High-efficiency solar cells based on nanophotonic design

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Emily Kosten
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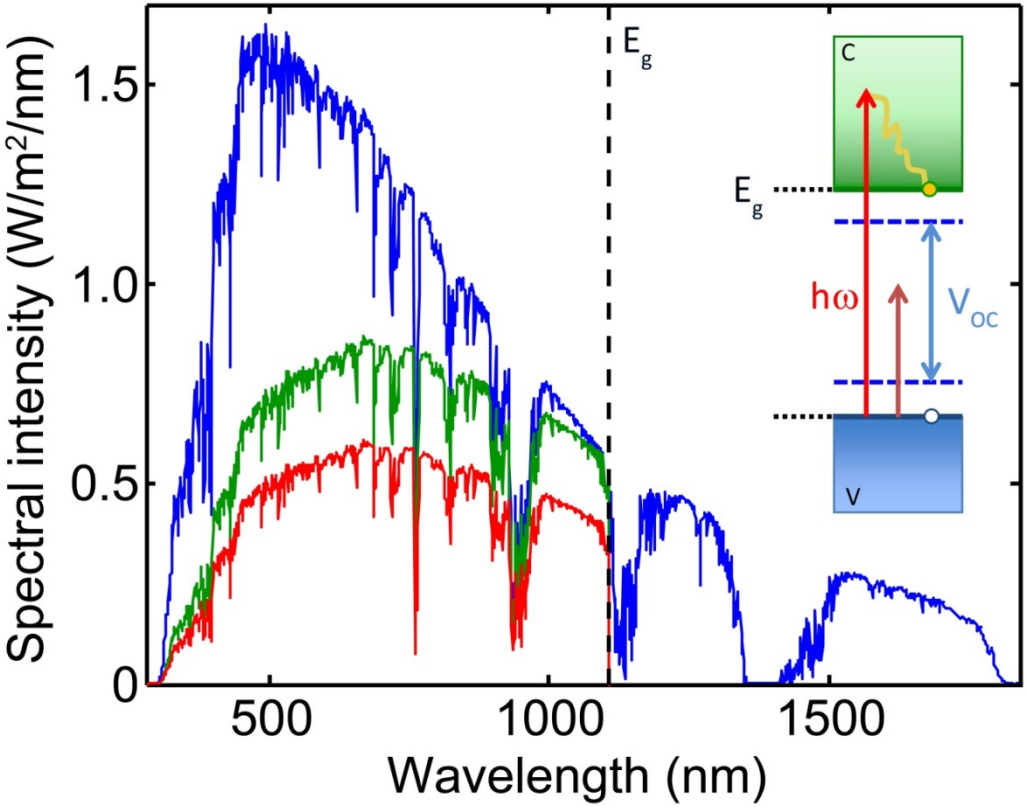
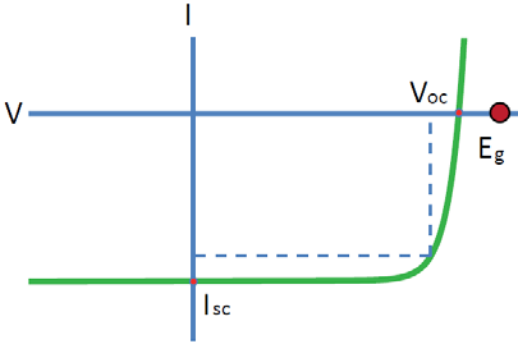
Outline

- Status of PV efficiencies, fundamental limits
- Light management to enhance PV efficiency
  c-Si, a-Si:H, CIGS, organic
- New: the plasmo-electric effect
- Conclusions, outlook

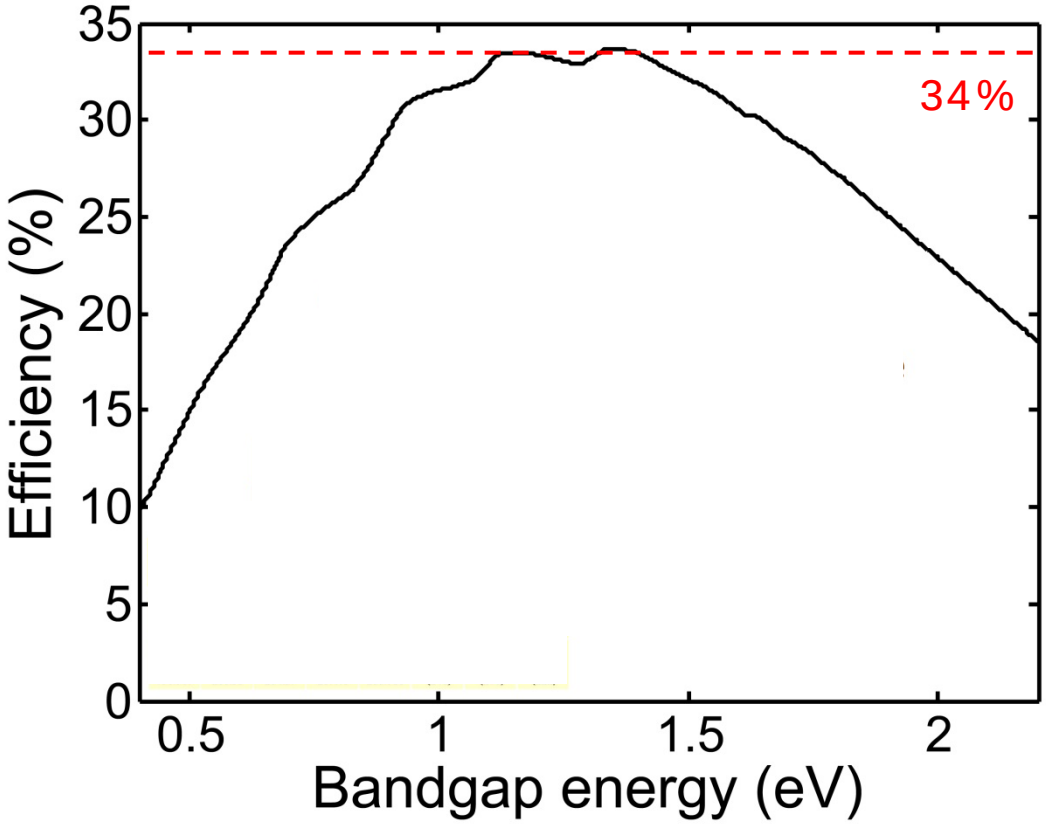
Solar spectrum and Shockley-Queisser limit



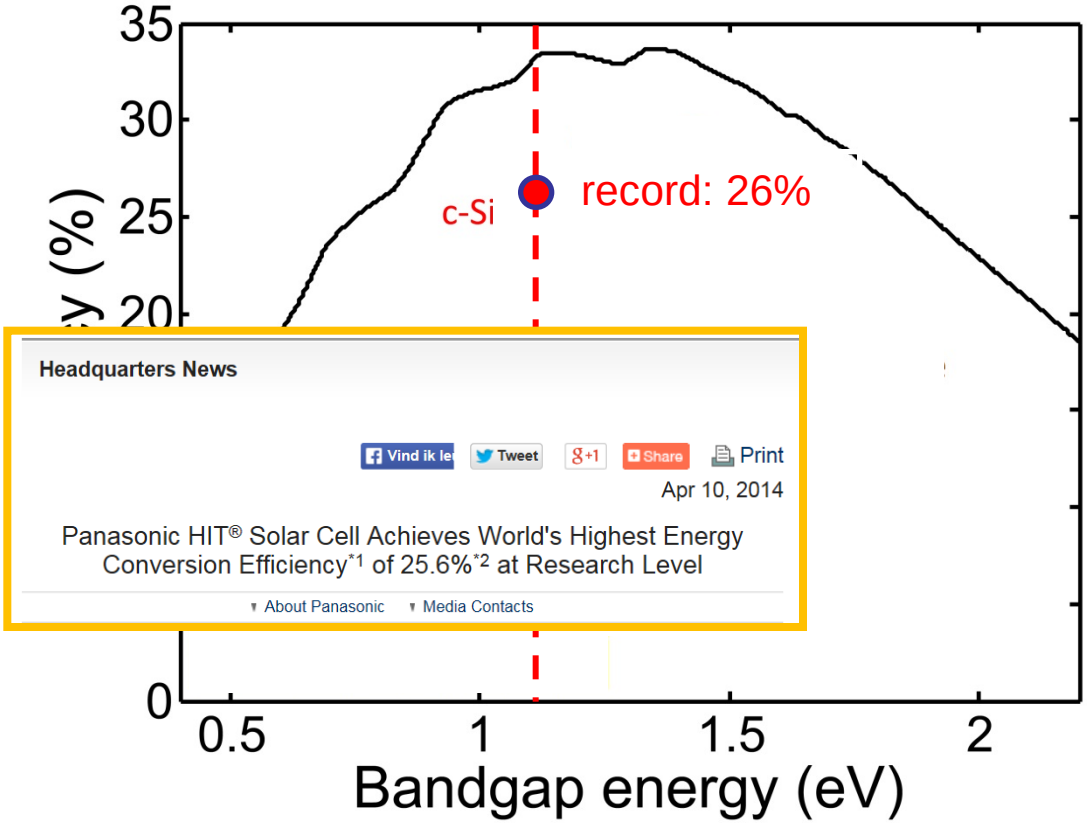


$$I_{ext} = I_0 \exp(V/kT) - I_{SC}$$

Shockley-Queisser efficiency limit: 34%



Silicon is ideal: SQ limit = 33 %



Headquarters News

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Apr 10, 2014

Panasonic HIT® Solar Cell Achieves World's Highest Energy Conversion Efficiency*1 of 25.6%*2 at Research Level

About Panasonic Media Contacts

Bell System Solar Battery Converts Sun's Rays into Electricity!

Bell Telephone Laboratories invention has great possibilities for telephone service and for all mankind

Ever since Archimedes, men have been searching for the secret of the sun.

For it is known that the same kindly rays that help the flowers and the grains and the fruits to grow also send us almost limitless power. It is nearly as much every three days as in all known reserves of coal, oil and uranium.

If this energy could be put to use – there would be enough to turn every wheel and light every lamp that mankind would ever need.

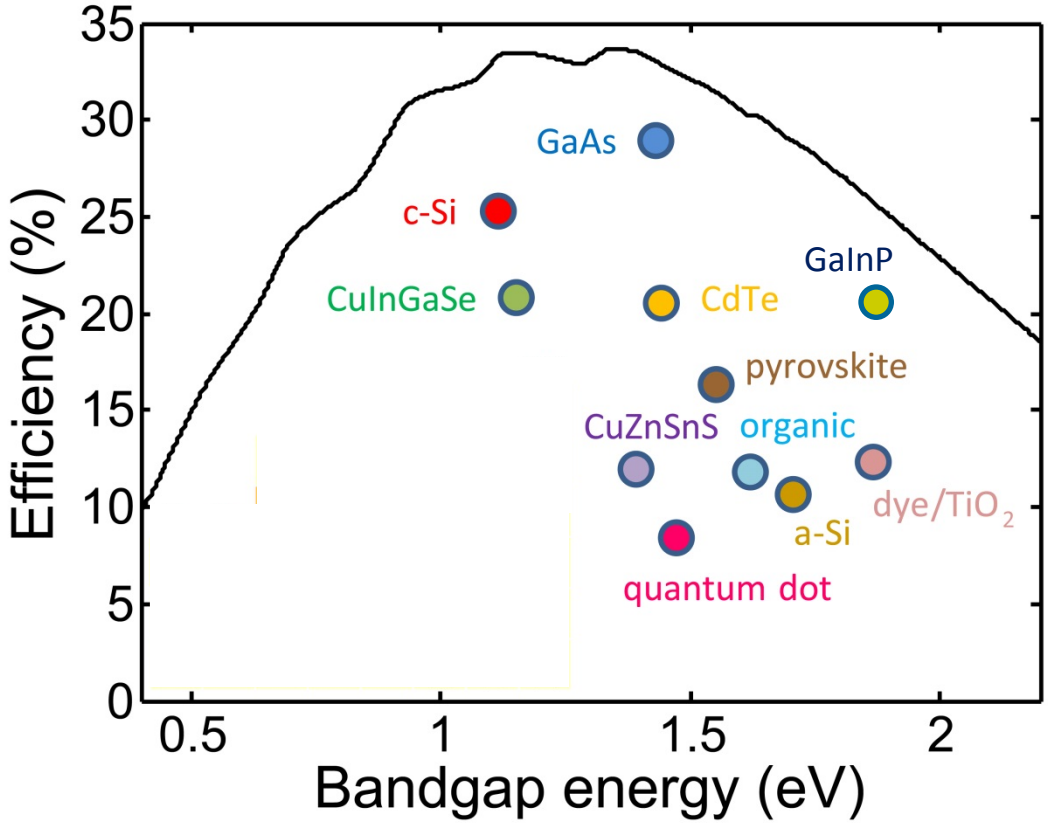
The dream of ages has been brought closer by the Bell System Solar Battery. It was invented at the Bell Telephone Laboratories after long research and first announced in 1954. Since then its efficiency has been doubled and its usefulness extended.

There's still much to be done before the battery's possibilities in telephony and for other uses are fully developed. But a good and pioneering start has been made.

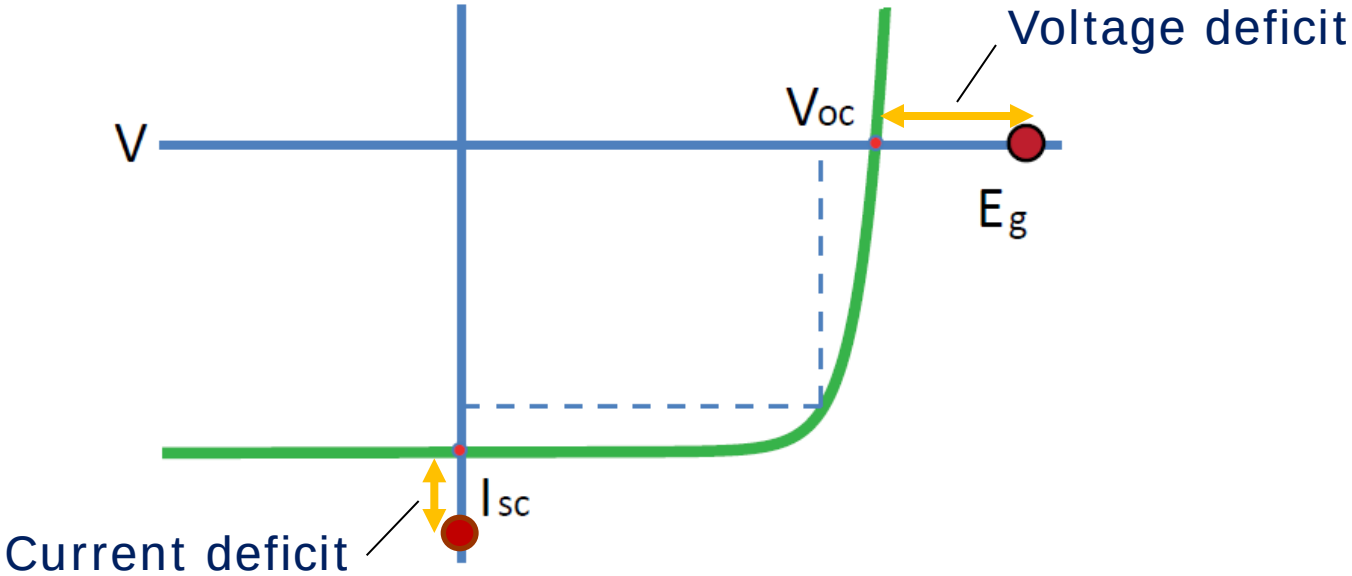
The progress so far is like the opening of a door through which we can glimpse exciting new things for the future. Great benefits for telephone users and for all mankind may come from this forward step in putting the energy of the sun to practical use.

BELL TELEPHONE SYSTEM

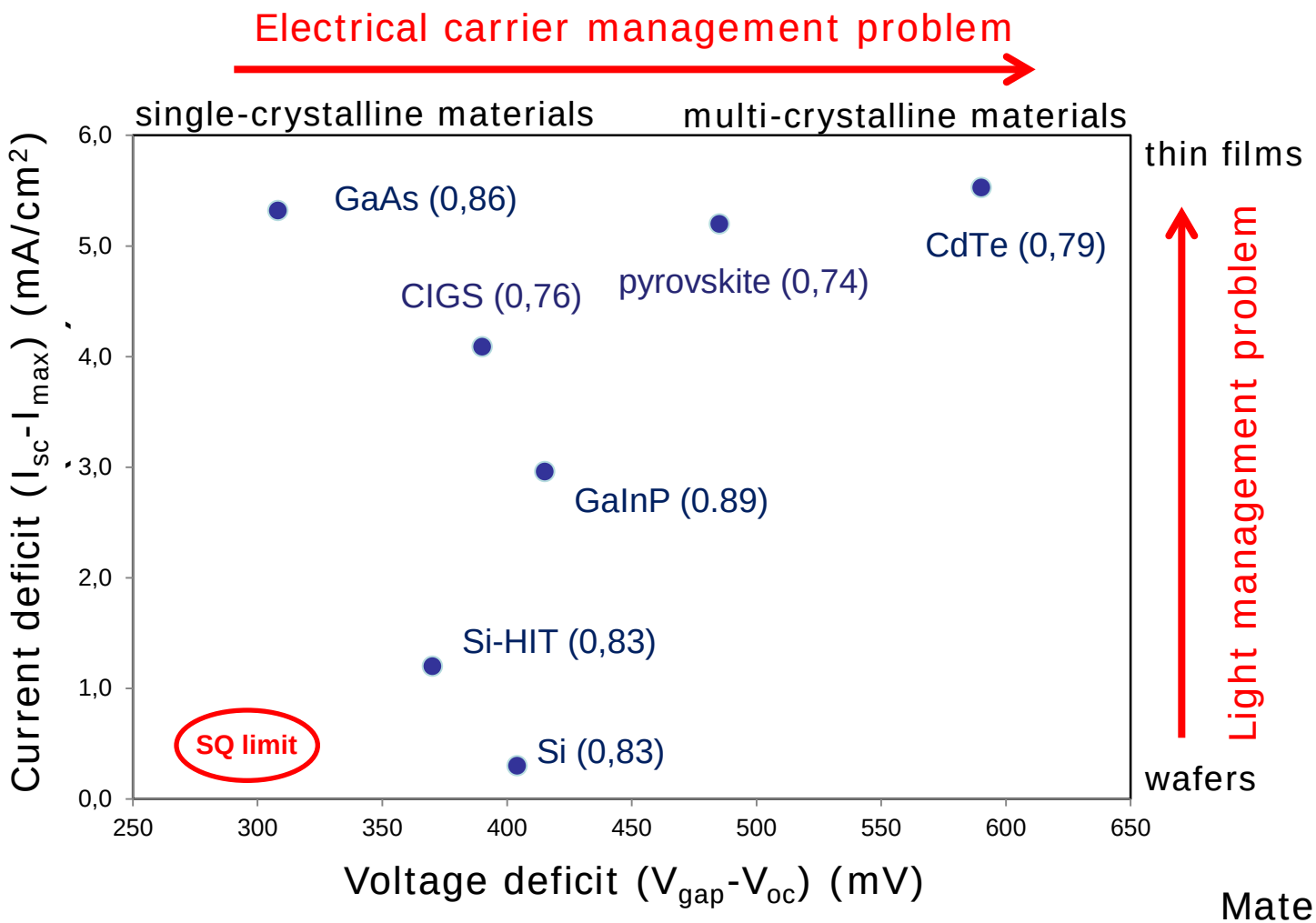
Record efficiencies of solar cell materials



Voltage and current deficit

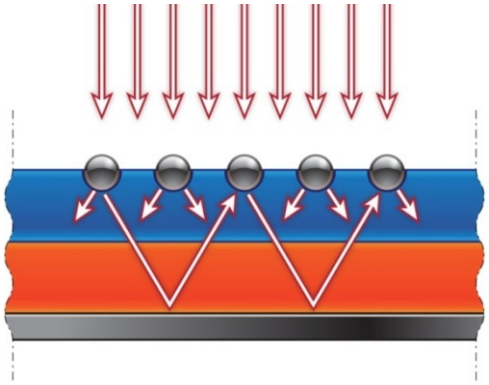


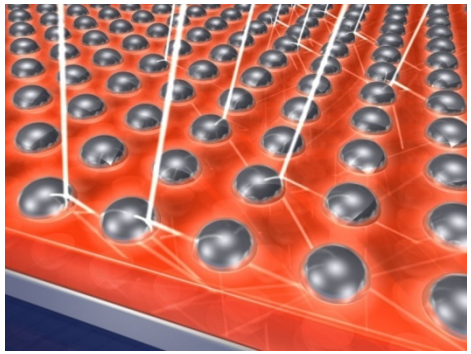
Voltage & current deficits

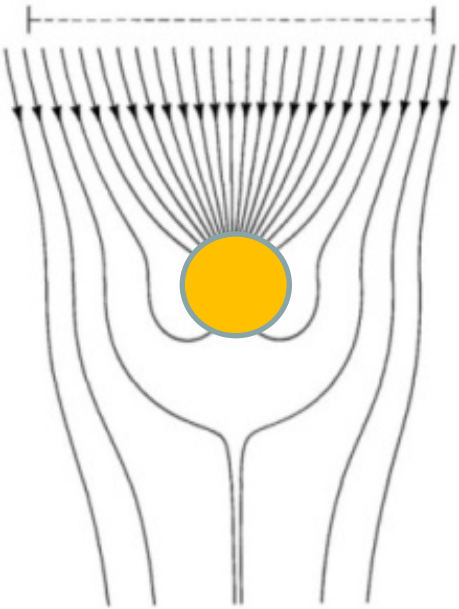


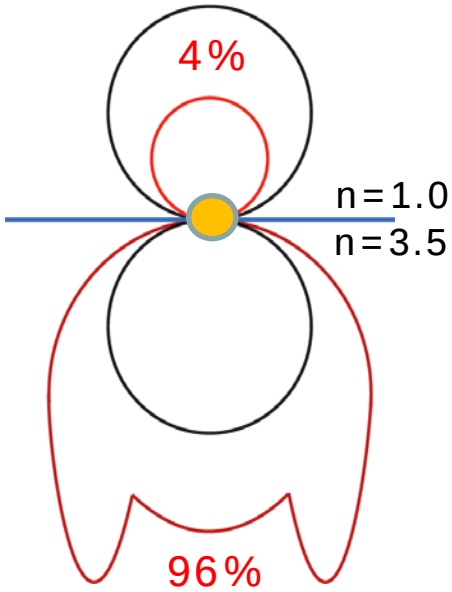
Materials with cell efficiency > 15%

Light coupling and trapping by resonant light scatterers





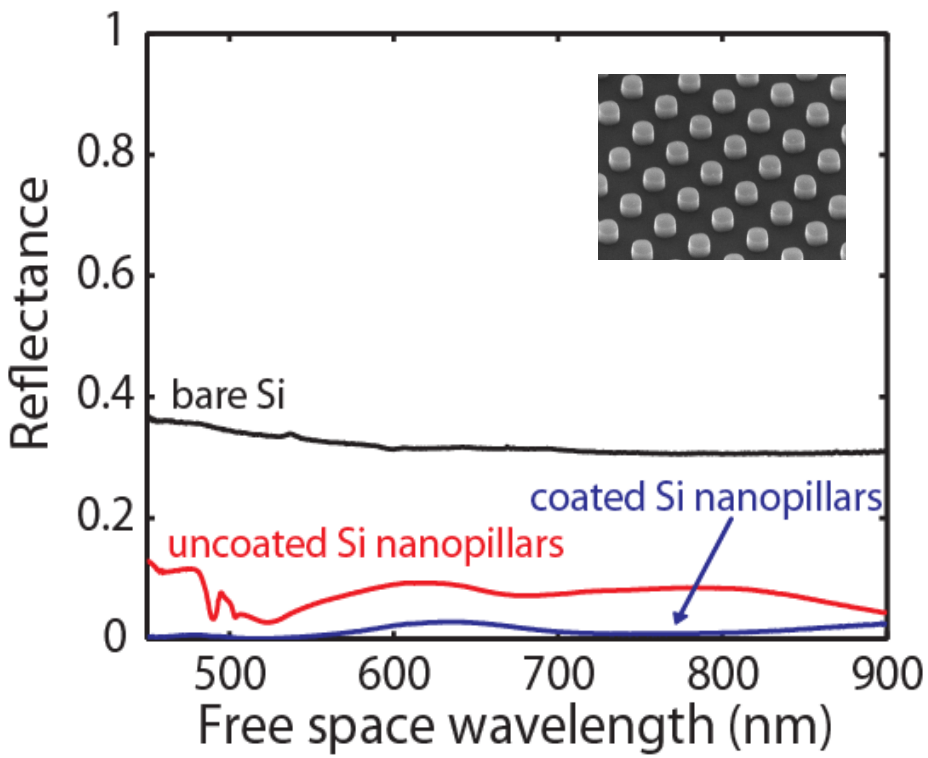


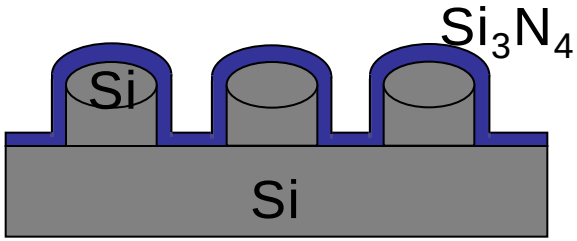


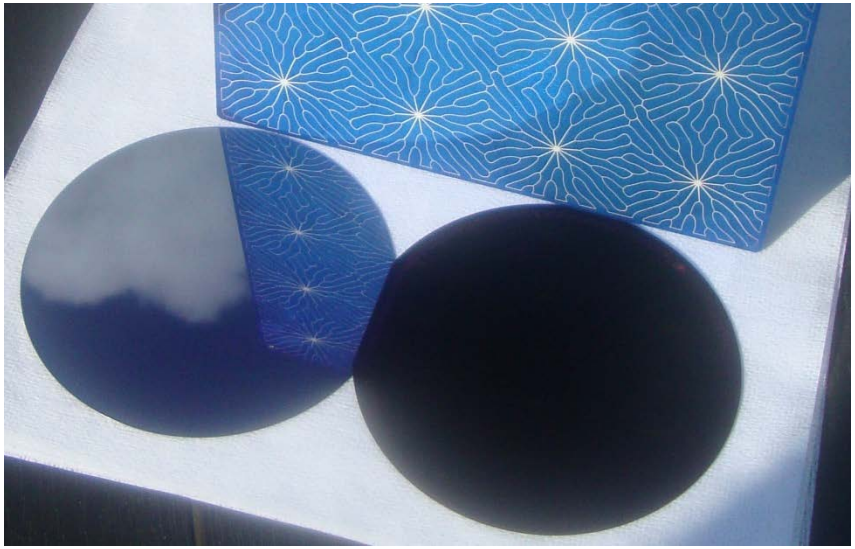
H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010)

Black silicon using leaky Mie resonances

Average reflectivity: 1.3%



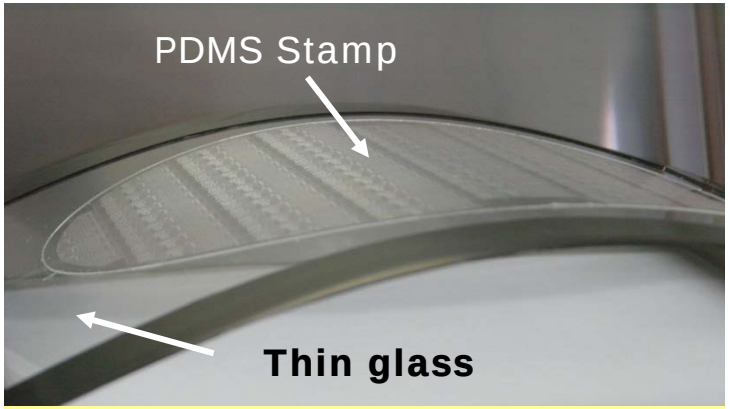




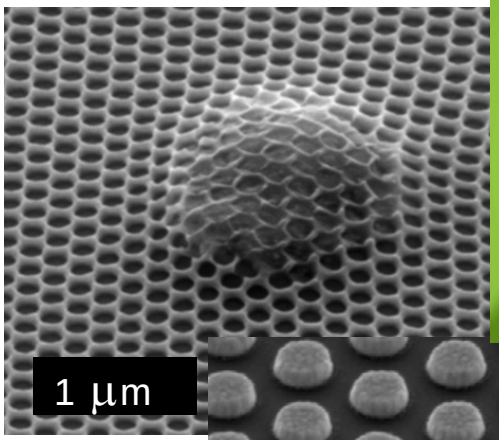
Piero Spinelli
Nature Comm. **3**, 692 (2012)

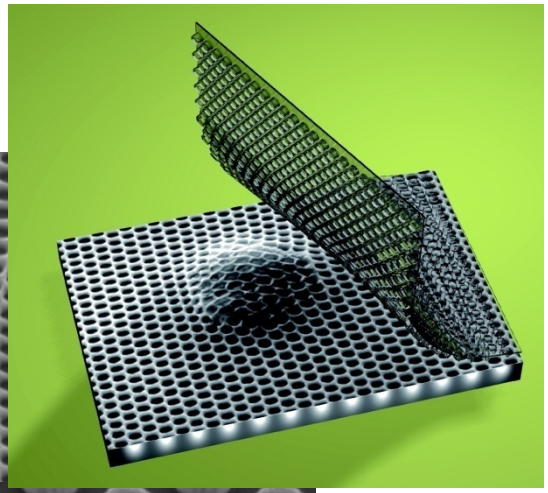
PHILIPS

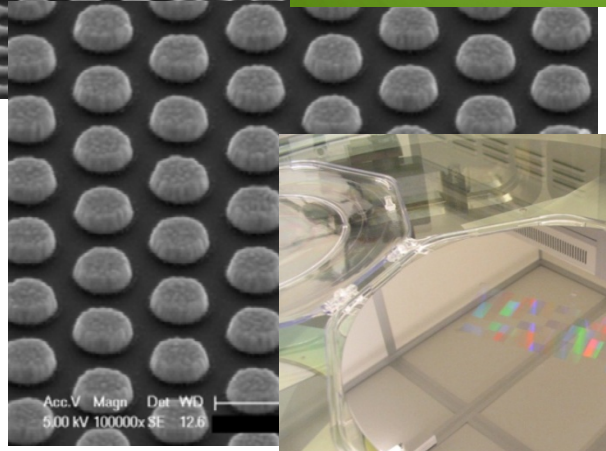
Substrate conformal imprint lithography

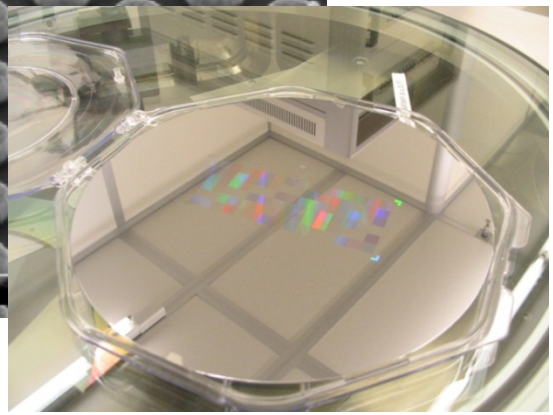


PDMS stamp (6”) on 200 µm AF-45 glass







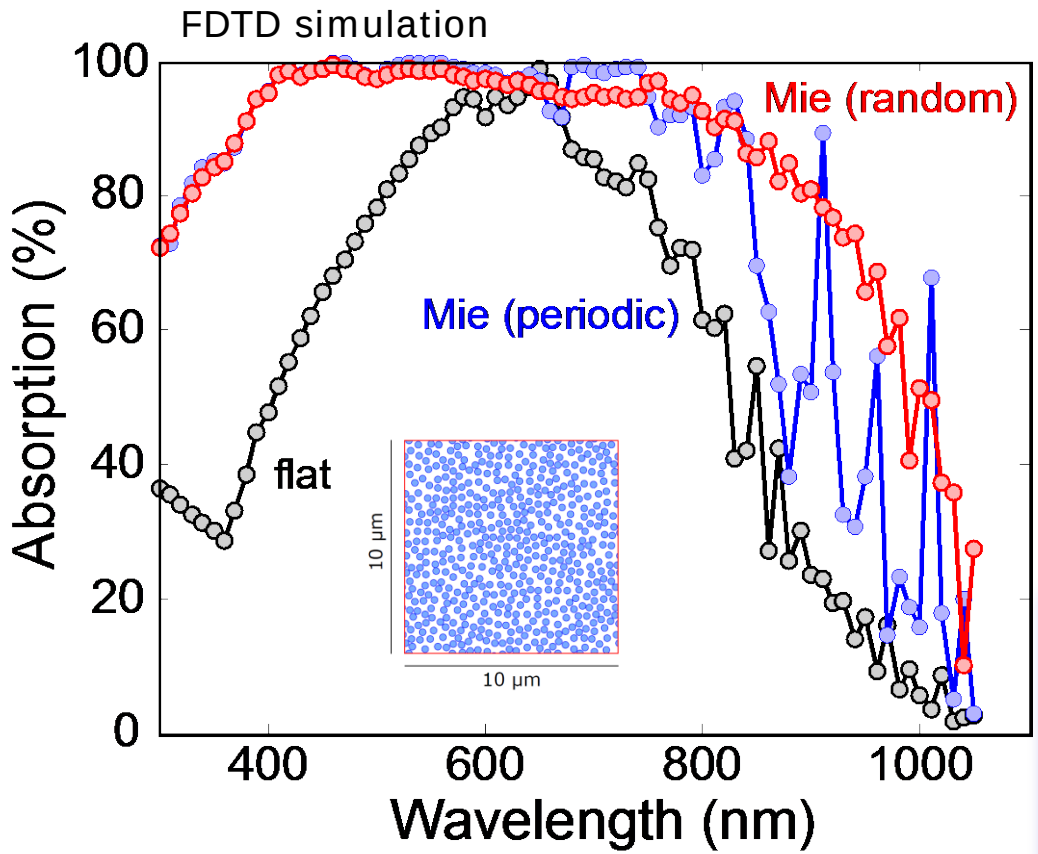


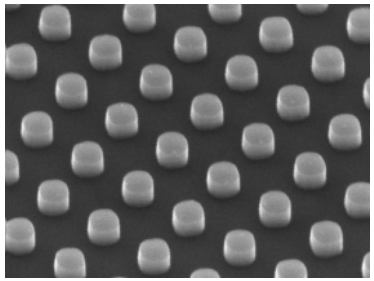
Full-wafer soft nano-imprint

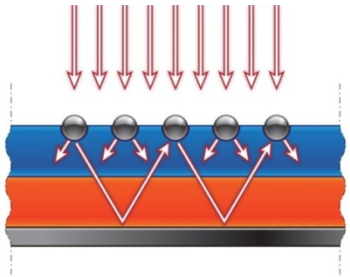
- Flexible rubber on thin glass
- Conform to substrate bow and roughness
- No stamp damage due to particles

Light trapping in 5 μm crystalline Si slab

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





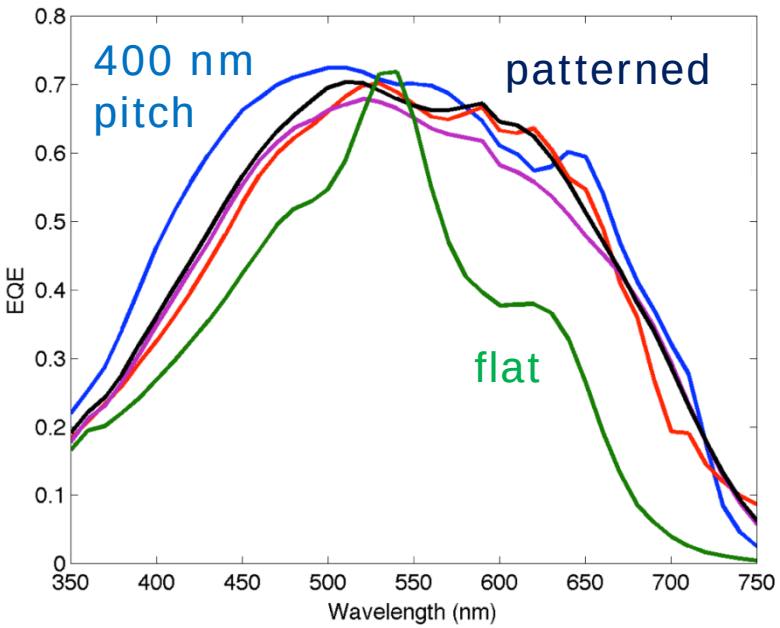


Enables 20 μm thick Si solar cell with efficiency > 23 %

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

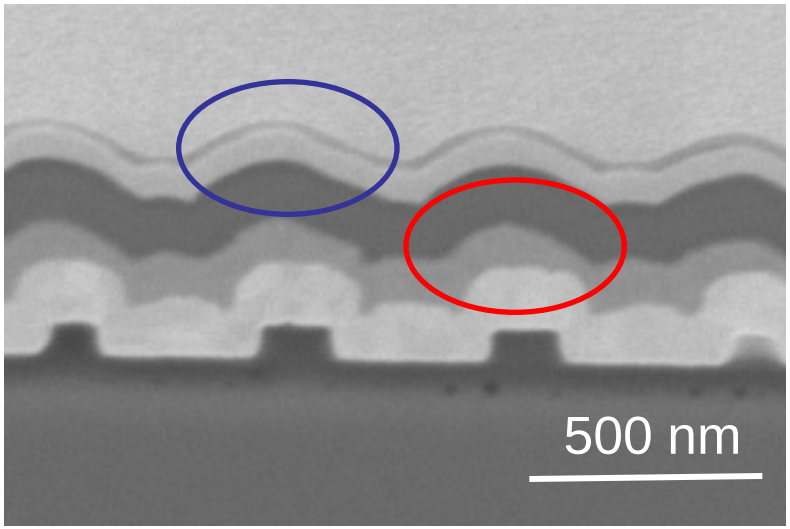
Ultra-thin a-Si:H solar cell: 90 nm *i*–layer

Experiment

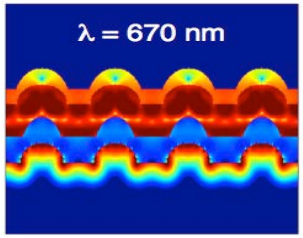


The solar cell as an optical integrated circuit

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

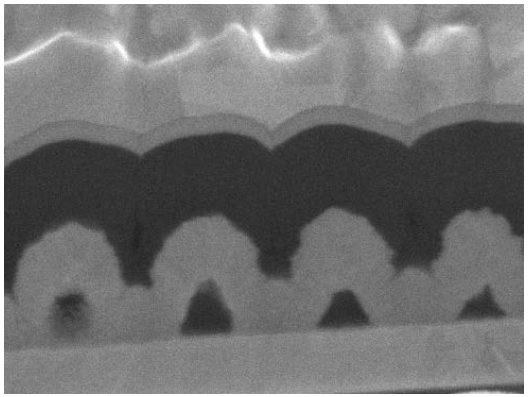


ITO
a-Si:H
ZnO:Al
Ag
sol-gel

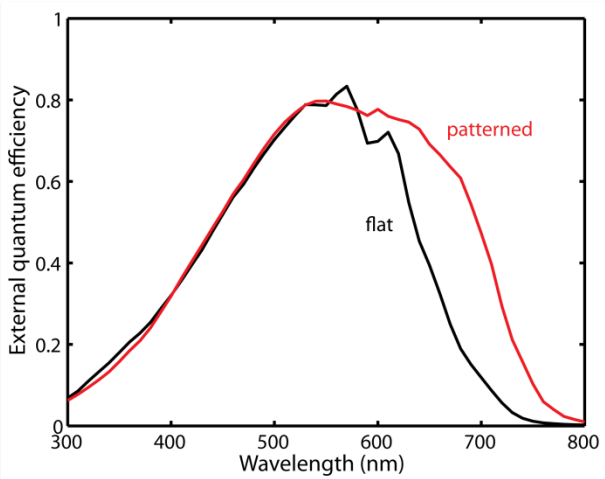


Vivian Ferry, Claire van Lare
Nano Lett. **11**, 4239 (2011), Optics Express **21**, 20739 (2013)

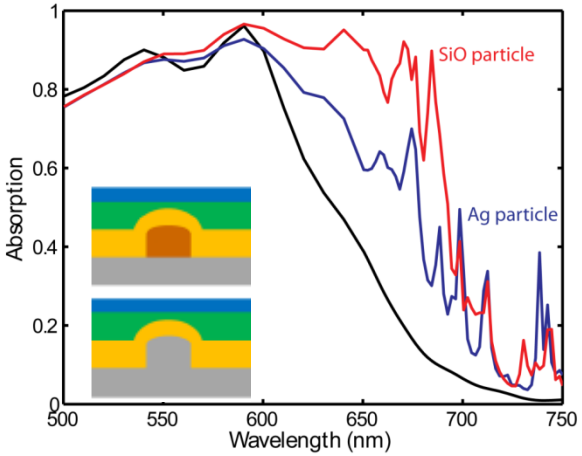
Dielecrtic light trapping nanostructures (a-Si:H)



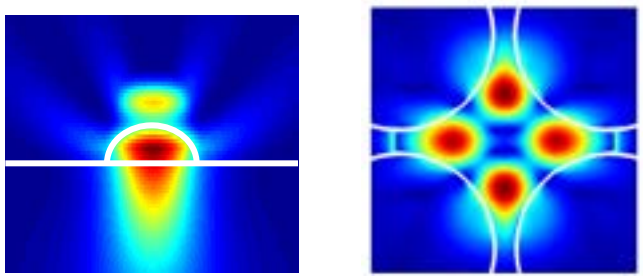
Dielectric scattering pattern



Efficient light trapping

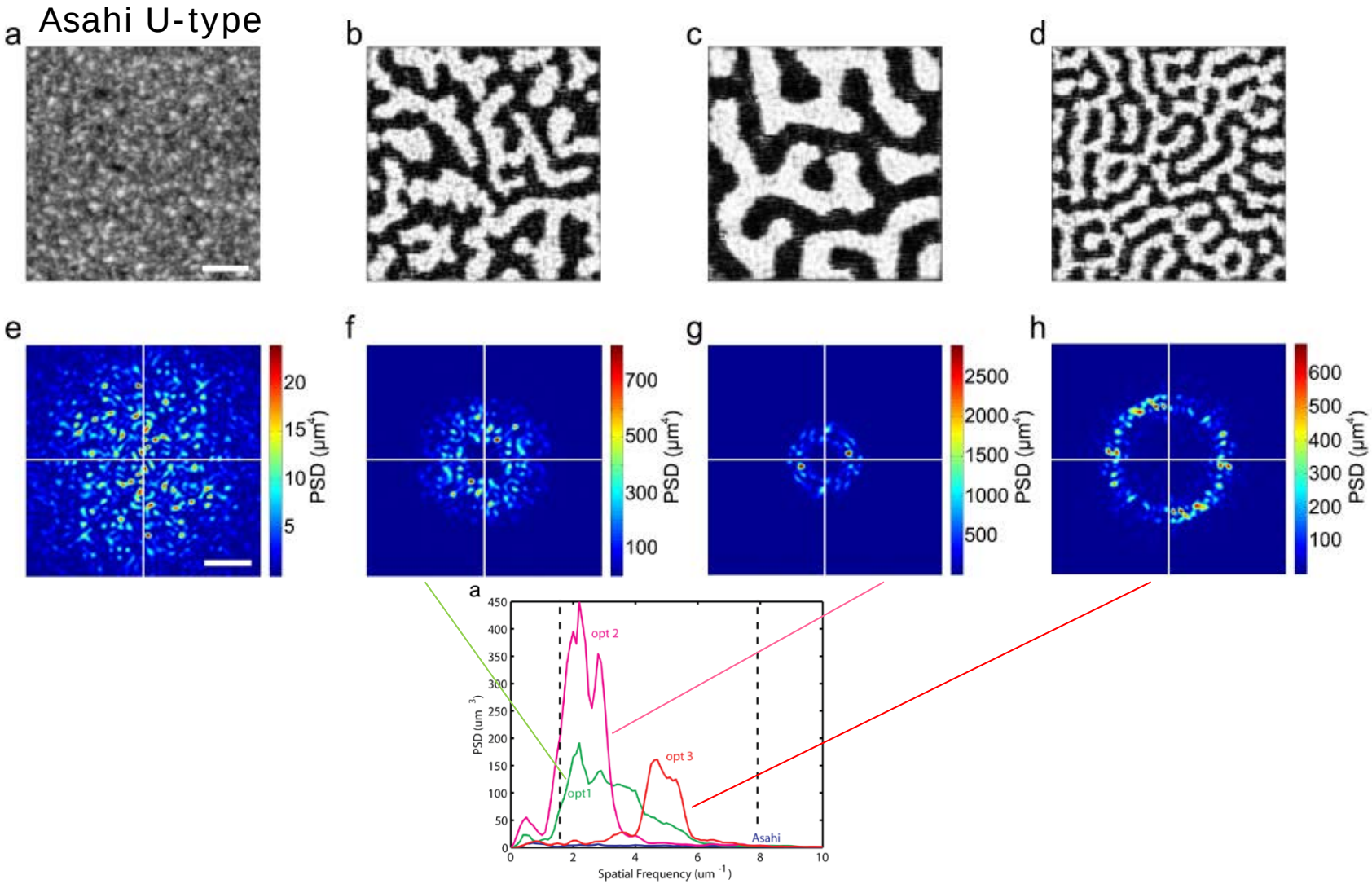


Dielectric outperforms metallic

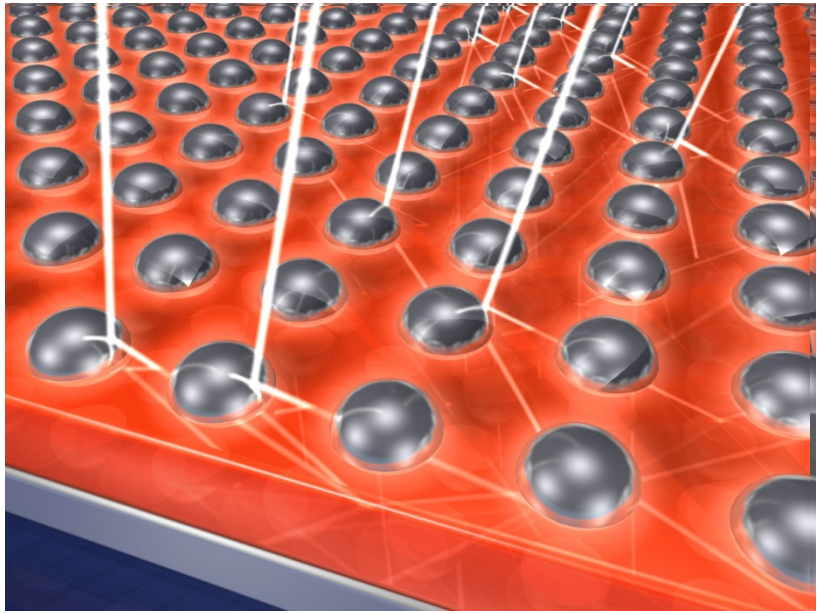


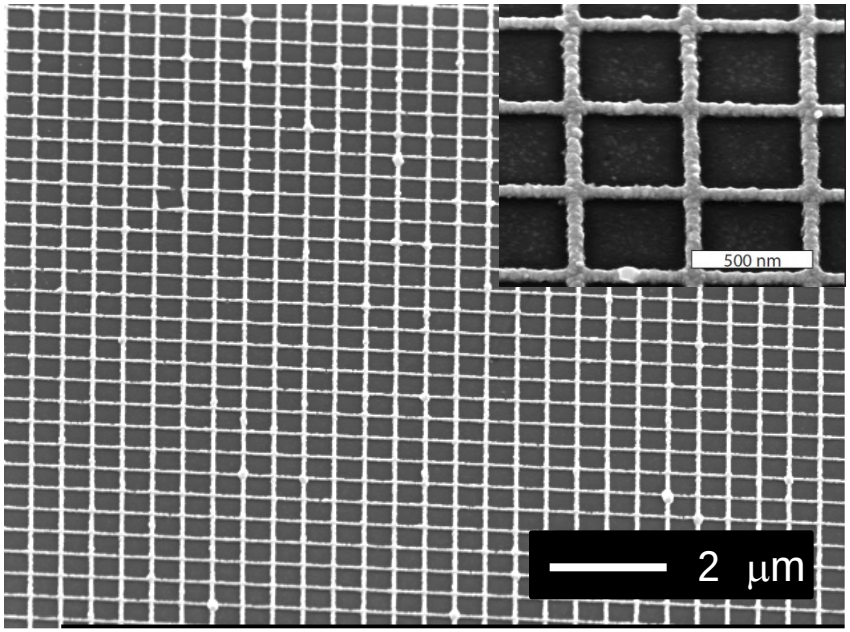
Resonance in AZO and a-Si

Optimizing spatial frequency of scattering pattern



Transparent conductive silver nanowire network

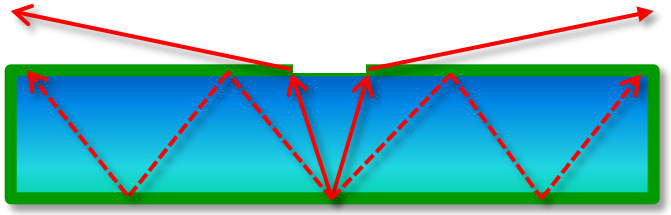




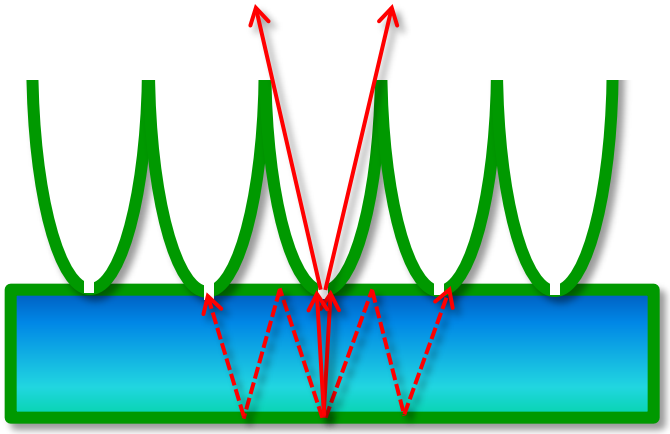
Ag nanowire network fabricated with electron beam lithography
width: 45-110 nm
height: 60 nm

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

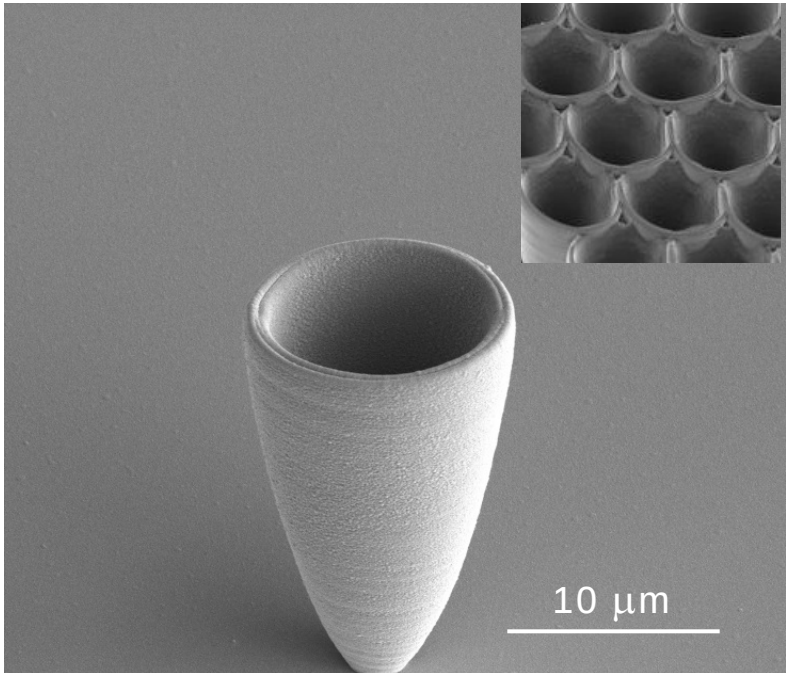
Enhanced light trapping by limiting emission angle



max: $4n^2$

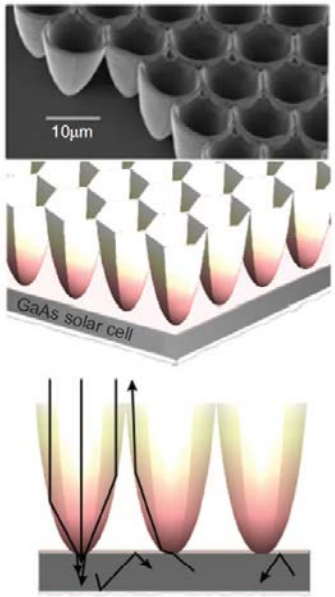


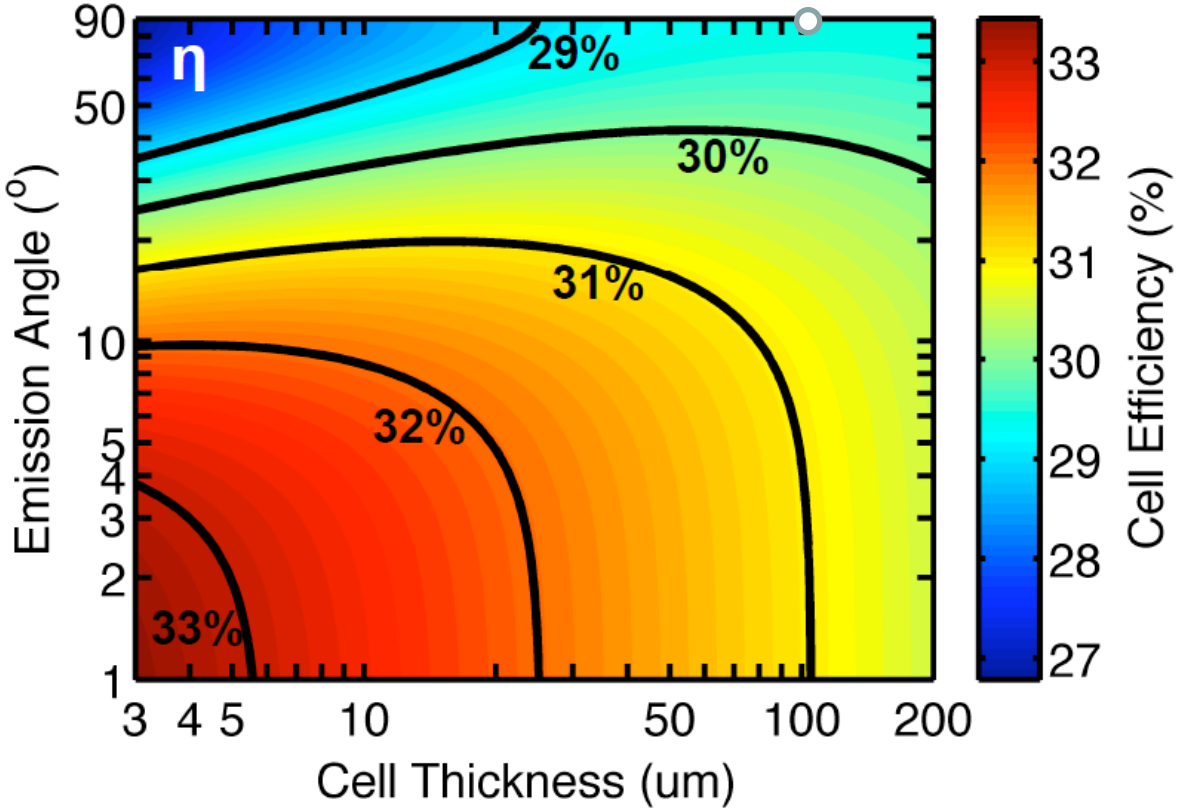
max: $>4n^2$



Appl. Phys. Lett. **99**, 151113 (2011)
Emily Kosten, Light Sci. Appl. **2**, e45 (2013)

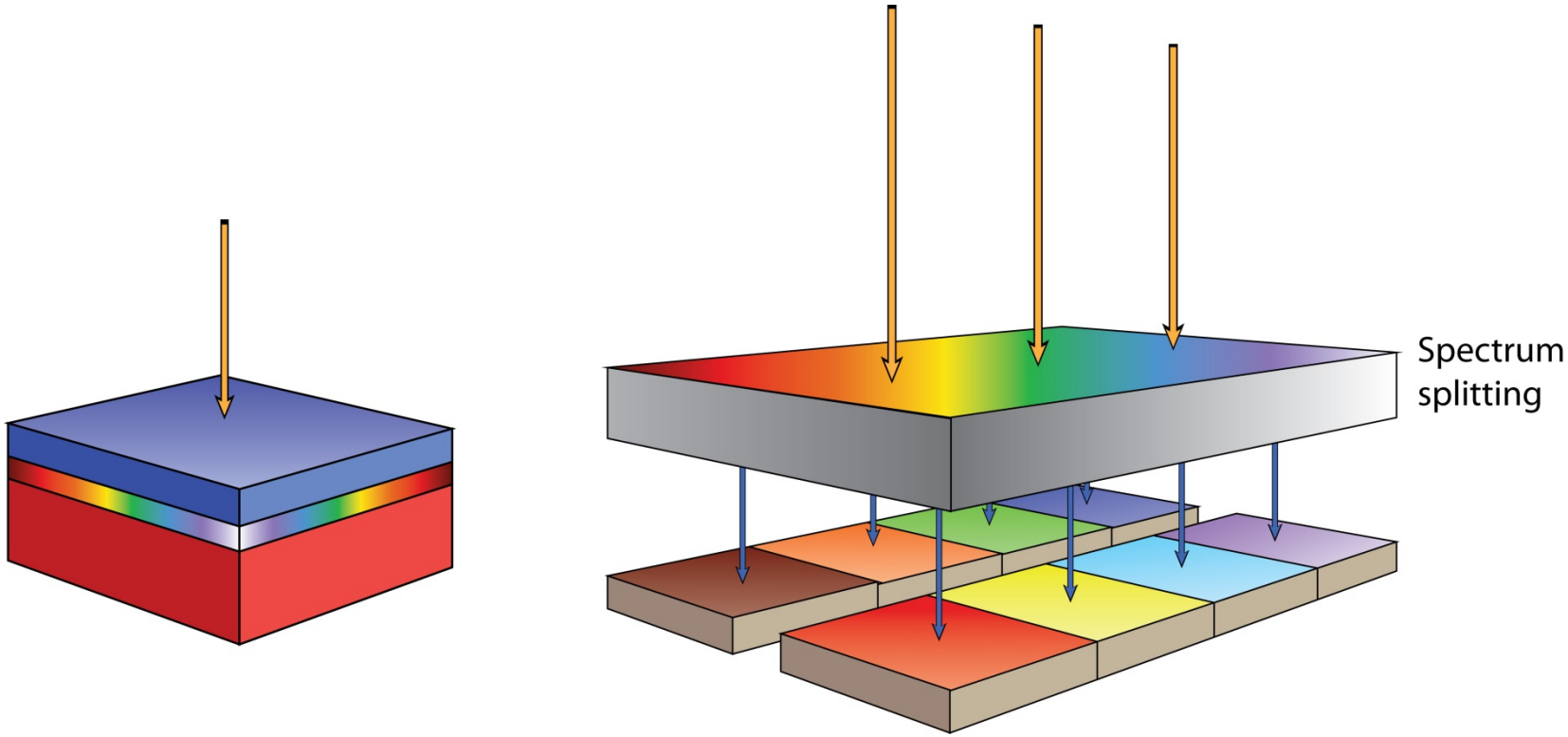
Effect of angle restriction on Si solar cells





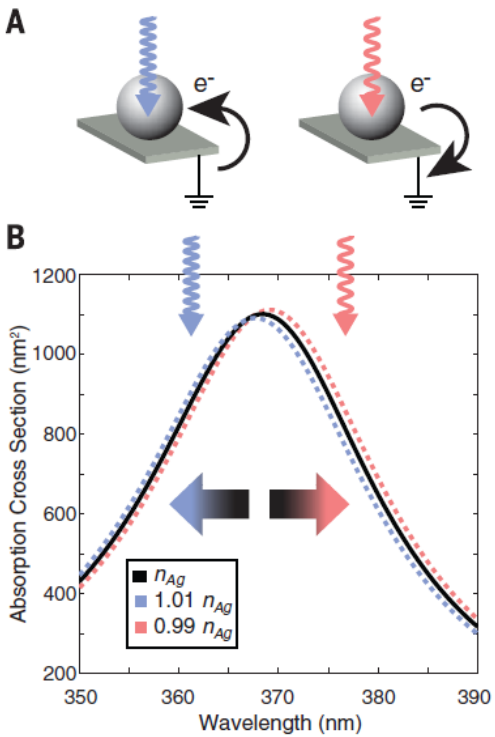
Emily Kosten, Bonna Newman
J. Photovolt. **4**, in press (2014)

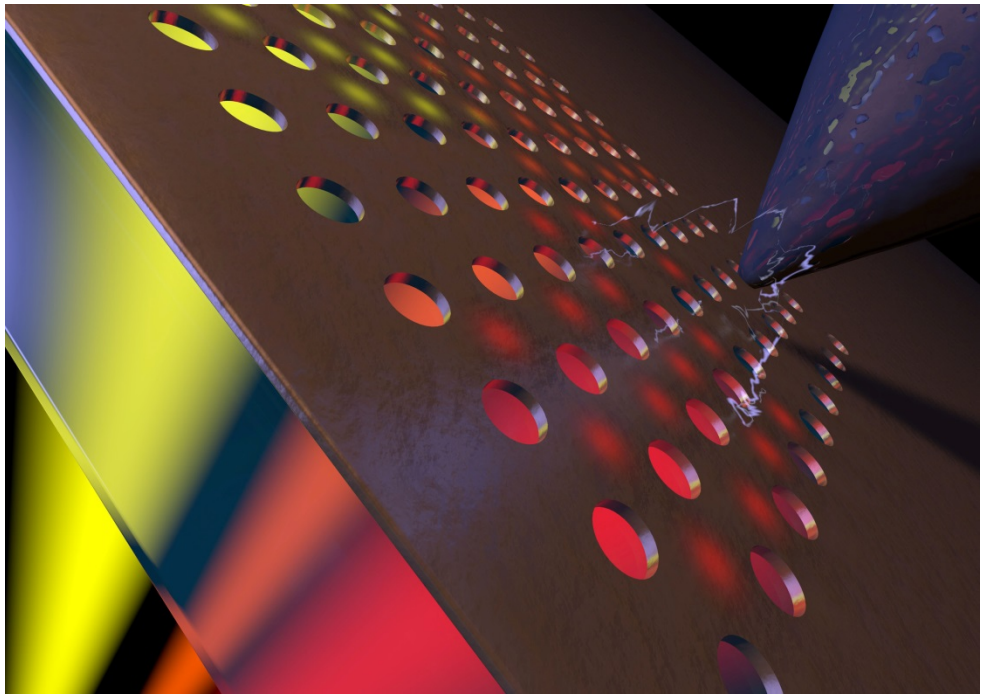
Parallel multi-junction solar cell architecture



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

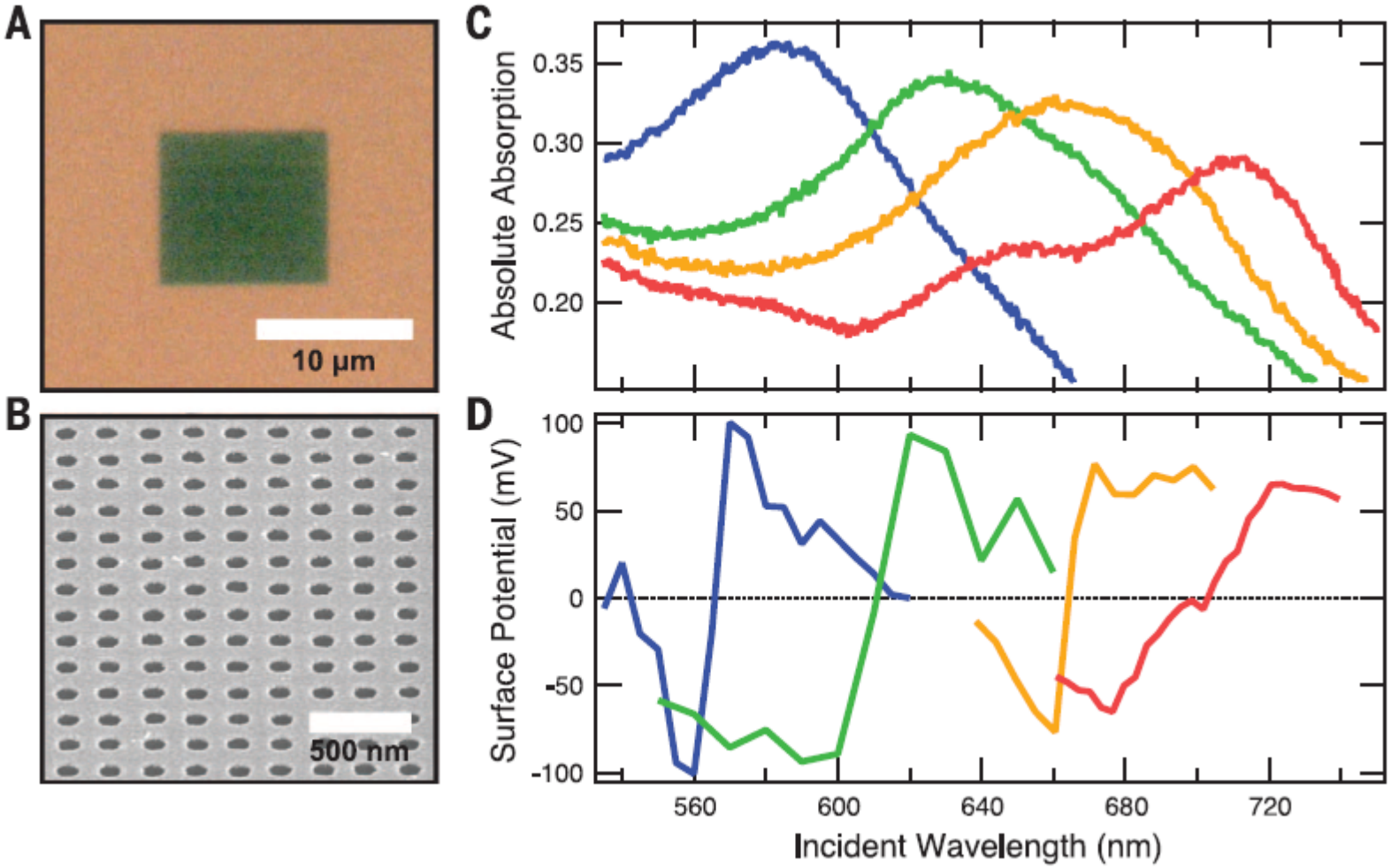
Plasmo-electric effect in metal nanostructures





Jorik van de Groep, Matt Sheldon
Science **346**, 828 (2014)

Plasmo-electric effect in metal nanostructures



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Jorik van de Groep, Matt Sheldon
Science **346**, 828 (2014)

Light Management in New Photovoltaic Materials Team

Solardam consortium
AMOLF-UvA-VU

www.erbium.nl

Thank you