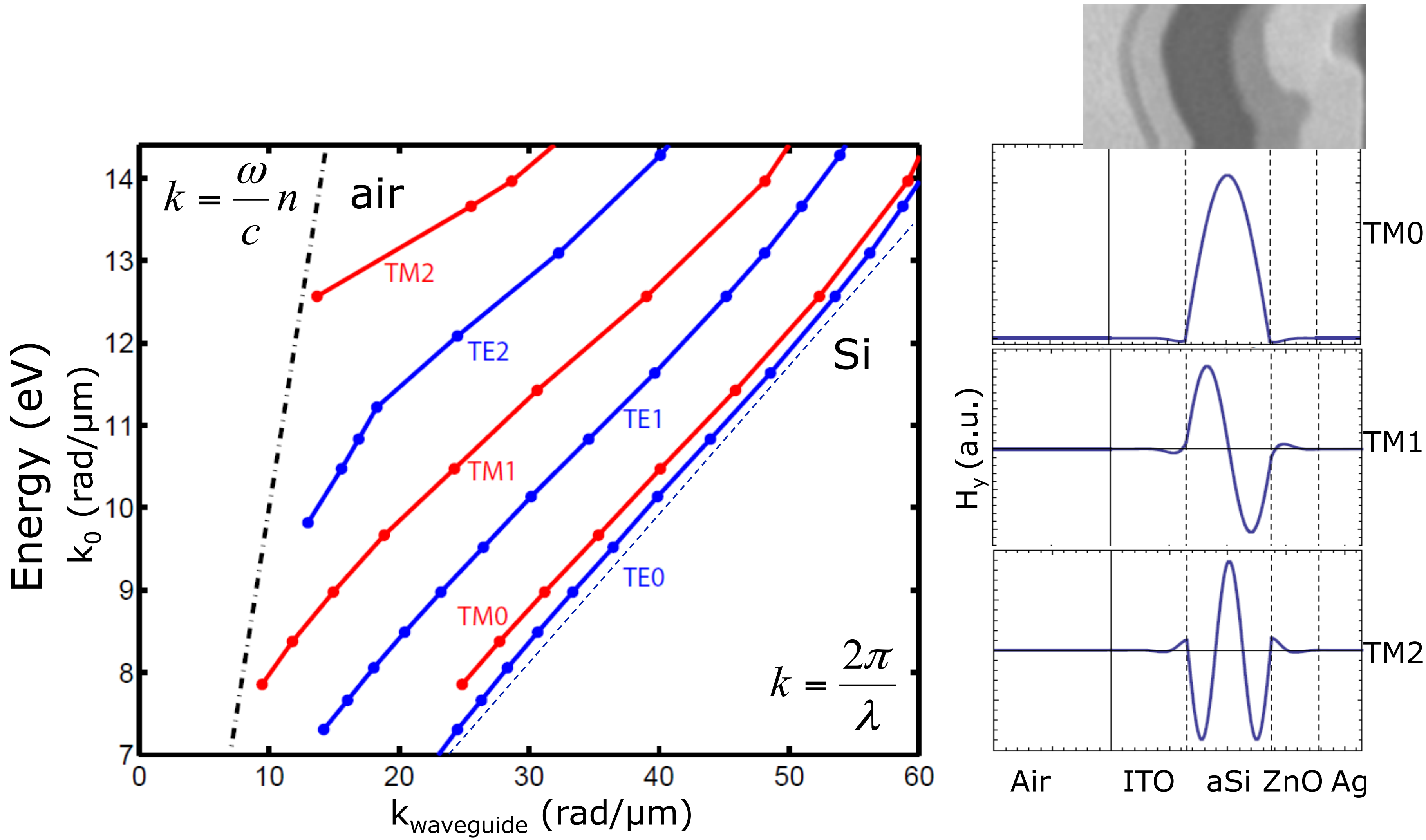




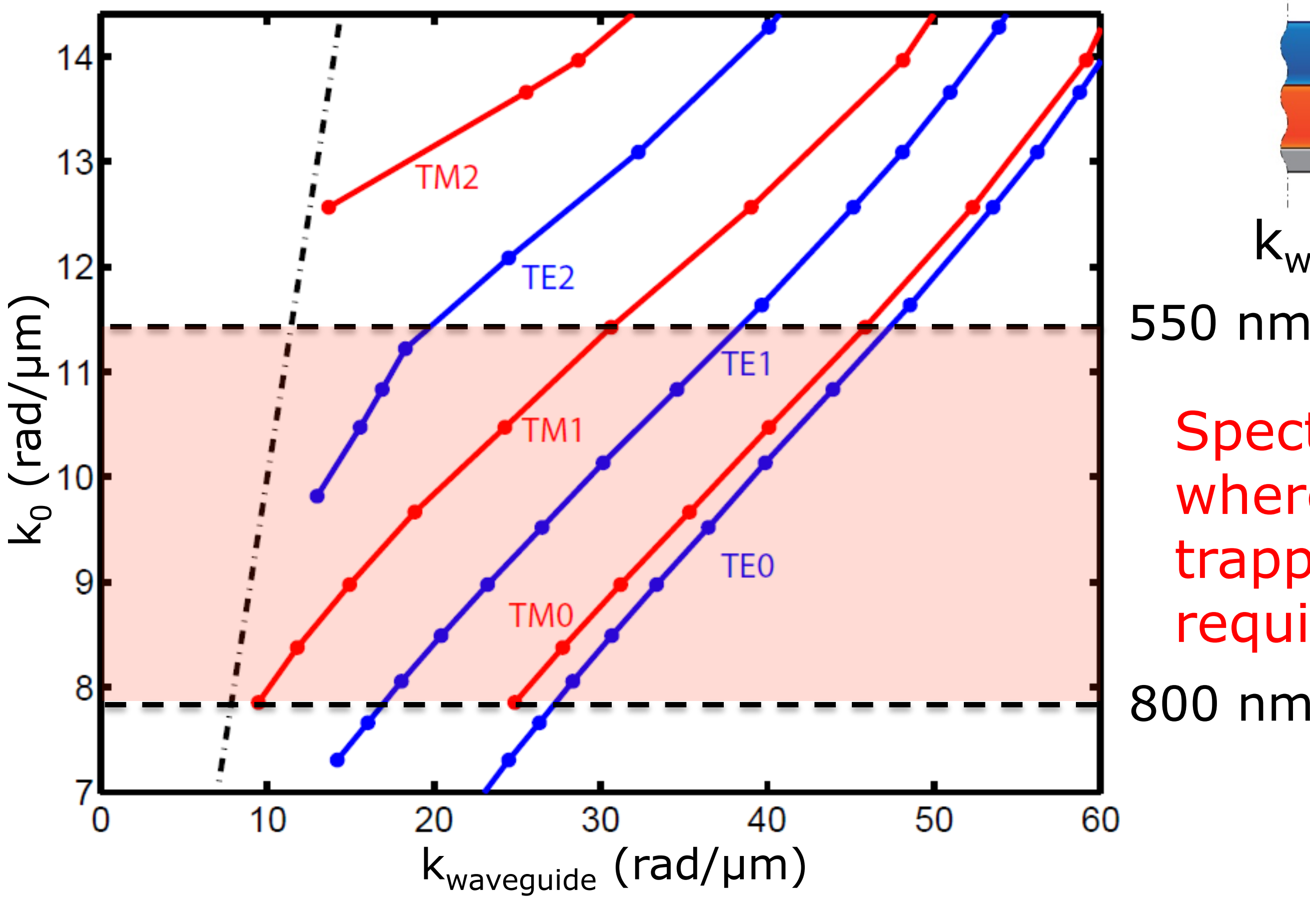
The solar cell as an optical integrated circuit

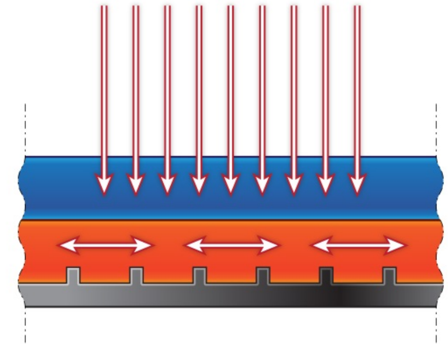
Vivian Ferry, Claire van Lare
Nano Lett. **11**, 4239 (2011), Optics Express **21**, 20739 (2013)

Thin-film solar cells are optical waveguides



Thin-film solar cells are optical waveguides

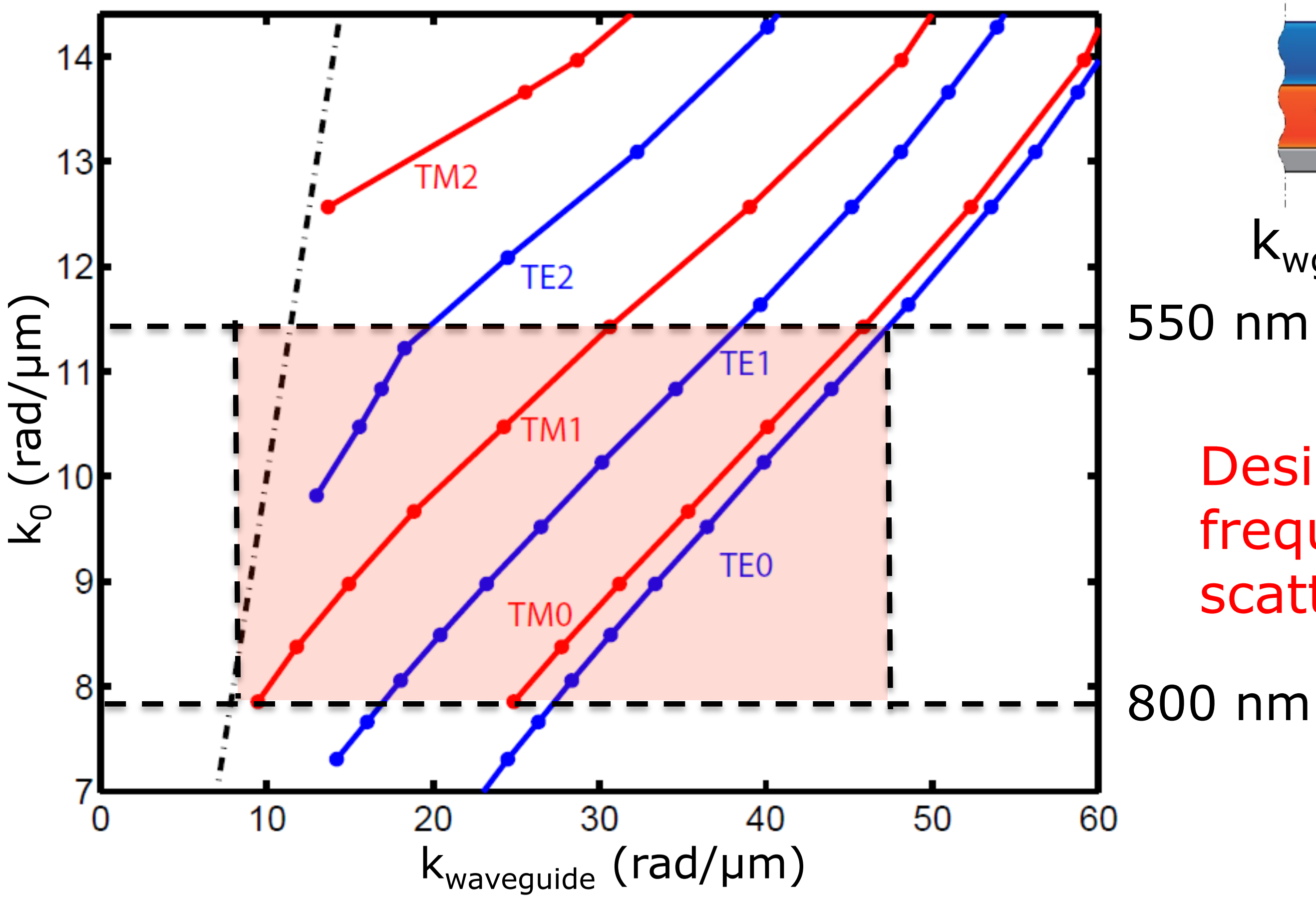


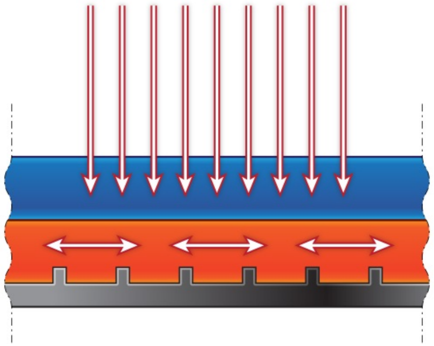


$k_{wg}=k_o \sin(\varphi)+nk_{gr}$

Spectral range where light trapping is required

Thin-film solar cells are optical waveguides

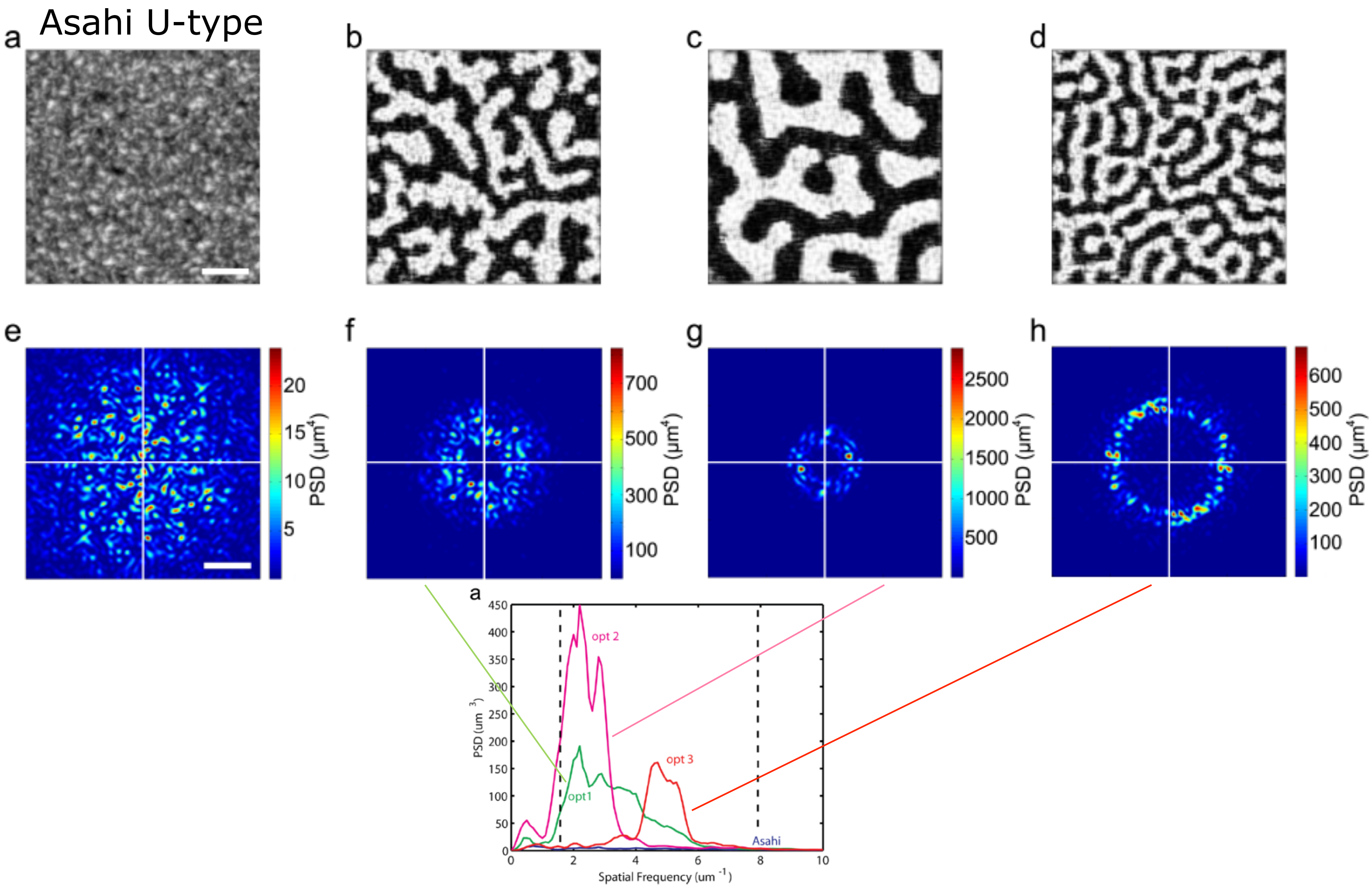




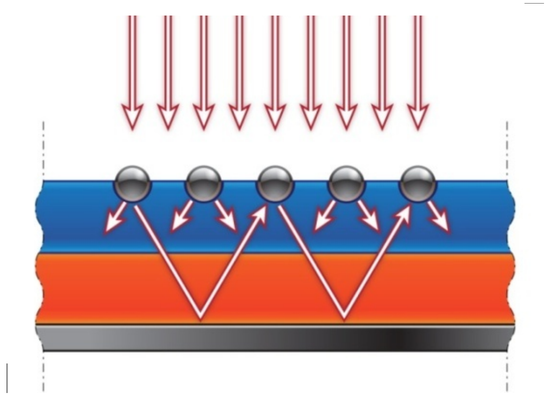
$k_{wg}=k_o\sin(\varphi)+nk_{gr}$

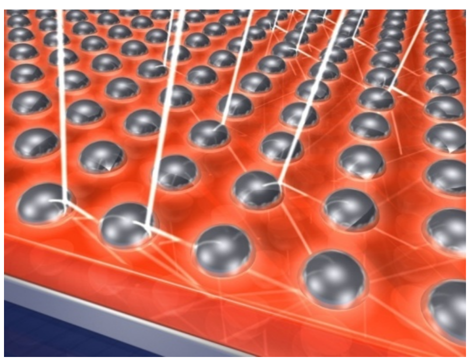
Desired spatial frequencies in scattering pattern

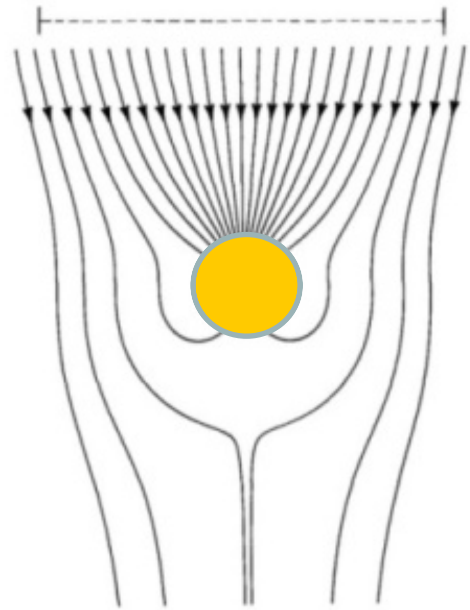
Optimizing spatial frequency of scattering pattern

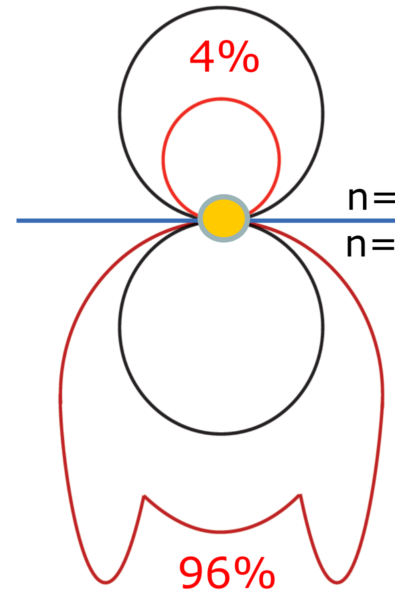


Light coupling and trapping by resonant light scatterers





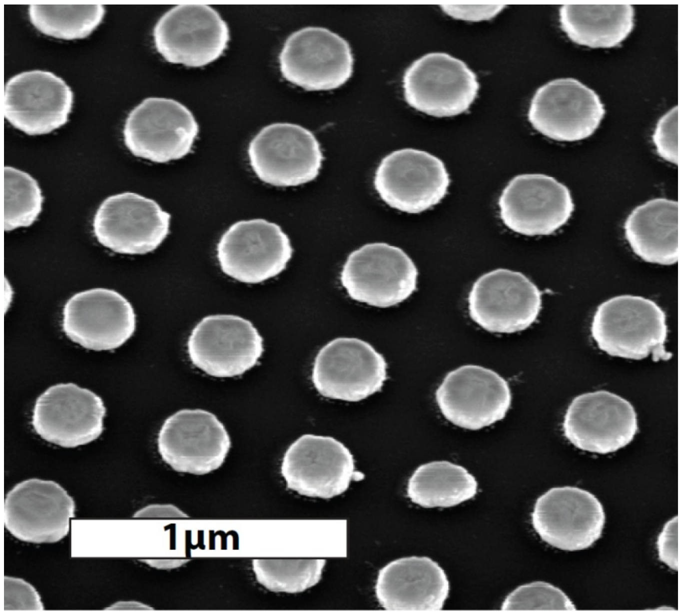




H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010)

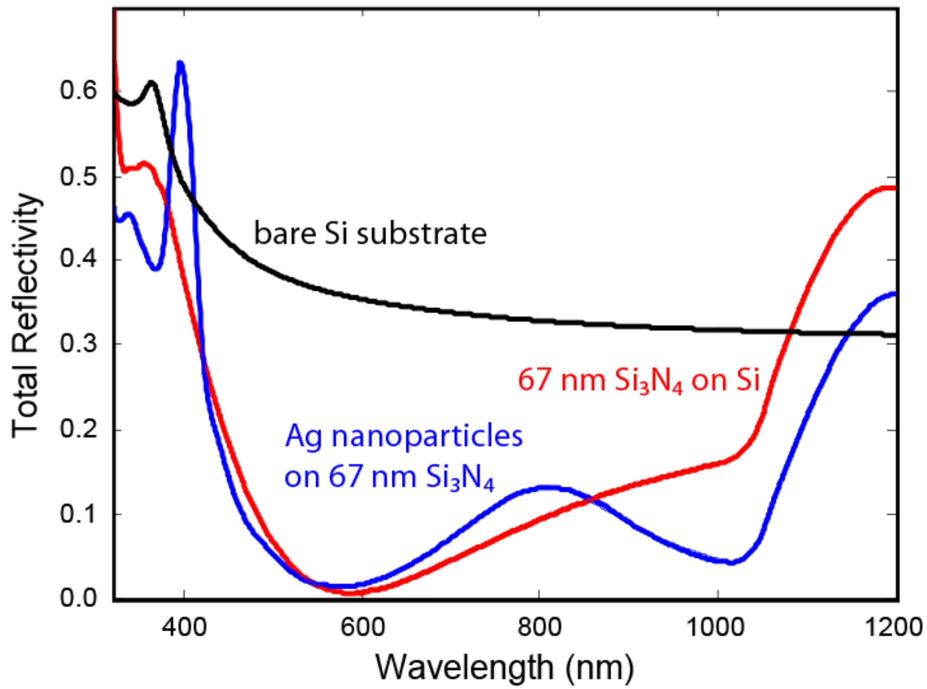
Ag nanoparticle anti-reflection coating on Si

Ag nanoparticles on Si wafer



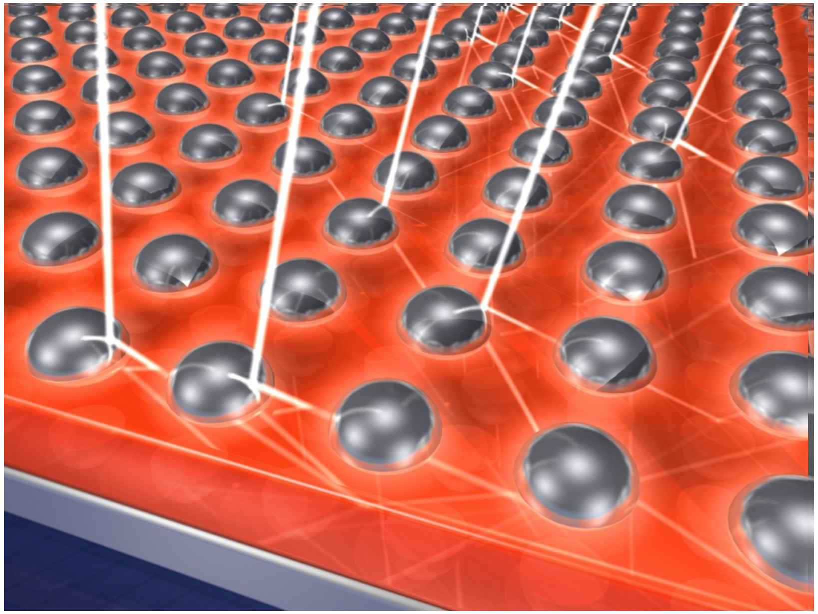
nanoparticles made with soft-imprint

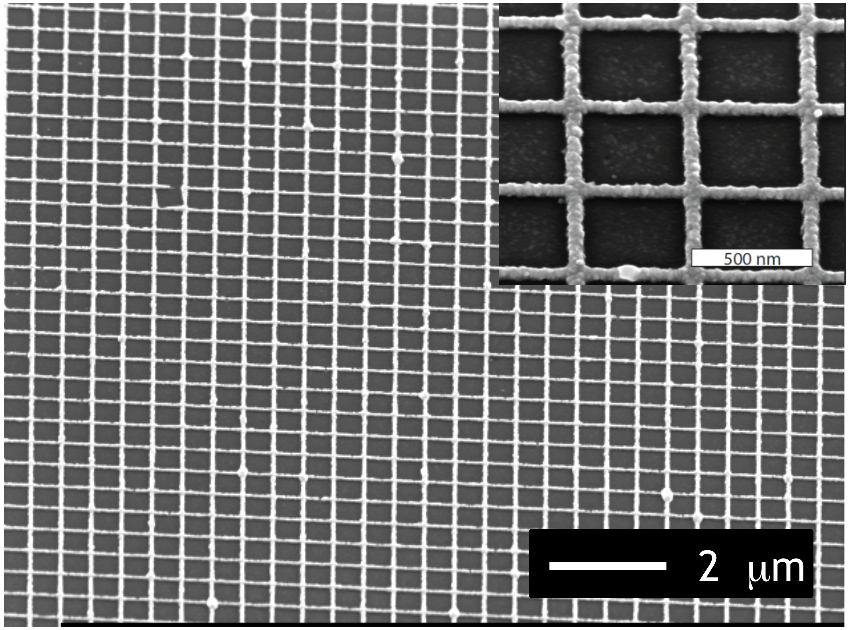
Reflectivity data



Piero Spinelli
Nano Lett. **11**, 1760 (2011)

Transparent conductive silver nanowire network



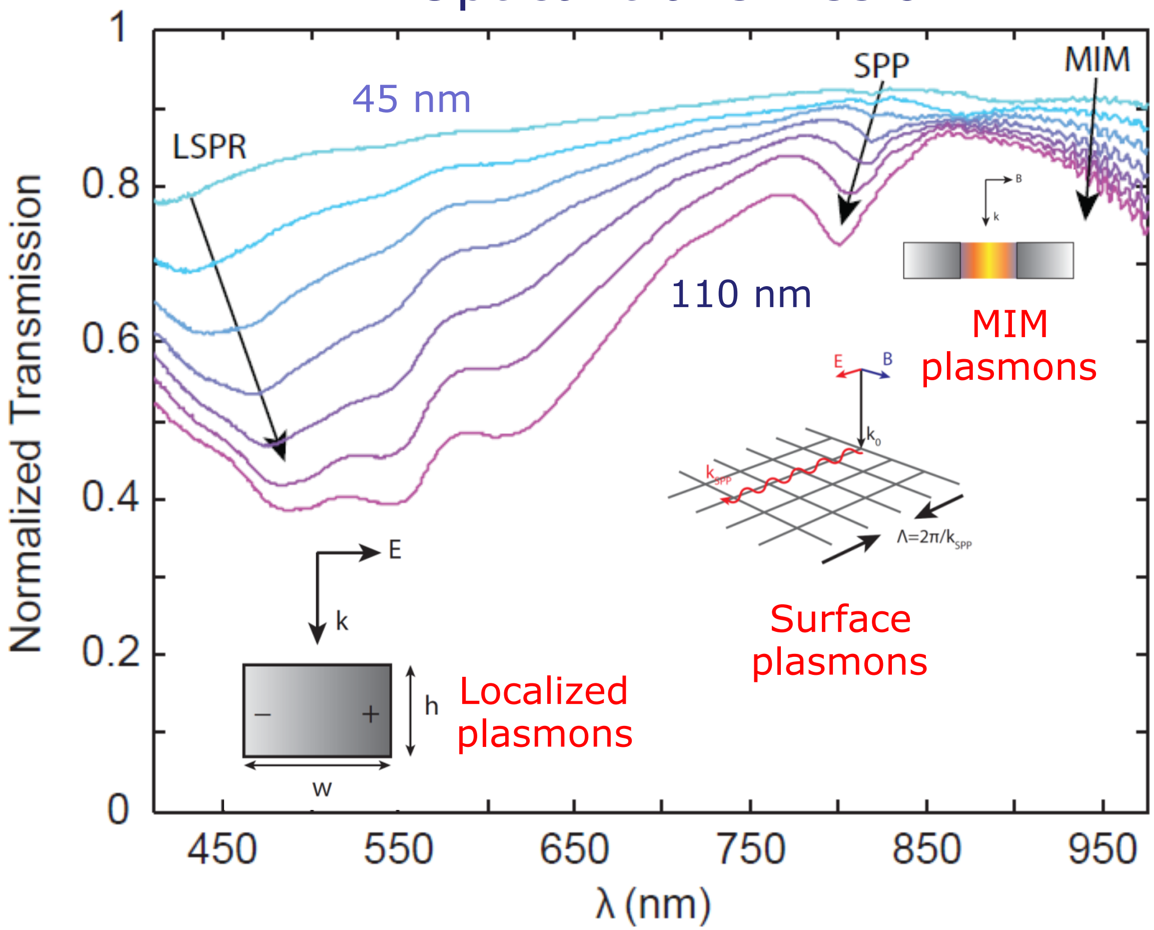


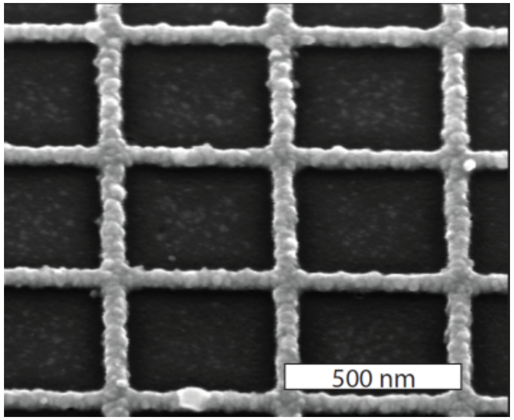
Ag nanowire network fabricated with electron beam lithography
width: 45-110 nm
height: 60 nm

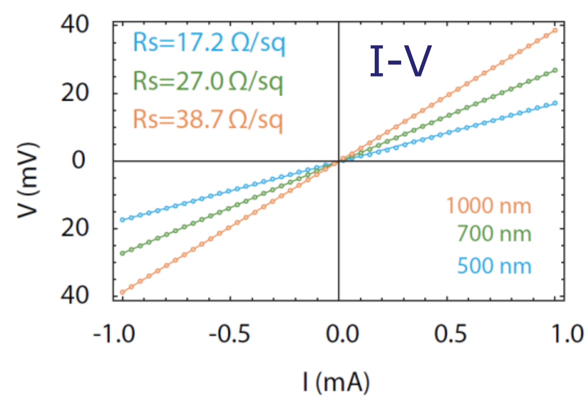
Jorik van de Groep, Piero Spinelli
Nano Lett. **12**, 3138 (2012)

Transparent conductive silver nanowire network

Optical transmission





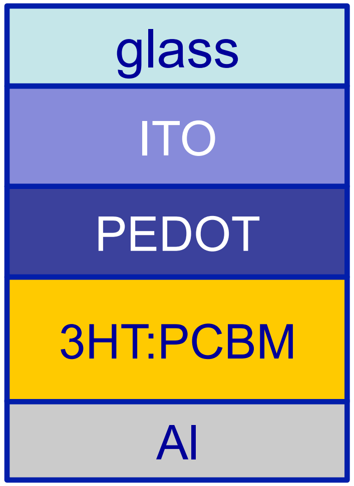


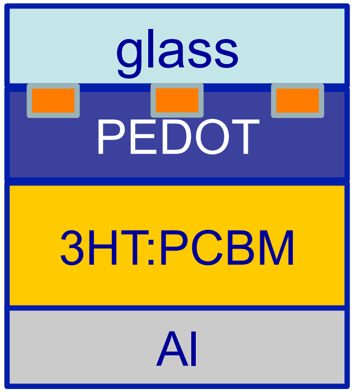
Equal to ITO

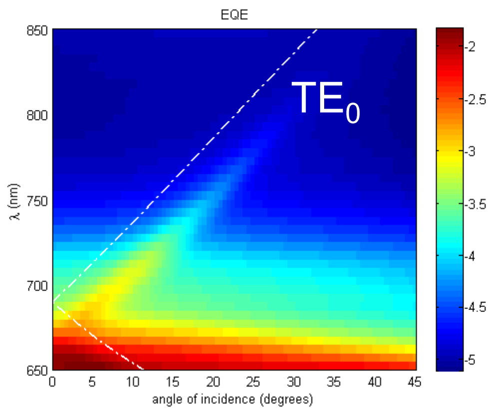
Jorik van de Groep, Piero Spinelli

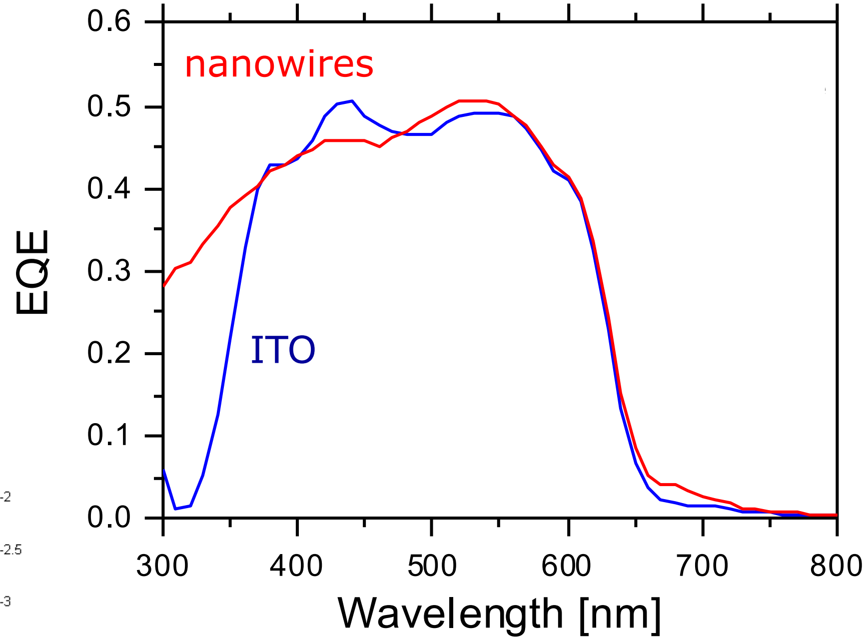
Nano Lett. **12**, 3138 (2012)

Spectral response of polymer cells with Ag networks



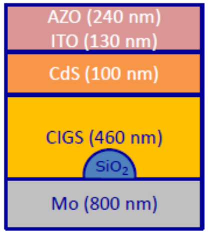






Jorik van de Groep, Dhritiman Gupta

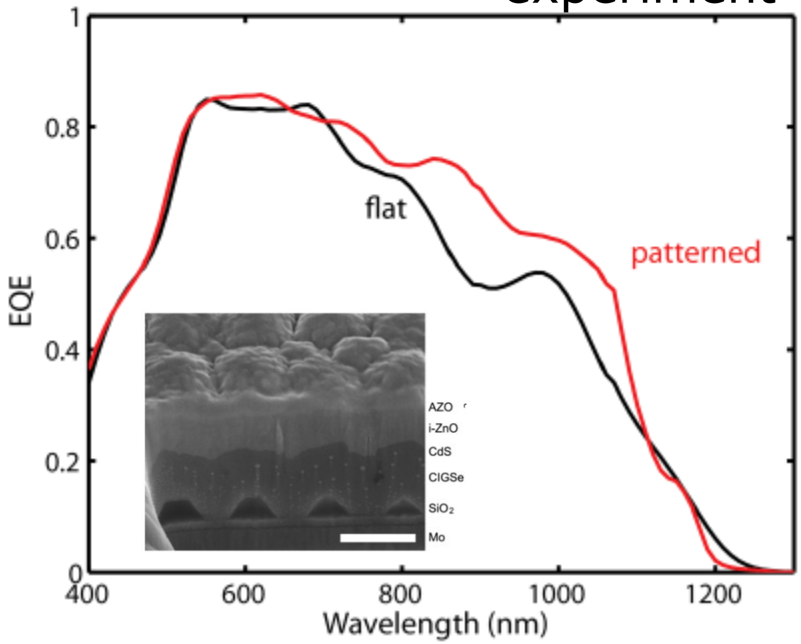
Nanopatterned thin (460 nm) CIGSe cells



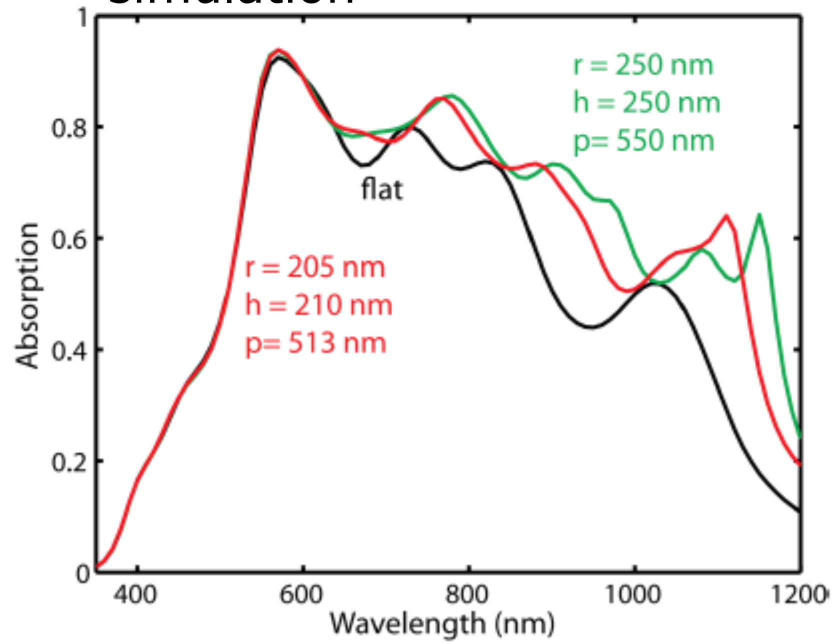
V (V)

cell type	V_{oc} (mV)	J_{sc} (mA/cm^2)	J_{sc} from EQE (mA/cm^2)	FF (%)	efficiency (%)
flat	583	28.6	28.2	67.4	11.0
patterned	592	30.6	30.5	68.2	12.4

experiment

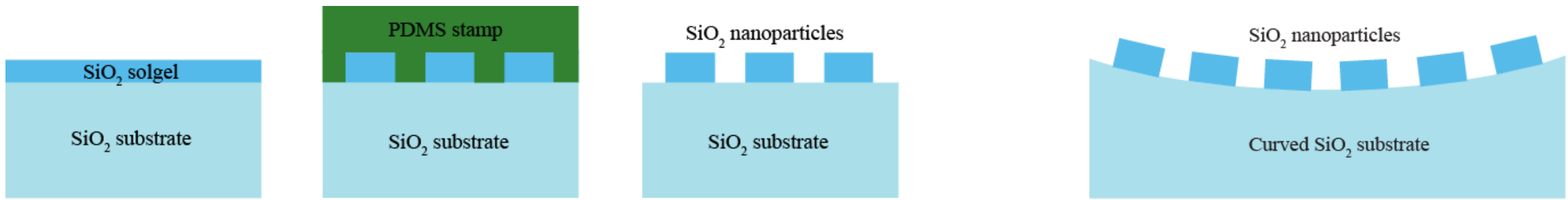


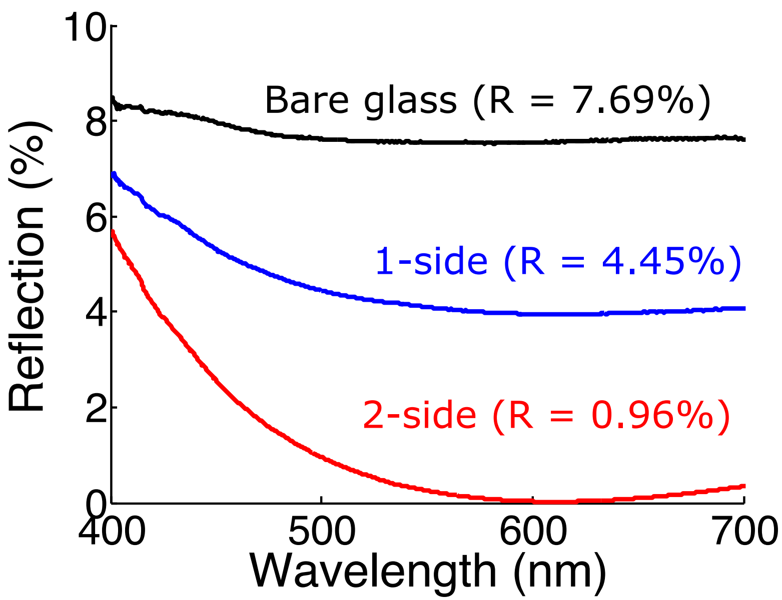
simulation

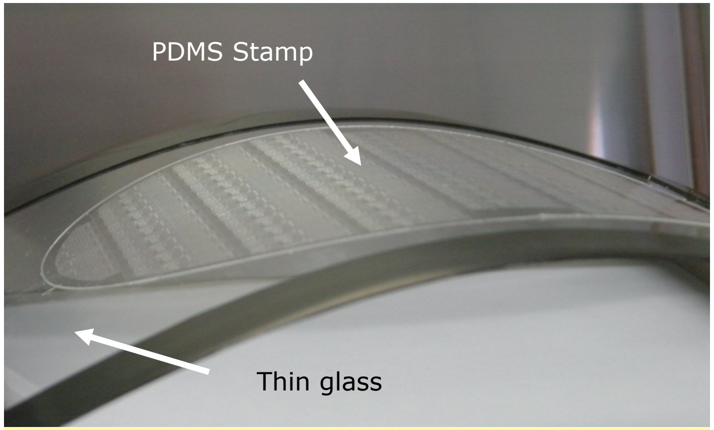


Claire van Lare, Guanchao Yin

Nano-glass



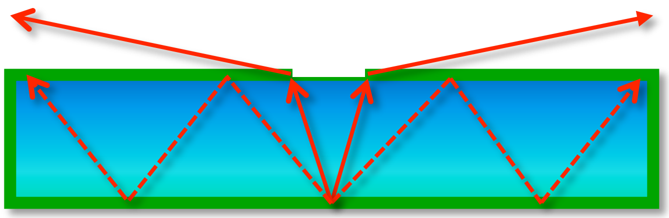




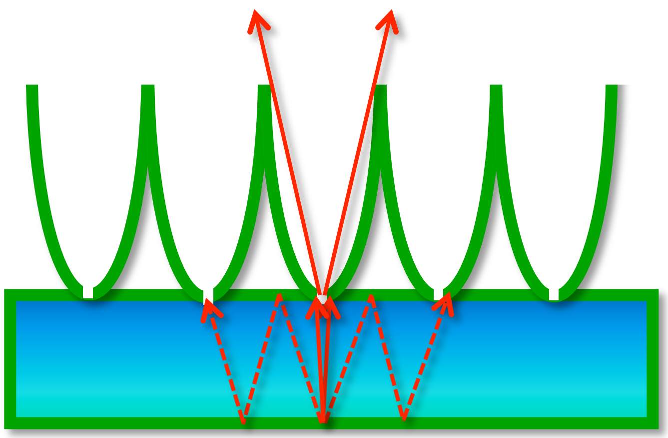
PDMS stamp (6”) on 200 µm AF-45 glass

Piero Spinelli, Jorik van de Groep

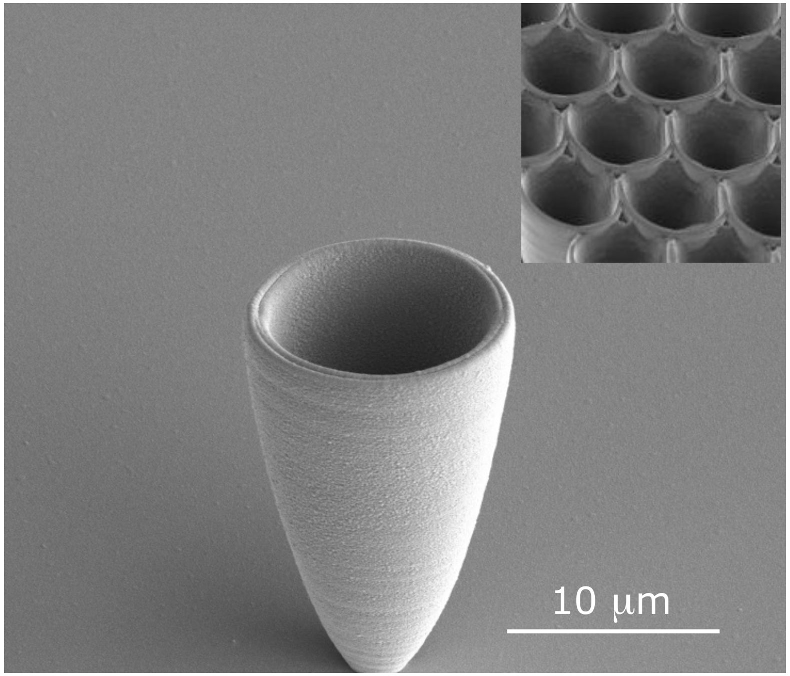
Enhanced light trapping by limiting emission angle



max: $4n^2$

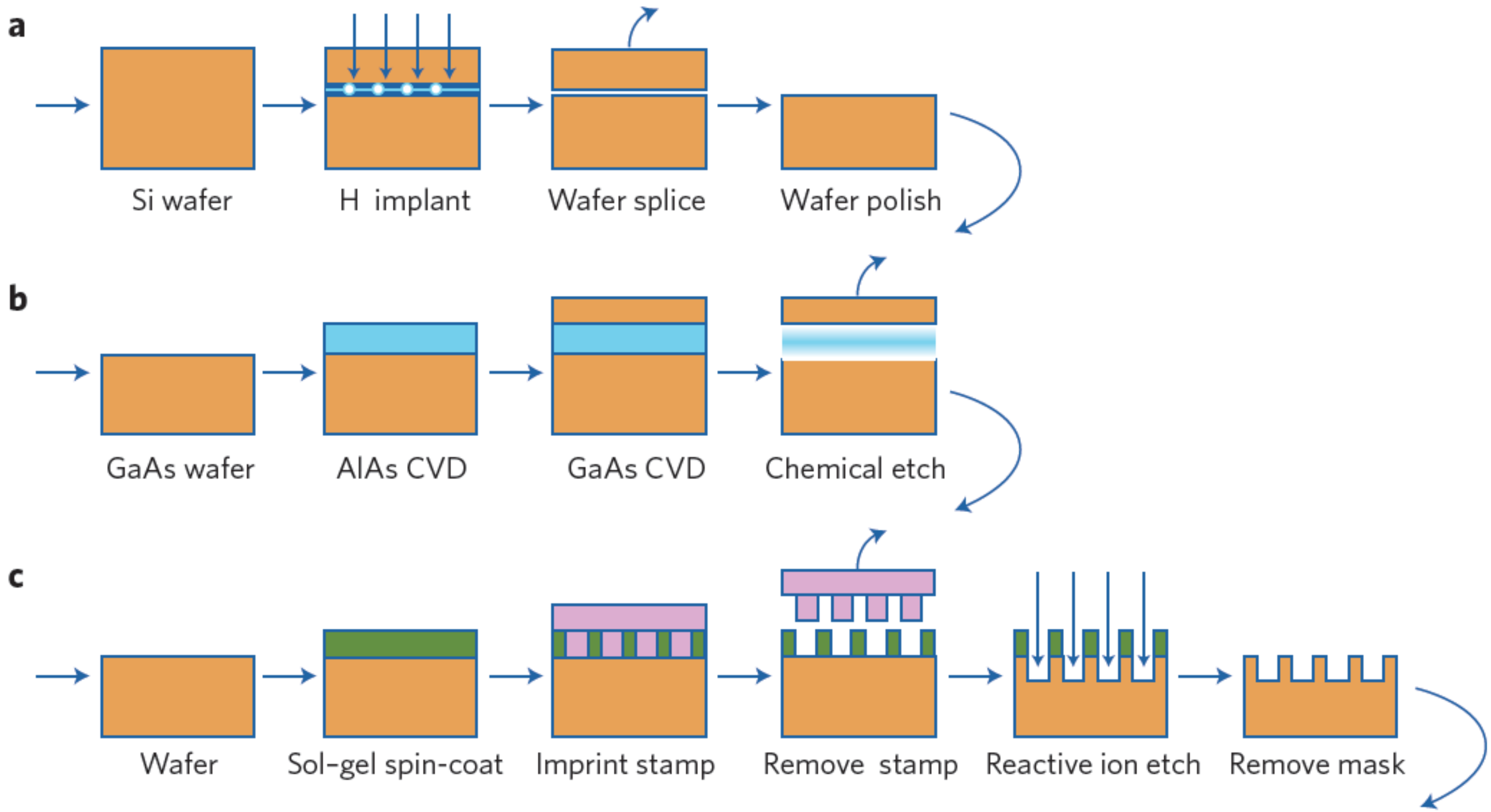


max: $>4n^2$



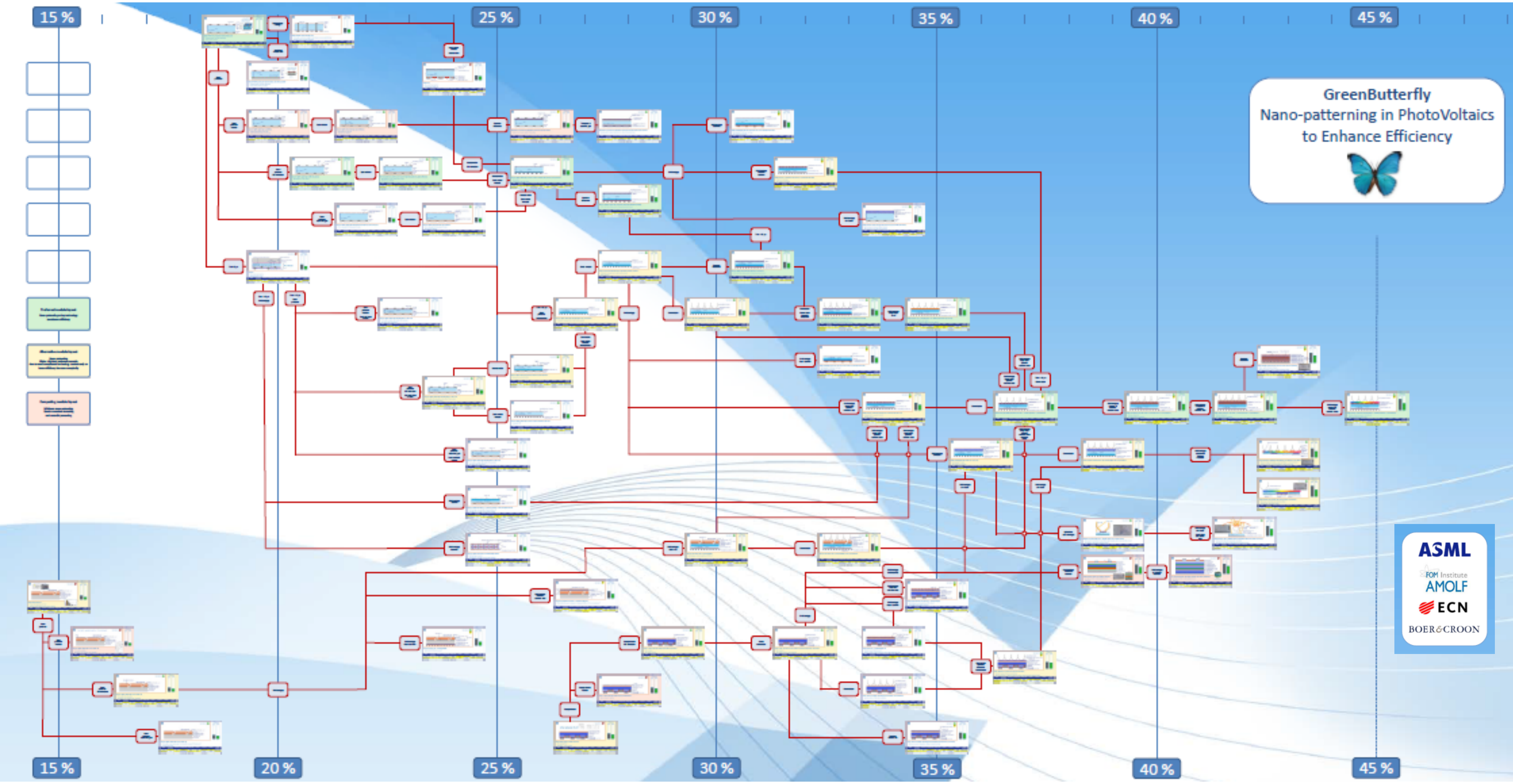
Appl. Phys. Lett. **99**, 151113 (2011)
A. Polman and H.A. Atwater, Nature Mater. **11,** 174 (2012)

Scalable inexpensive large-area layer transfer and nanofabrication techniques



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

Roadmap nanopatterning for photovoltaics



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www.erbium.nl
Thank you