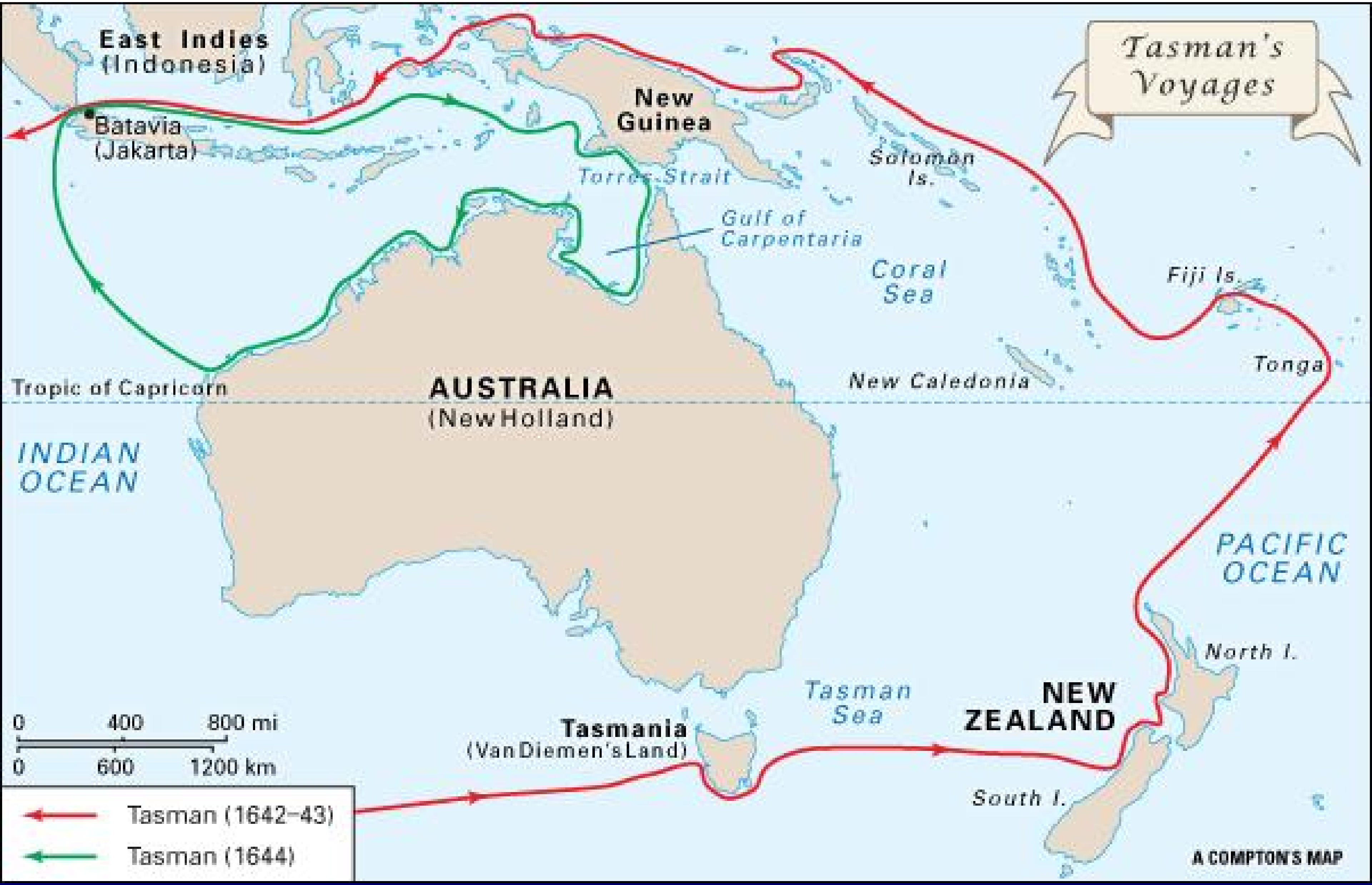


Abel Tasman: the first Dutchman trying to find Australia (1642)

Light Management in New Photovoltaic Materials

Albert Polman

Center for Nanophotonics, AMOLF
Amsterdam, The Netherlands

AMOLF

Verena Neder
Mark Knight
Andrea Cordaro
Tom Veeken
Magda Sola Garcia
Joris Schefold
Jorik van de Groep
Mark Knight
Piero Spinelli
Claire van Lare

ECN

Paula Bronsveld
Stefan Luxembourg
Wim Sinke

HZB Helmholtz Zentrum Berlin

Guanchao Yin
Martina Schmid

SCIL Nanoimprint solutions

Marc Verschuuren

THE UNIVERSITY OF TEXAS AT AUSTIN

Nasim Estakheri
Andrea Alu

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Harry Atwater

Major challenges in PV research/technology

1) Cost reduction of a factor ~4 or more (towards 0.01 €/kWh)*
higher efficiencies, lower materials consumption,
ultra-fast processing

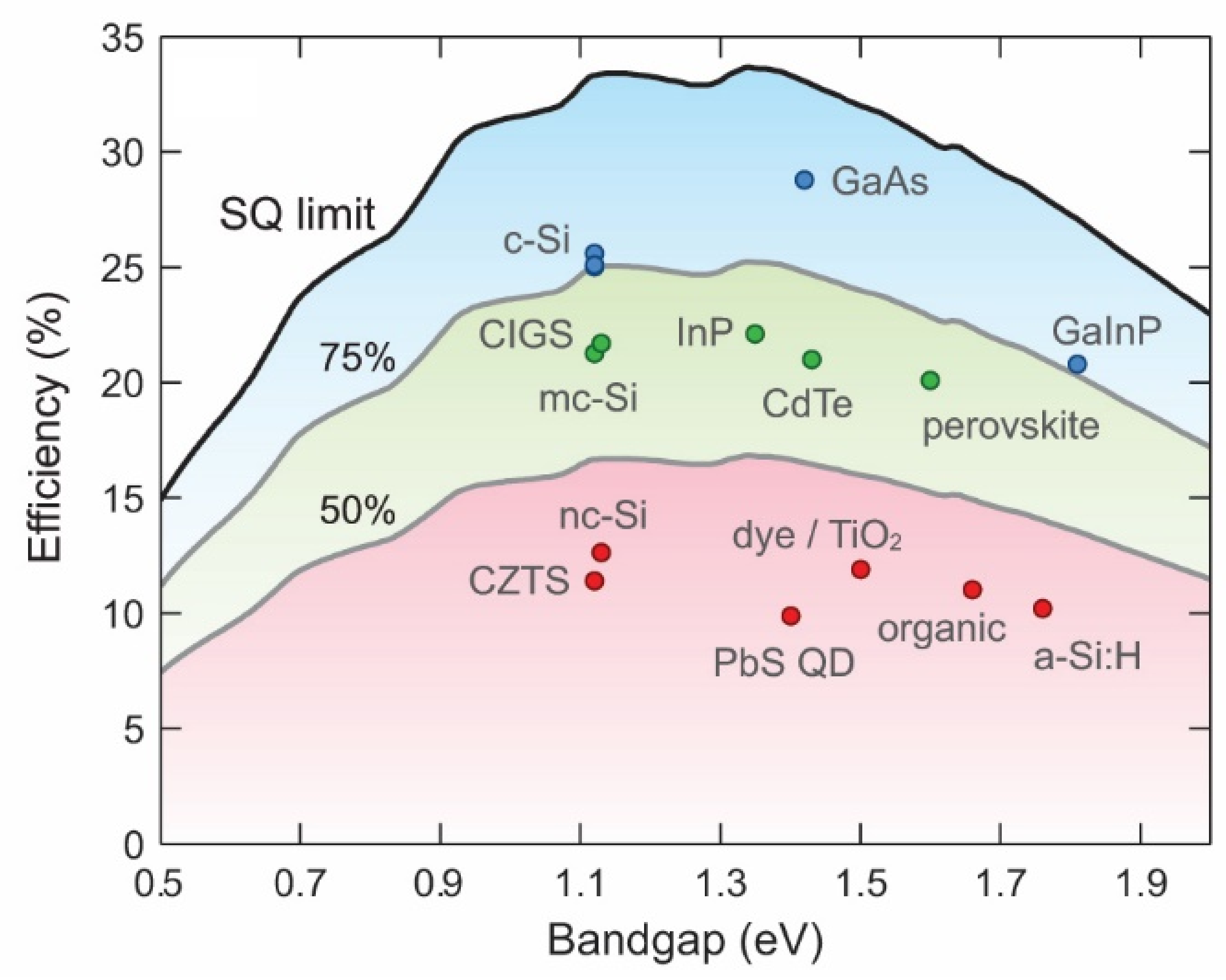
2) Develop new PV applications using tailored PV elements
flexible/ultra-light/colored/special shape

This can not be achieved using a "natural" Moore's-law type evolution.

This requires breakthroughs in physics, chemistry, materials science & engineering

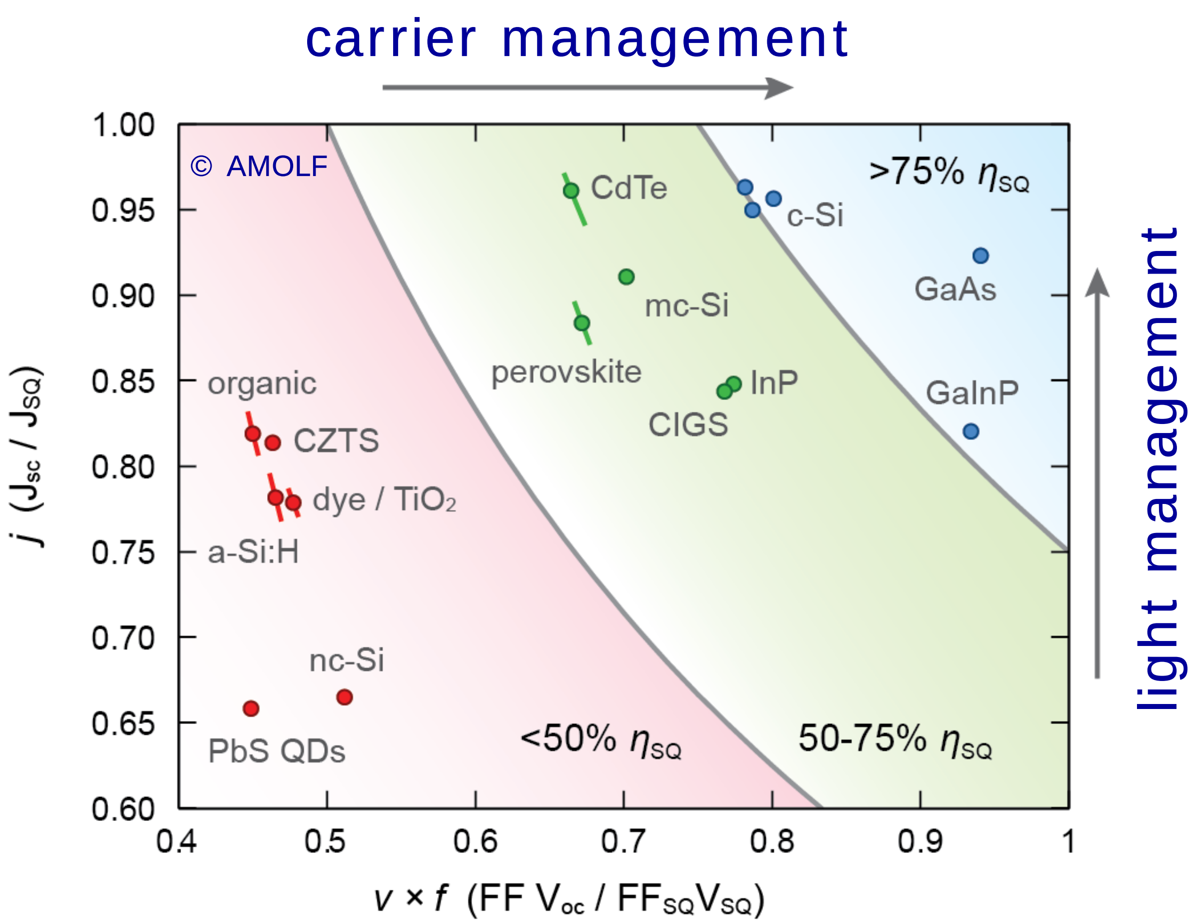
(*) R.C. Armstrong *et al*., Nature Energy **1**, 1 (2016)
N.M. Haegel *et al*., Science **357**, 141 (2017)
F. Creutzig *et al.*, Nature Energy **2**, 17140 (2017)

Record solar cell efficiencies

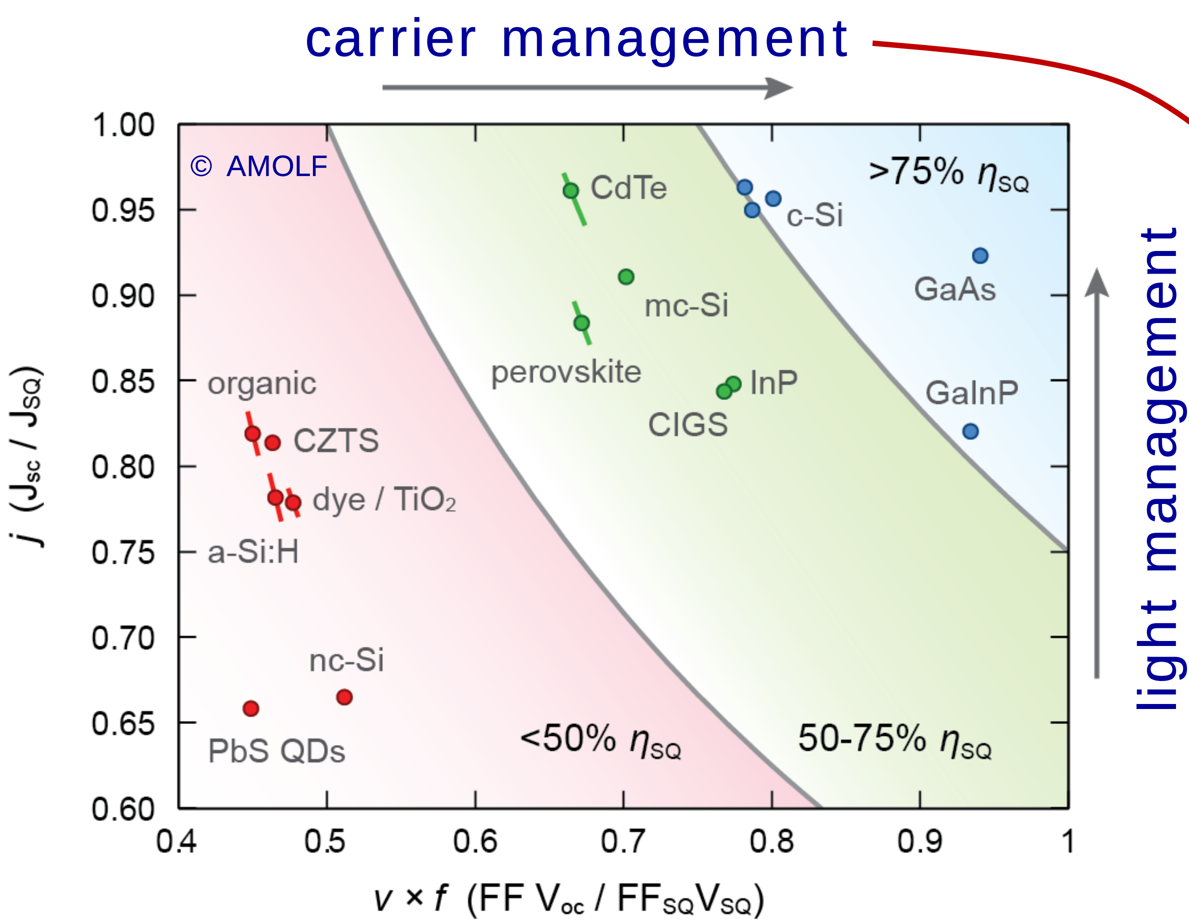


Science **352**, 207 (2016)

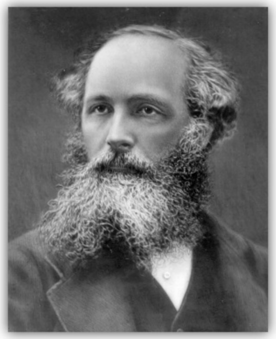
J_{sc} and V_{oc} relative to SQ limit for each material



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



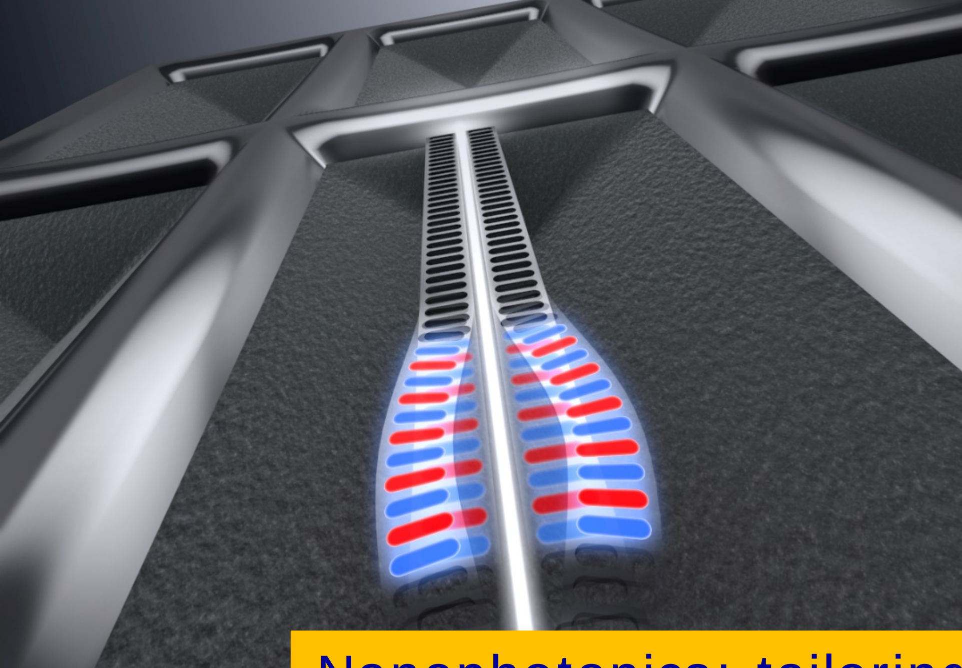
Schrődinger

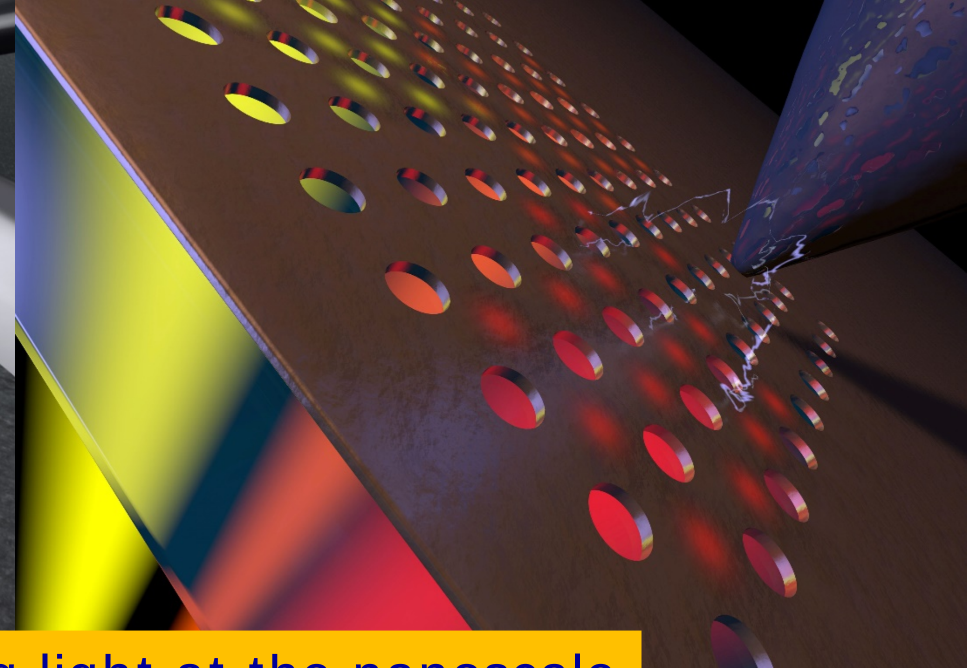


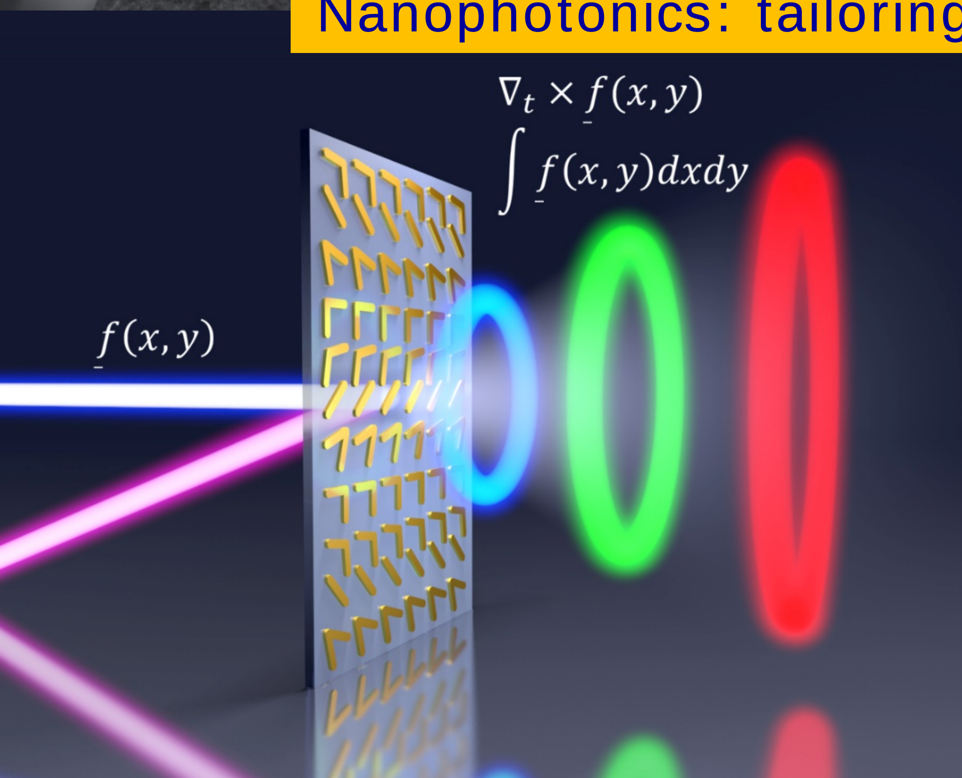
Maxwell

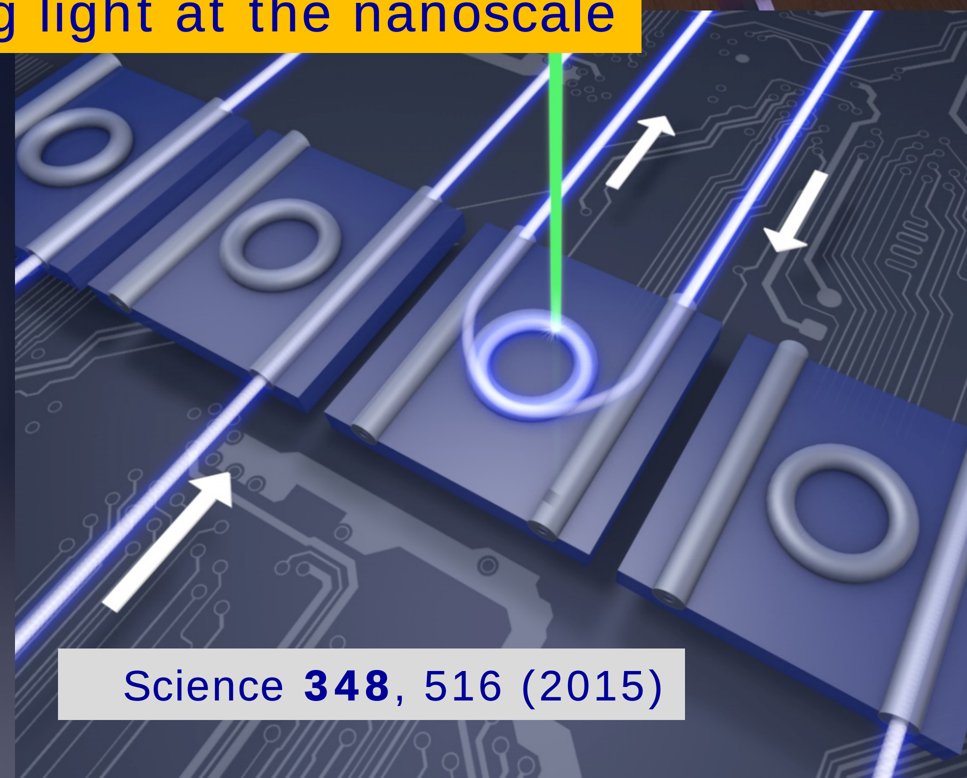
Science **352**, 207 (2016)

Nanophotonics: tailoring light at the nanoscale









Science **348**, 516 (2015)

Light Management in New Photovoltaics Materials (LMPV)

Albert Polman
Bruno Ehrler
Esther Alarcon Llado
Erik Garnett

Light management
LMPV
in new photovoltaic materials

Total PV research staff: 35-40
PhD students
Postdocs
Master students
+ 25 nanophotonics

AMOLF

LMPV research strategy

1) Light management in wafer/thin-film materials (25-30%)
    - Light trapping and concentration, angular restriction

2) Hybrid organic/inorganic solar cells (>30%)
    - Singlet fission, exceed SQ limit for single-gap cell

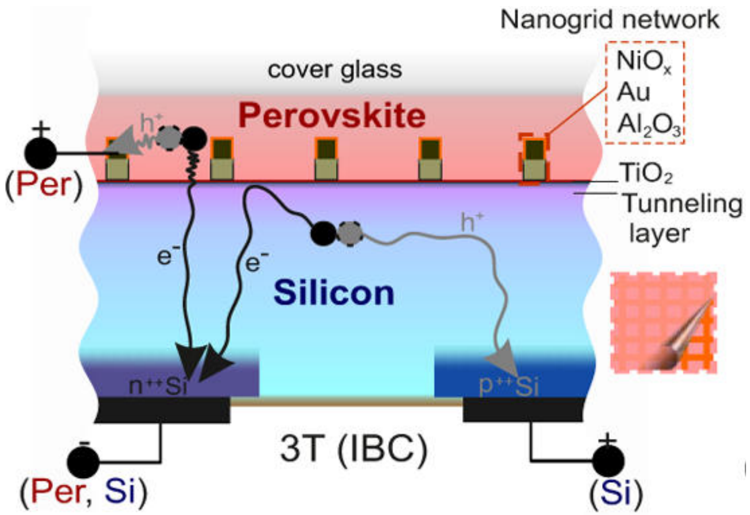
3) Dual-junction solar cells on silicon (>35%)
    - Perovskite on Si, III-V on Si

4) Multi-junction architectures (>35%)
    - Nanowires, parallel tandems

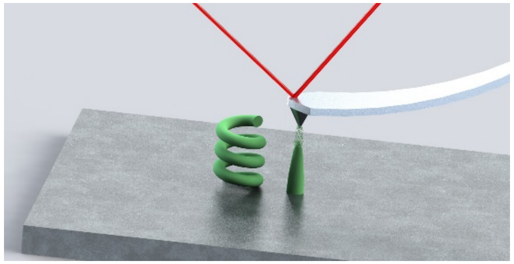
5) Alternative geometries
    - Flexible PV, colored PV, building-integrated PV

(+3D additive manufacturing, soft imprint, nanoscale spectroscopies)

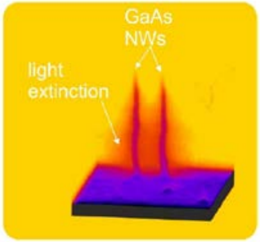
LMPV research highlights

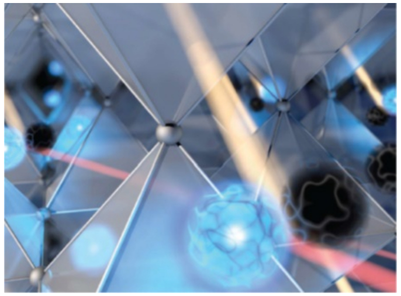


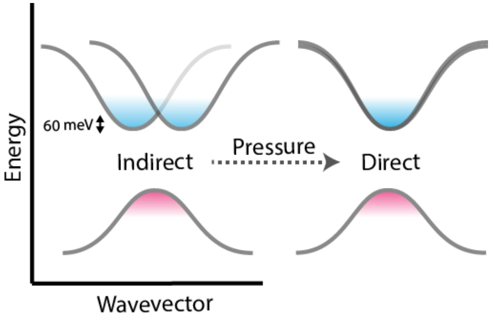
Nanoscale perovskite/Si contact design (Garnett group, Nano Lett. 2017)



Light capture in GaAs nanowires imaged (Alarcon group + EPFL, ACS Photon 2017)





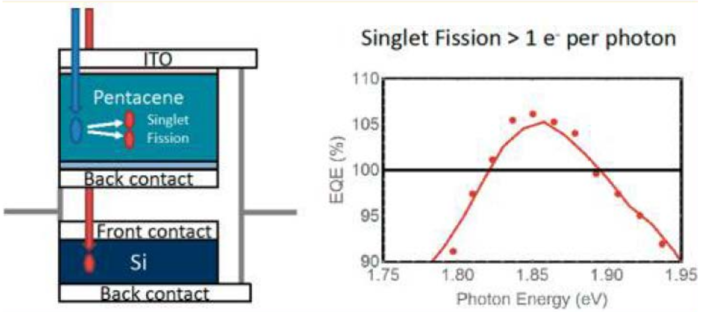


Bandstructure explains high efficiency of perovskites (Ehrler group, Energy Env. Sci. 2017)

AMOLF

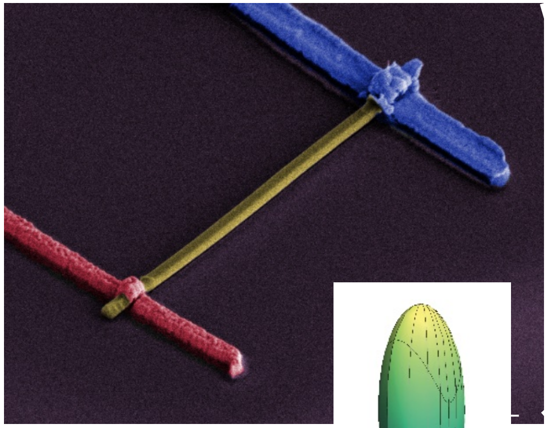
Credits: Erik Garnett, Bruno Ehrler, Esther Alarcon Llado

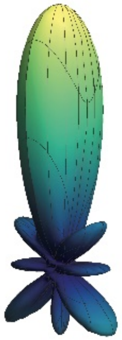
LMPV research highlights

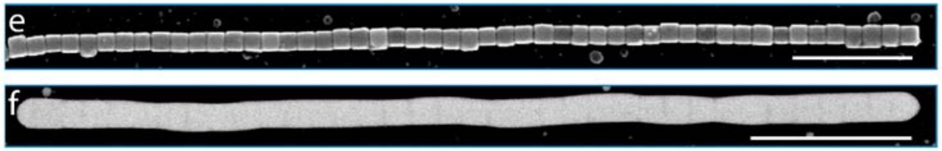


105% quantum efficiency in silicon–pentacene solar cell (Ehrler group + Cambridge, ACS Energy Lett. 2017)

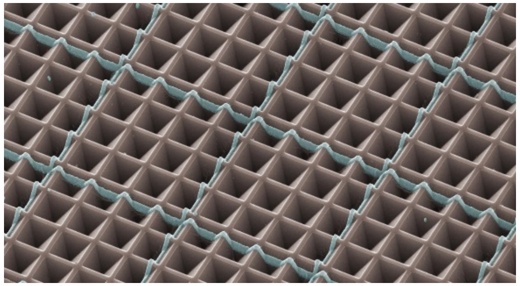
Limits and losses in nanowire solar cells quantified PV (Garnett group, Nature Nanotech. 2016)







Self-assembled single-crystalline Ag nanowires (Garnett & Polman groups + ECN, Adv. Mater. 2017)

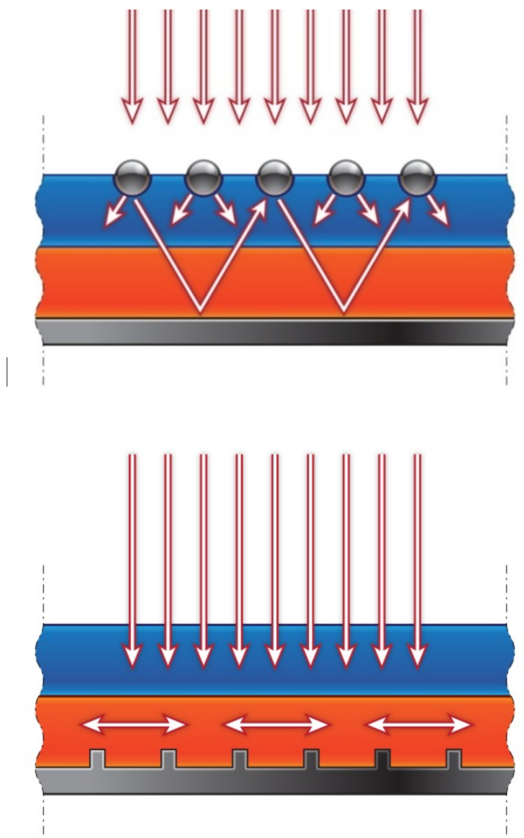


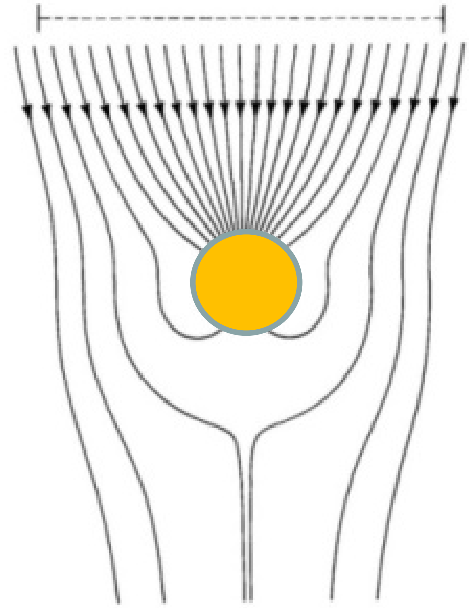
AMOLF

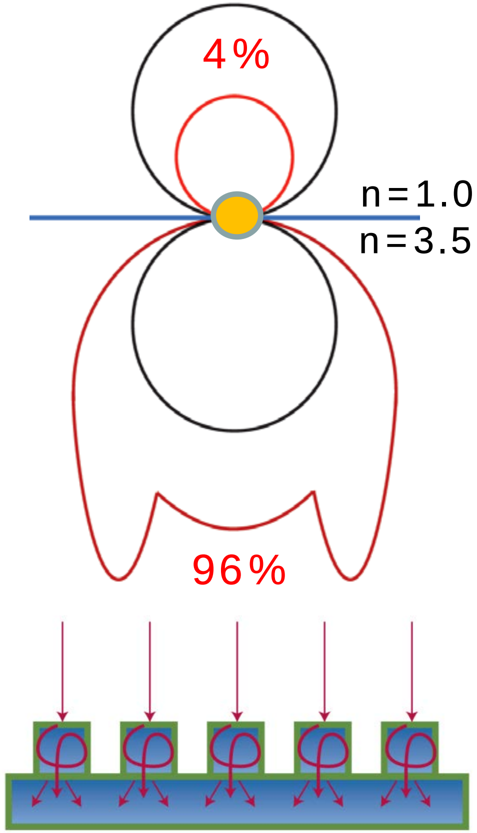
Credits: Erik Garnett, Bruno Ehrler, Esther Alarcon Llado

The scattering solar cell

Light coupling and trapping by resonant light scatterers







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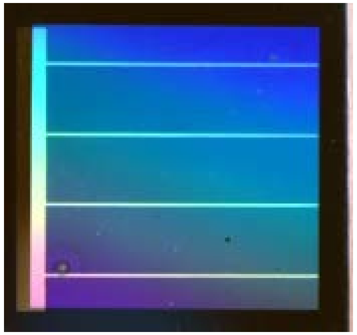
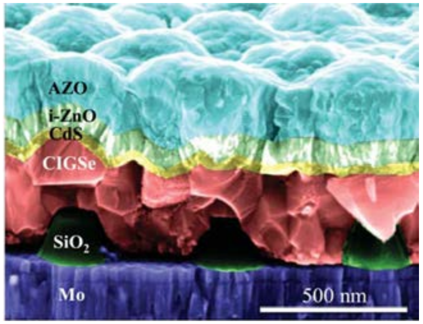
H.A. Atwater and A. Polman
Nature Mater. **9**, 205 (2010), Nature Mater. **11**, 174 (2012)

Outline

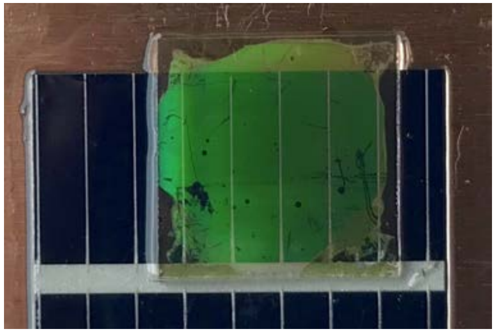
Plasmonic solar cells
transparent conductors



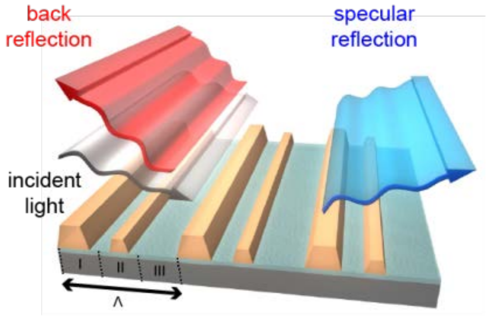
Scattering solar cells
light trapping



Colored solar cells
BIPV



Metasurfaces for PV
new designs



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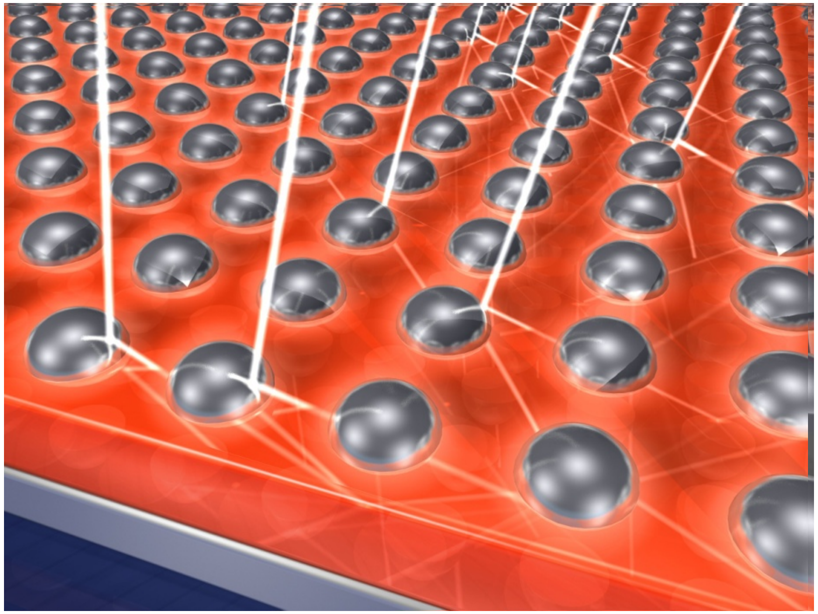
Transparent conductive silver nanowire network



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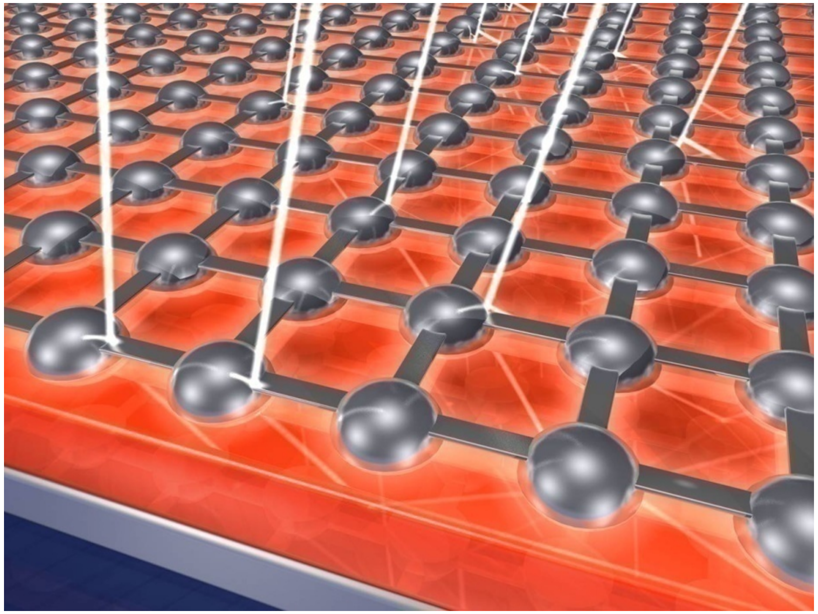
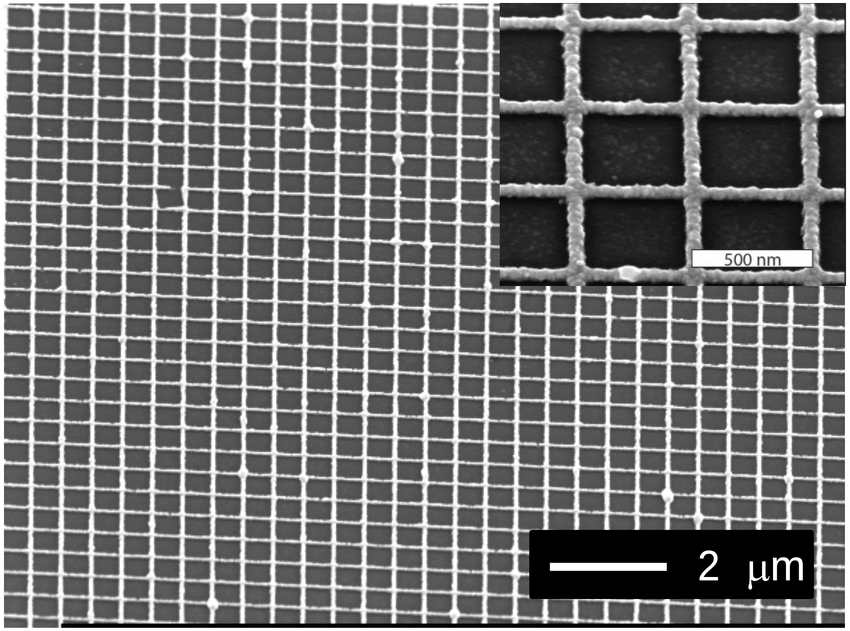
Jorik van de Groep, Piero Spinelli, Mark Knight
Nano Lett. **12**, 3138 (2012), Nano Energy **30**, 398 (2016)

Transparent conductive silver nanowire network



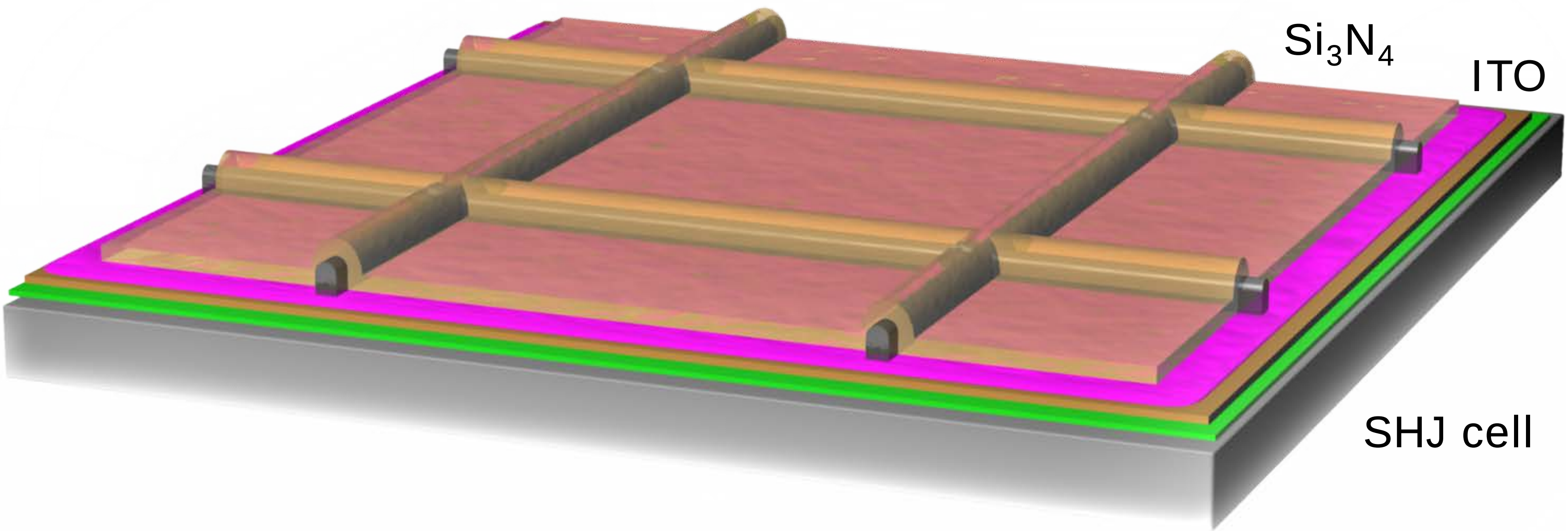


Ag nanowire network fabricated with electron beam lithography
width: 45-110 nm
height: 60 nm

Jorik van de Groep, Piero Spinelli, Mark Knight

Nano Lett. **12**, 3138 (2012), Nano Energy **30**, 398 (2016)

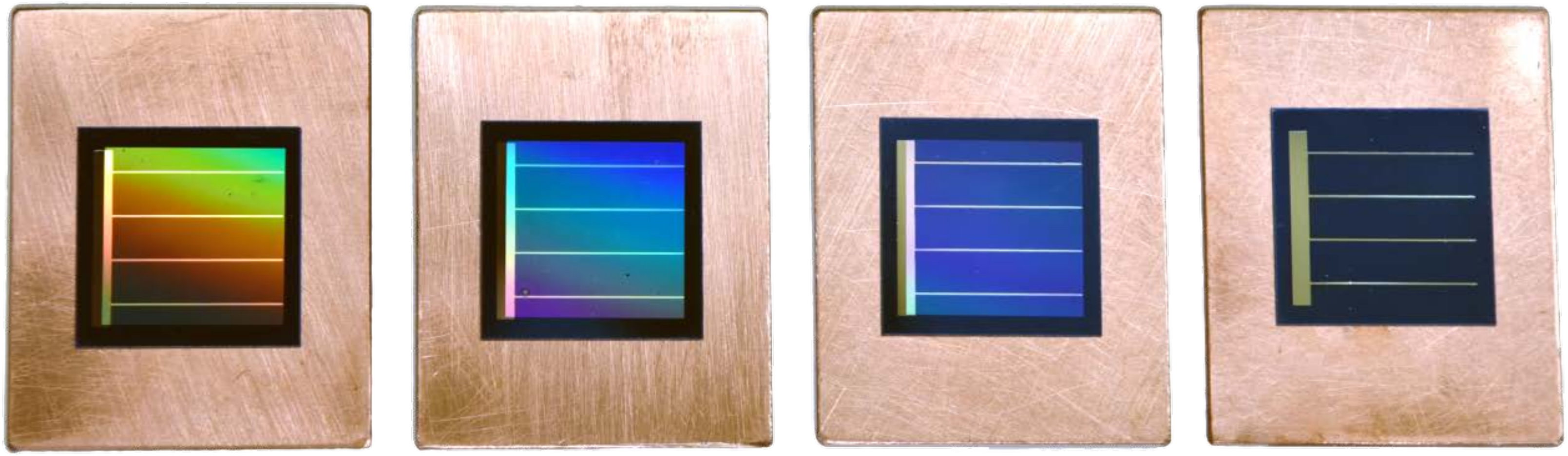
Ag nanowire hybrid electrode design



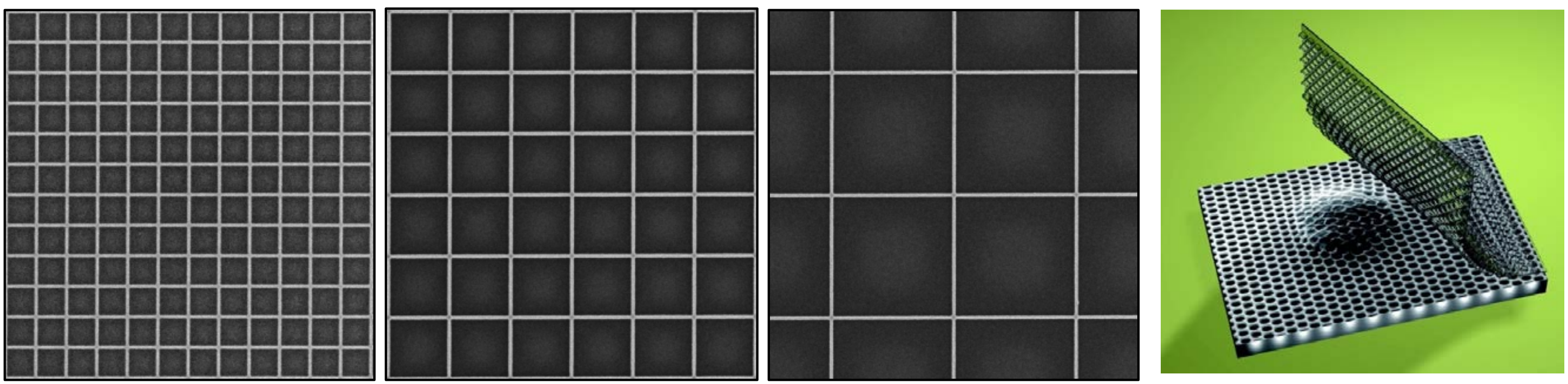
Ag nanowire patterned Si heterojunction solar cells

NW pitch : 1 µm | 2 µm | 4 µm | ITO only

1 cm



1 µm



Width: 80 nm
Height: 120 nm

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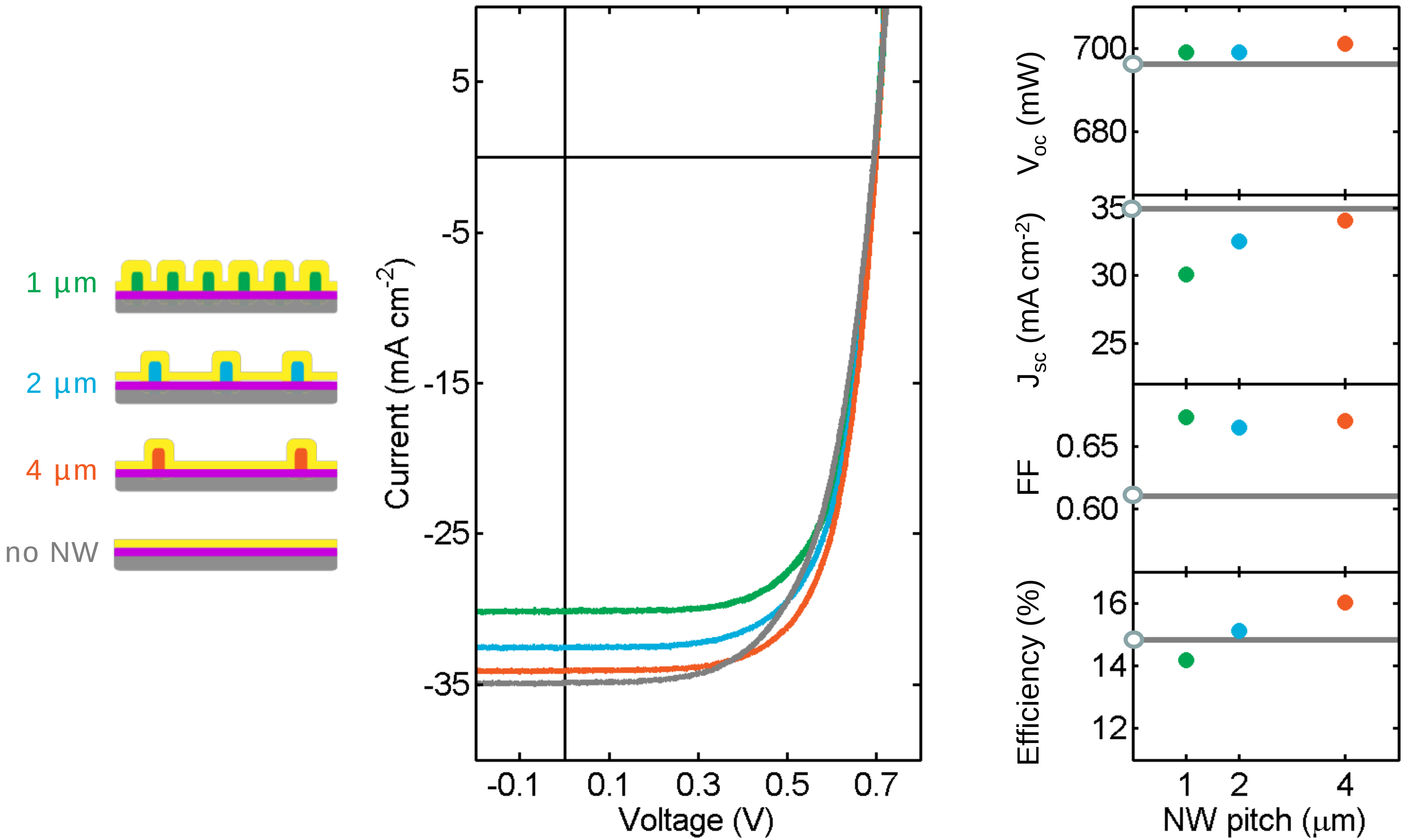
Mark Knight
Nano Energy **30**, 398 (2016)

Ag nanowire patterned Si heterojunction solar cells



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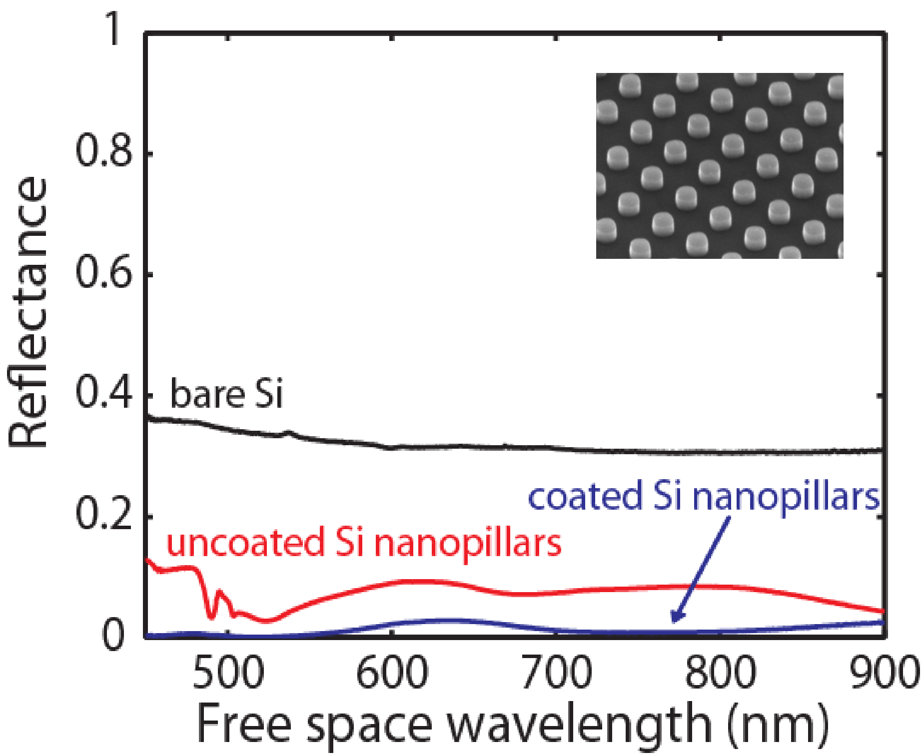
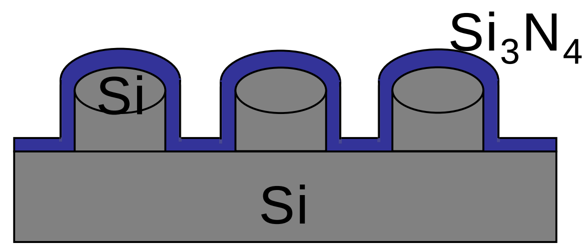
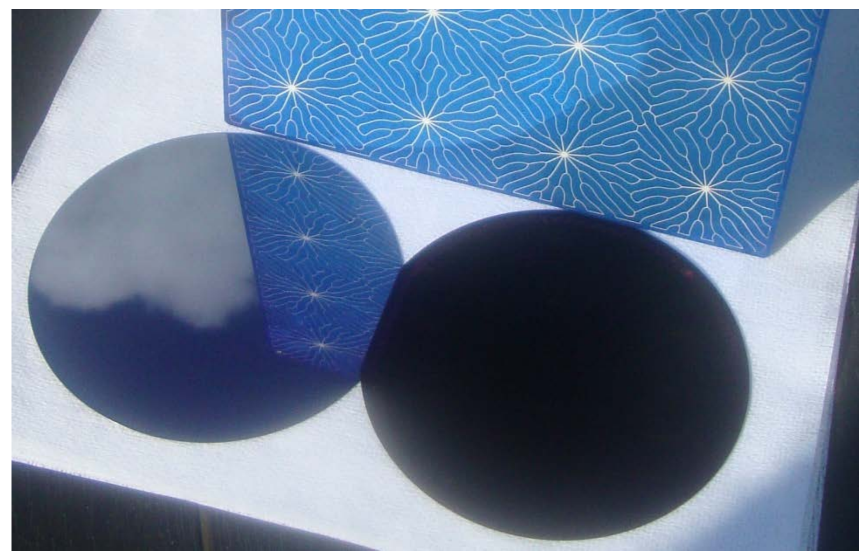
Mark Knight
Nano Energy **30**, 398 (2016)

Black silicon using leaky Mie resonances

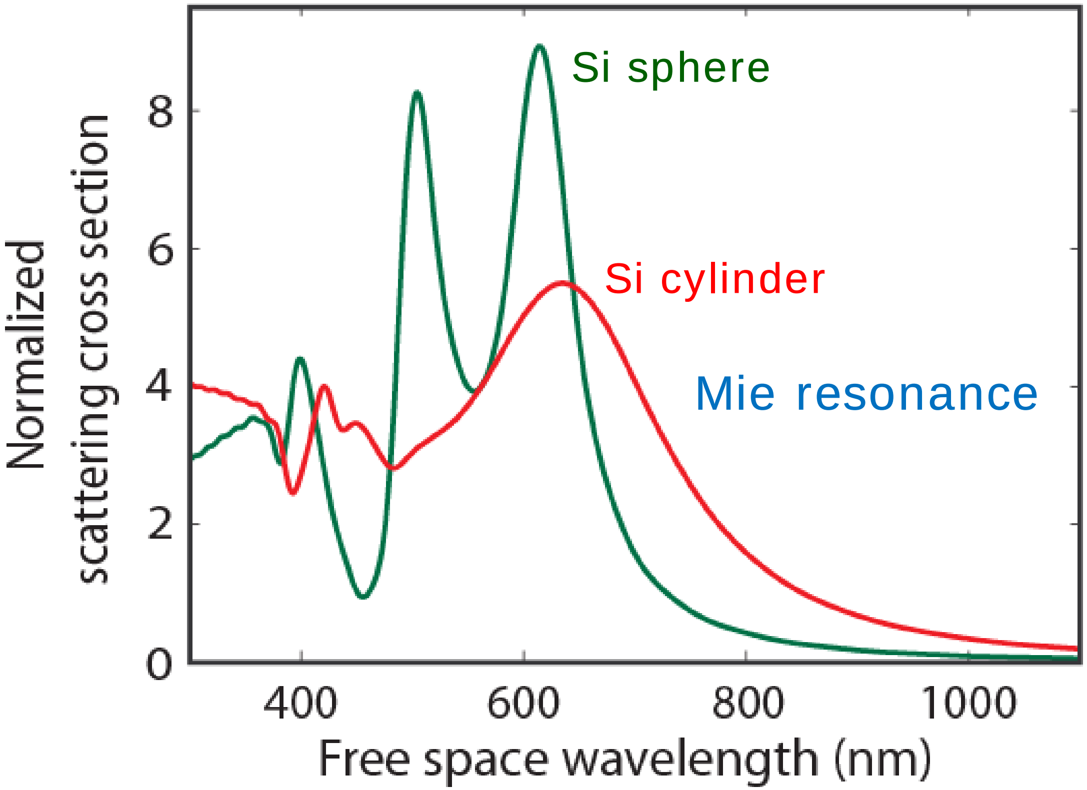
Average reflectivity: 1.3%

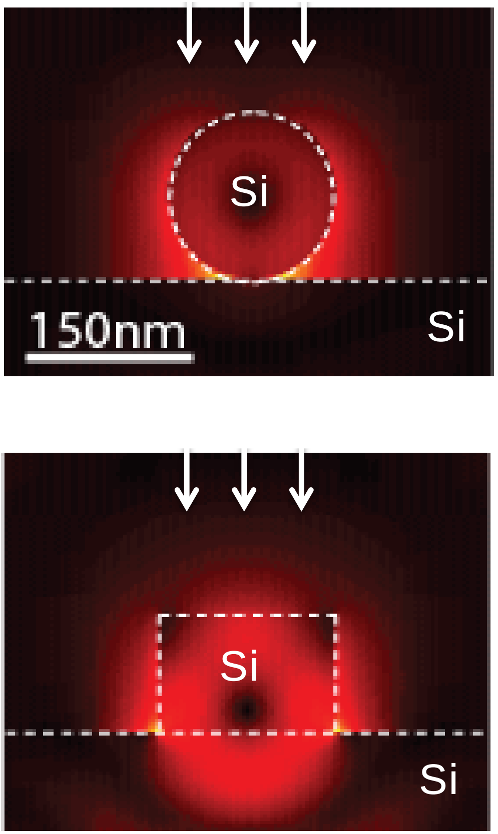






Silicon Mie scatterer on a Si substrate

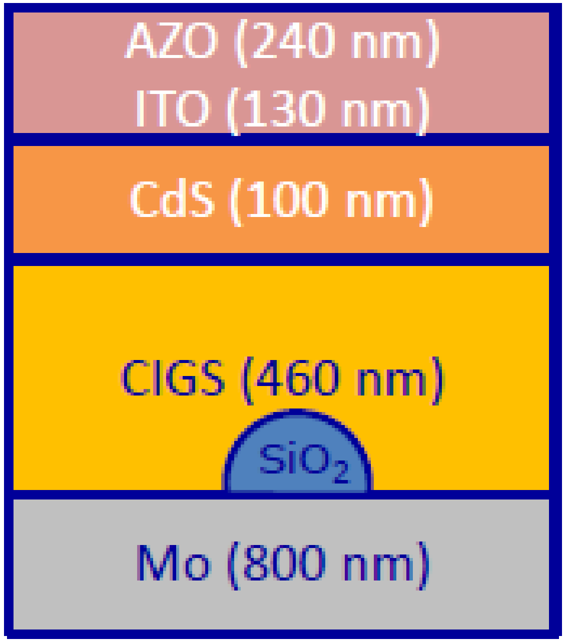


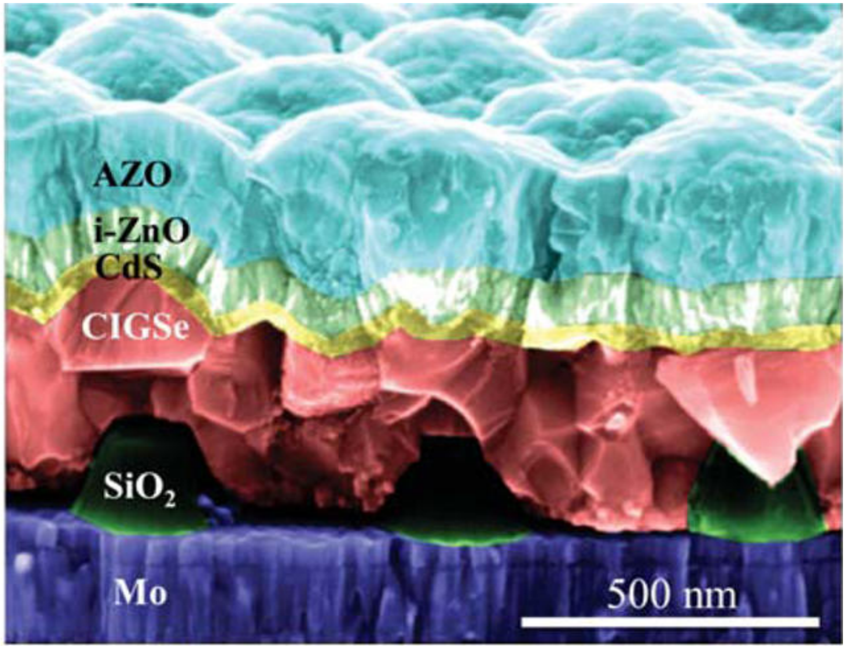


Silicon nano-cylinders act as cavities for light and direct light into the substrate

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

Nanopatterned ultrathin CIGS solar cells



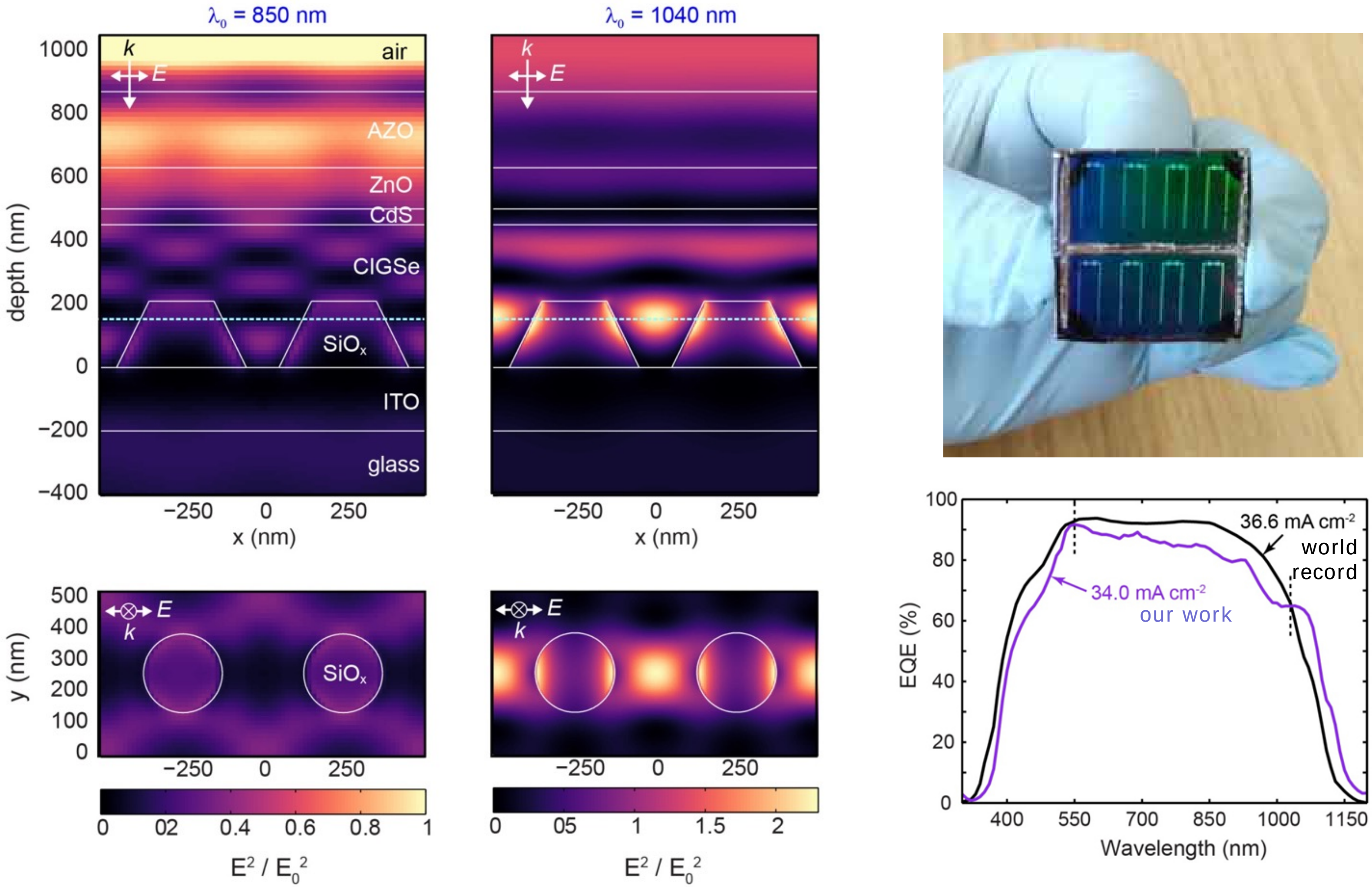


(CIGS record cells: thickness: 2.5-3.0 μm)

AMOLF

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

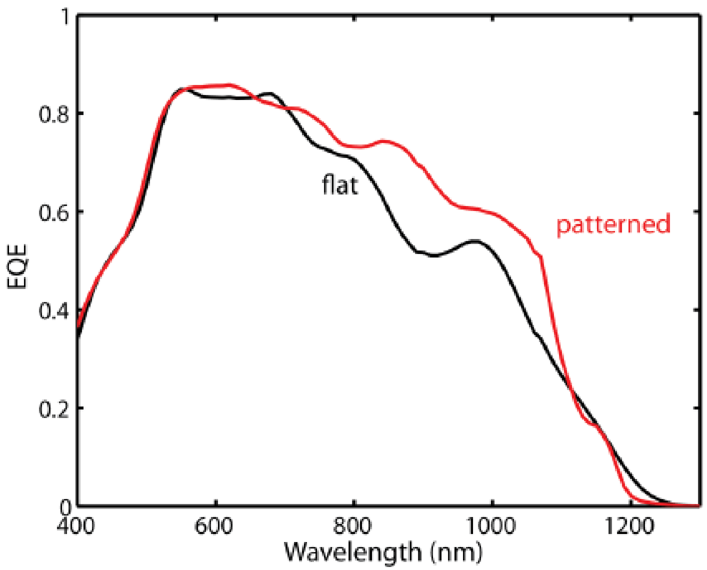
The solar cell as an optical integrated circuit

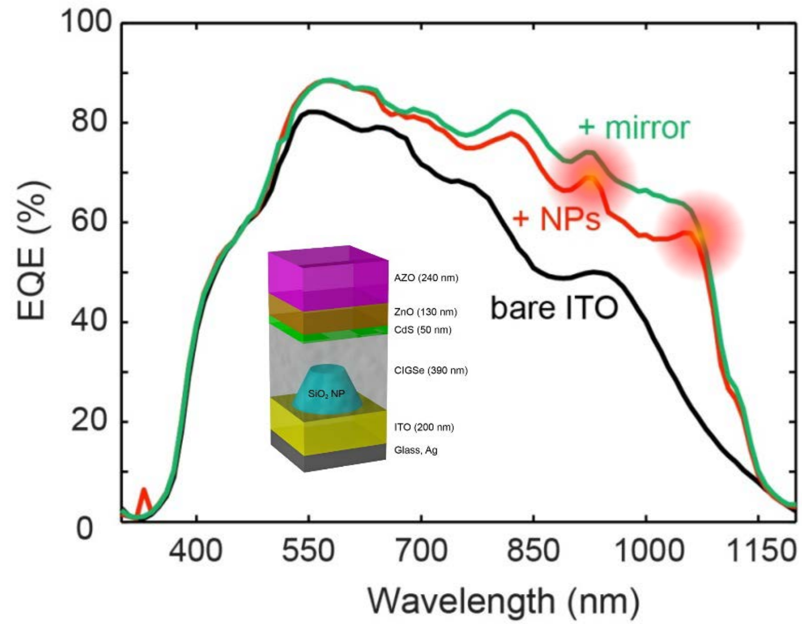


AMOLF

Mark Knight, Guanchao Yin, Claire van Lare
Adv. Opt. Mater. **4** (2017)

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

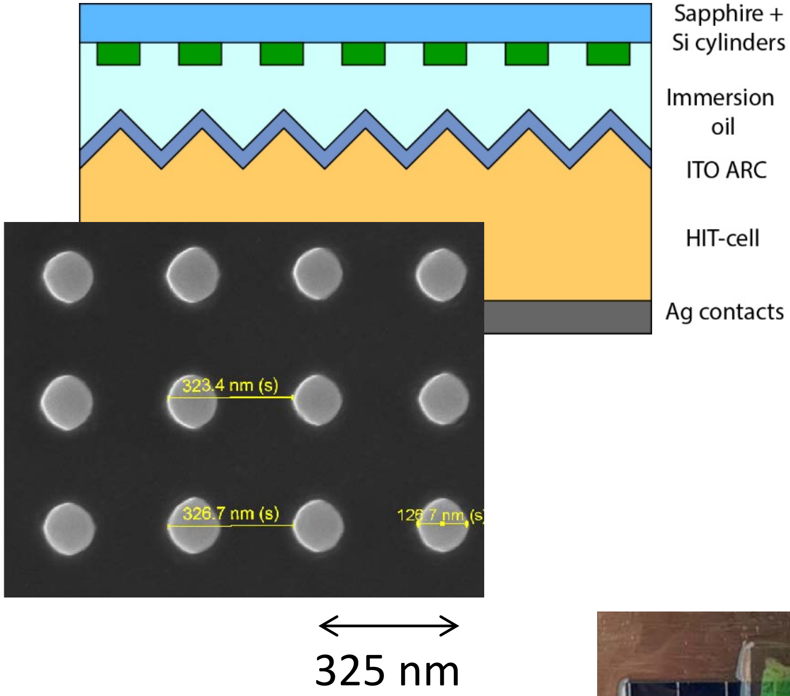
93% of world record

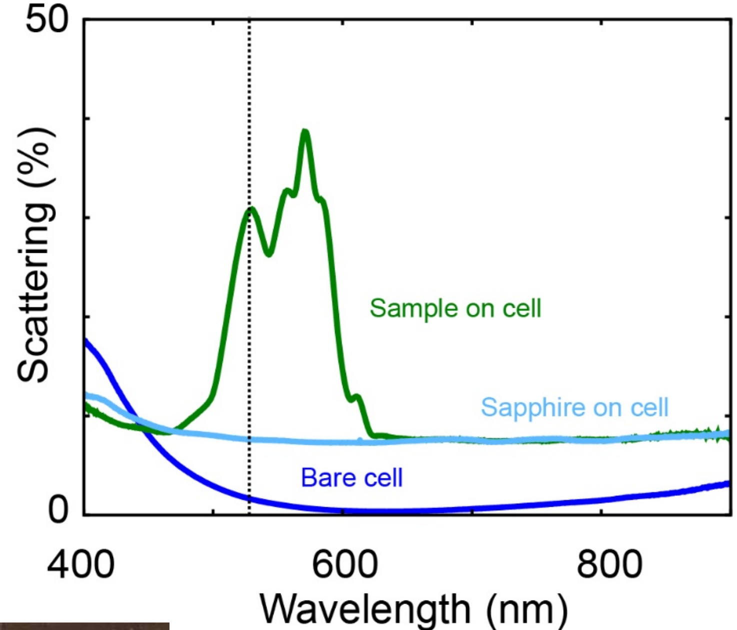
for 1/7th of the thickness

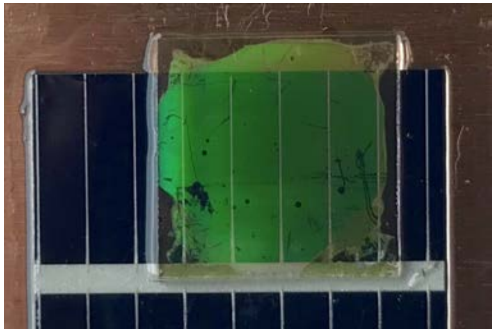
Mark Knight, Guanchao Yin, Magda Sola Garcia, Claire van Lare

ACS Nano **9**, 9603 (2015), Adv. Opt. Mater. **4** (2017)

Green Si HIT cells/minimodules



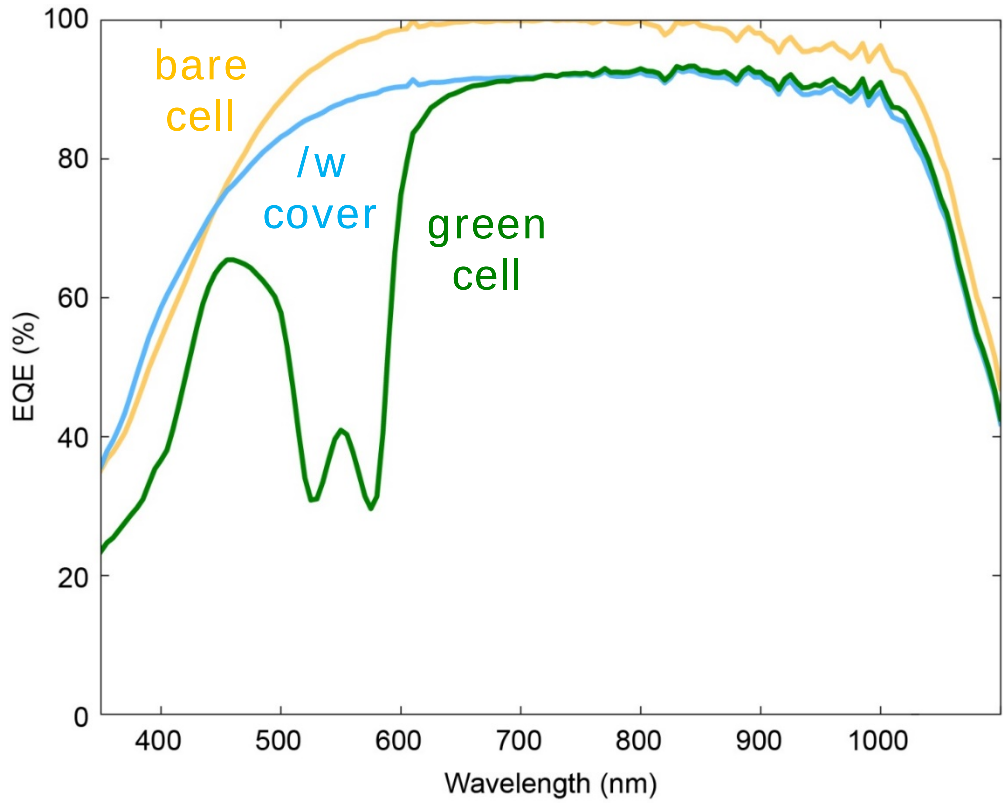




Si HIT cell

Verena Neder, Stefan Luxembourg
Appl. Phys. Lett. **111**, 073902 (2017)

EQE measurement



J_{sc} [mA/cm^2]

39,5

36,8

32,7

-7%

-11%

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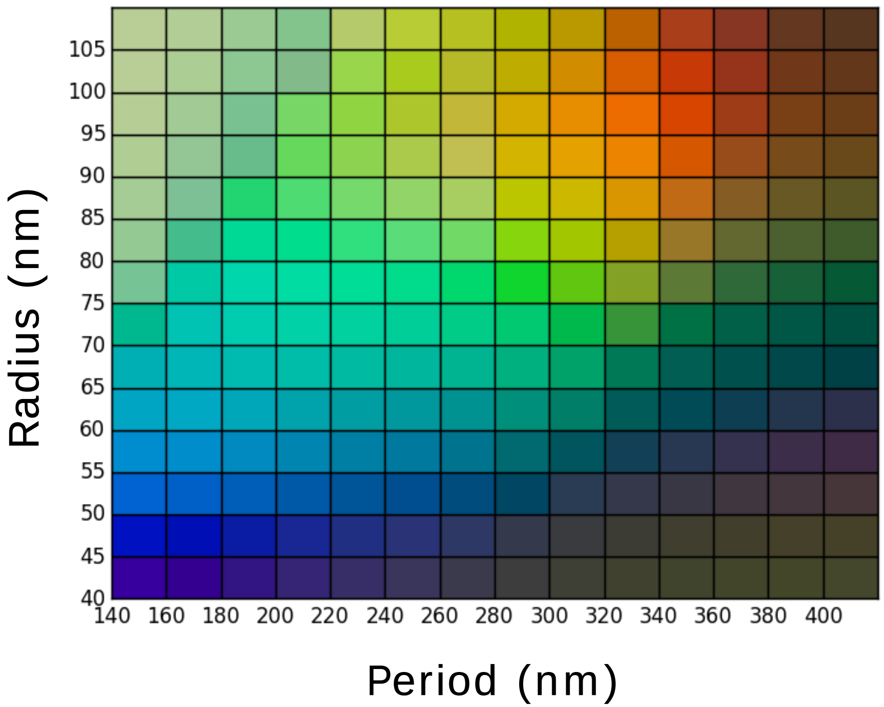
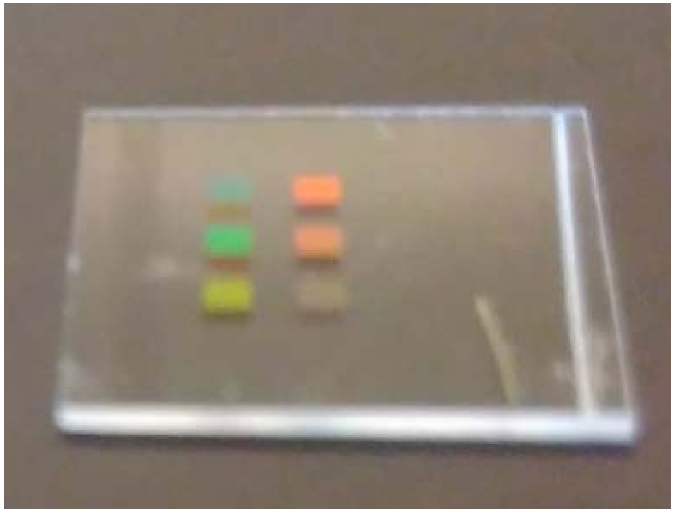
Verena Neder, Stefan Luxembourg
Appl. Phys. Lett. **111**, 073902 (2017)

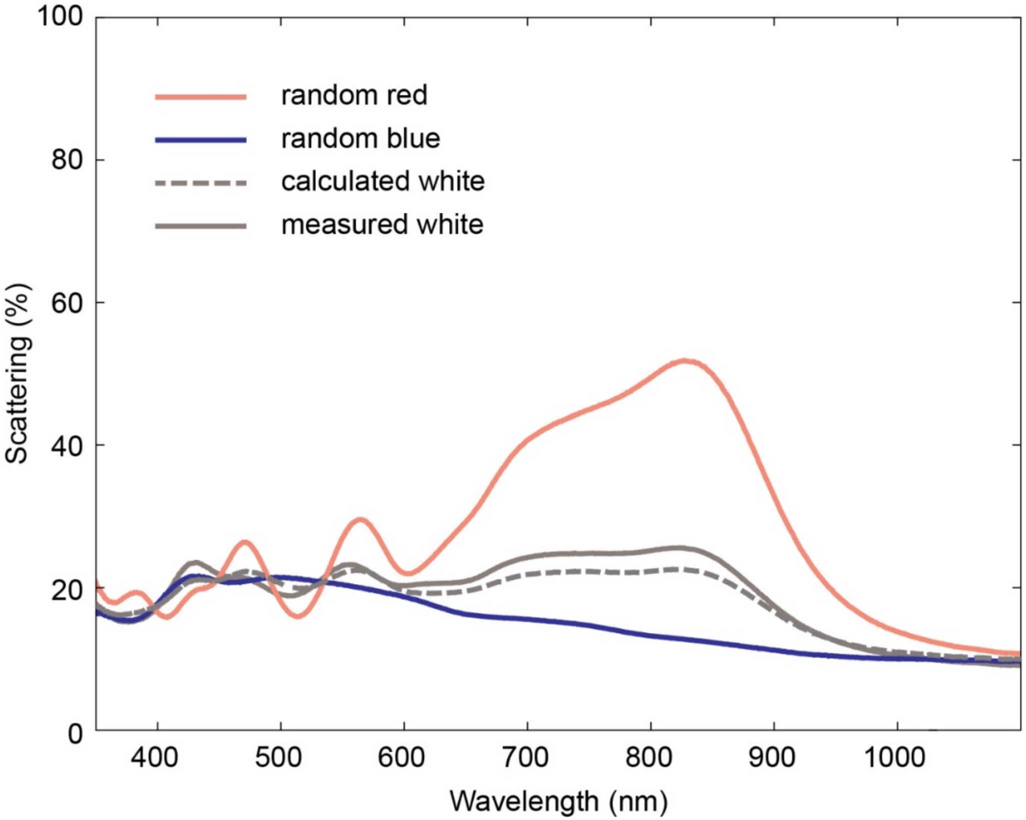
Creating other colors

Varying size and period of nano cylinders



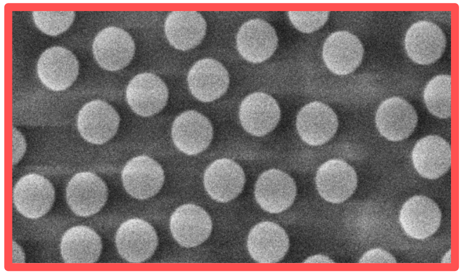


White light scattering by pixelated randomized arrays

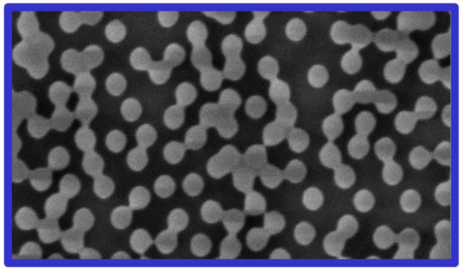


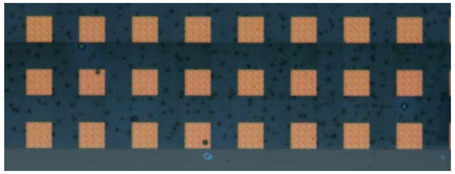
200 nm

25%



75%



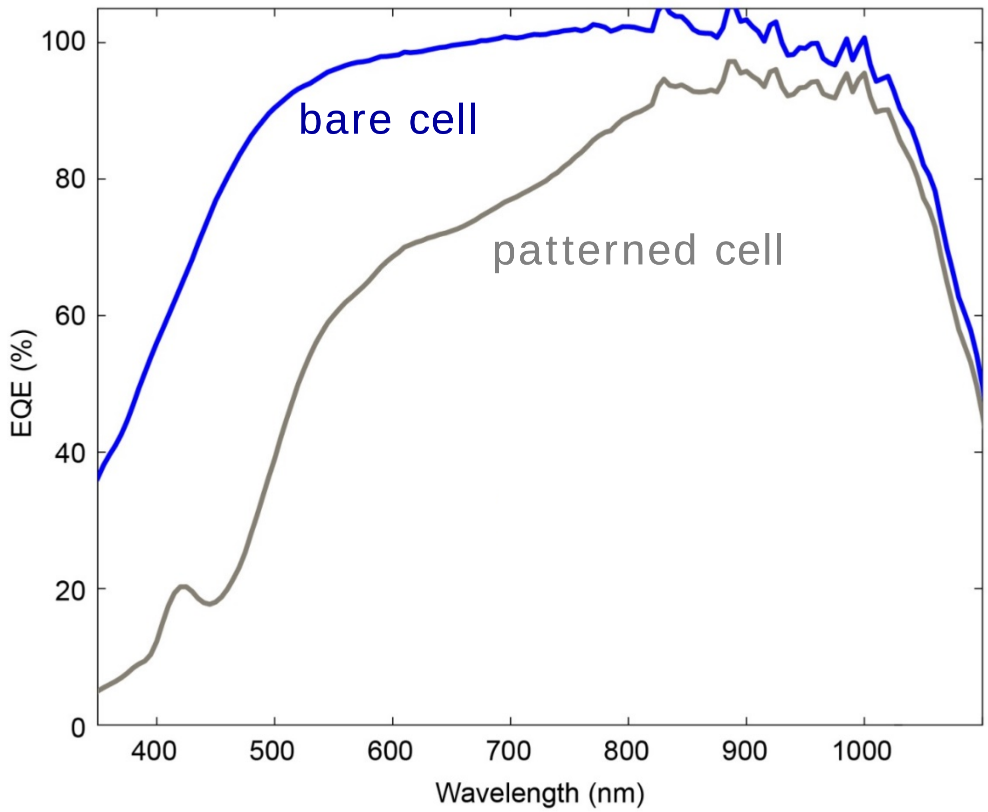


200 µm

AMOLF

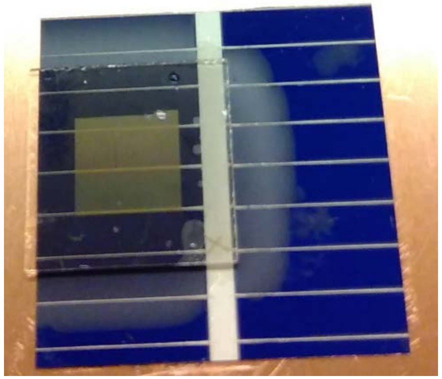
Verena Neder, Stefan Luxembourg
Proc. EU-PVSEC (2017), p. 34

White solar cell with 18%* loss in J_{sc}



J_{sc} [mA/cm^2]	
40,0	bare cell
30,3	covered white cell

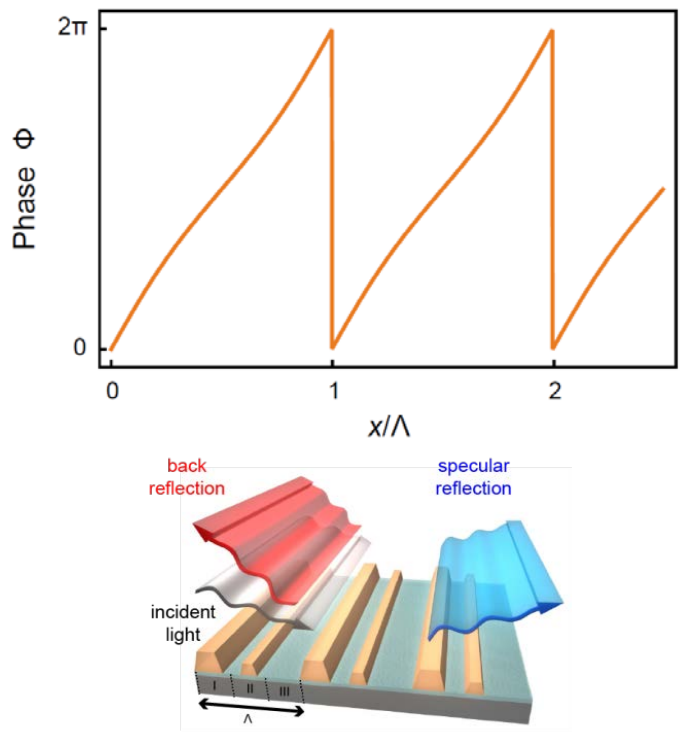
-25% (-18%)*



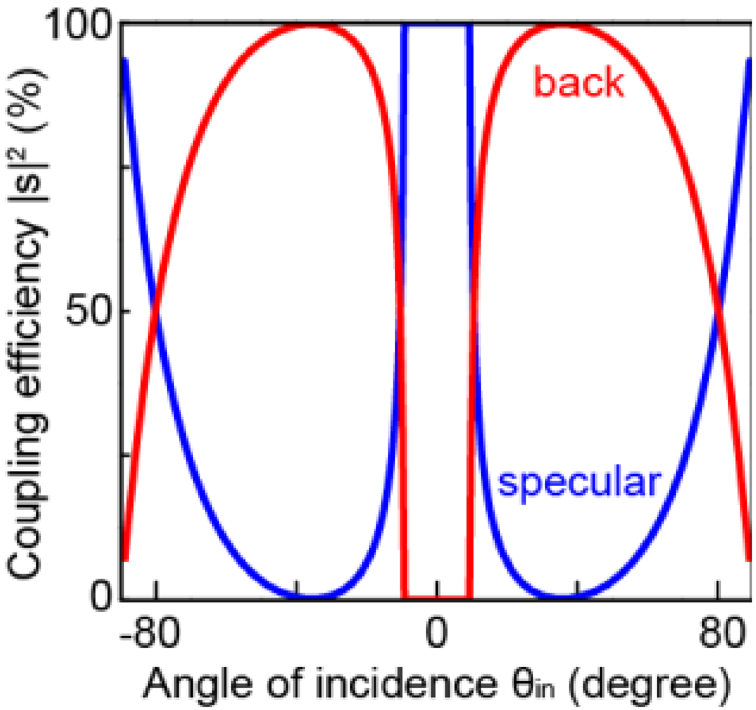
Verena Neder, Stefan Luxembourg
Proc. EU-PVSEC (2017), p. 34

Introducing metasurfaces for back reflection

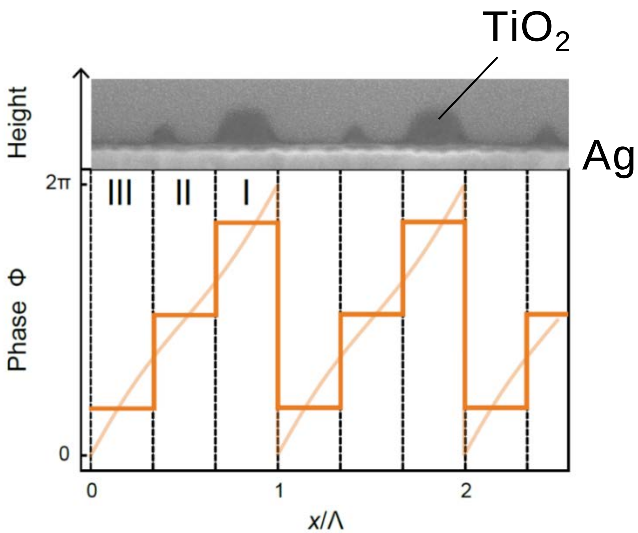
Analytical design of phase profile for back reflection with 100% efficiency

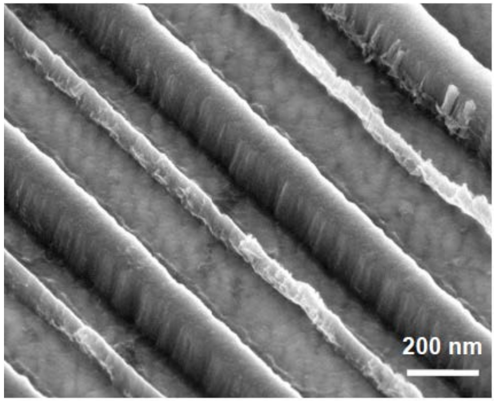


Calculated coupling efficiency to 1st diffraction order

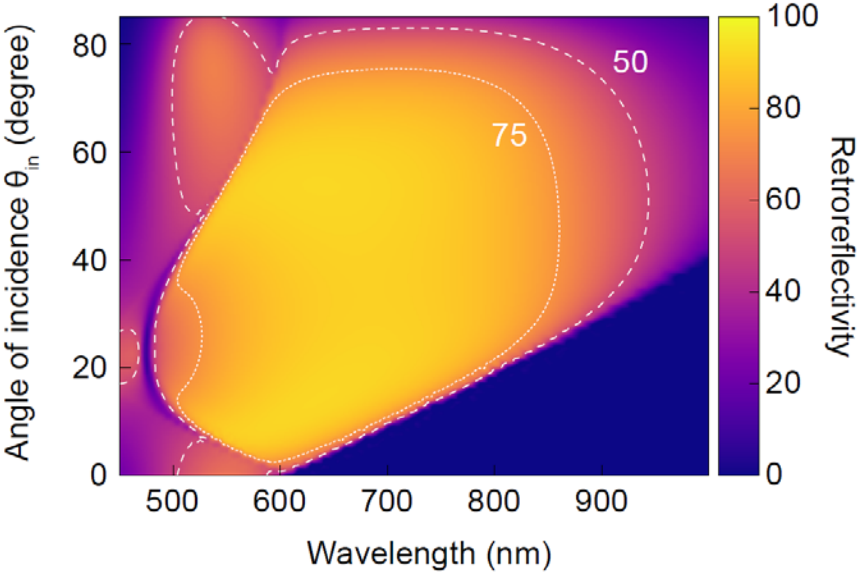


Performance of fabricated discretized design





Simulated coupling efficiency to 1st diffraction order



Coupling efficiency > 75%
θ_0 = 10-75°
λ=550-850 nm

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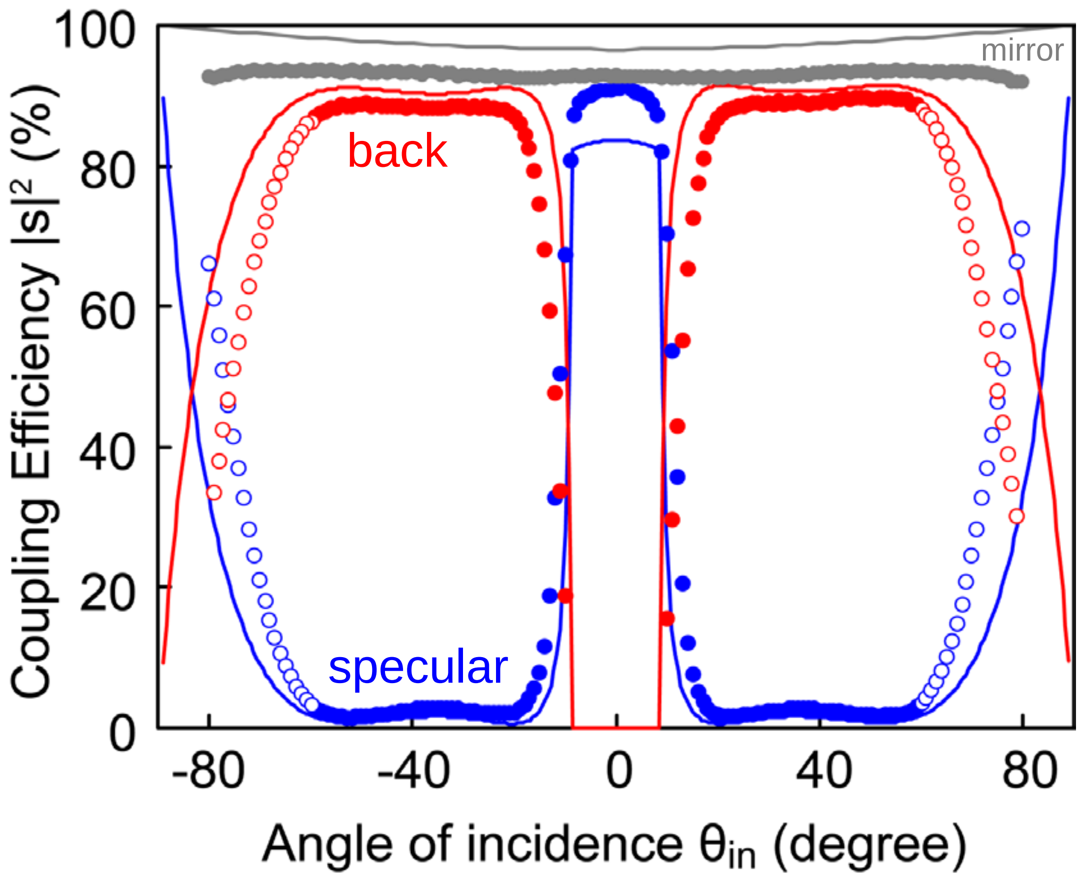
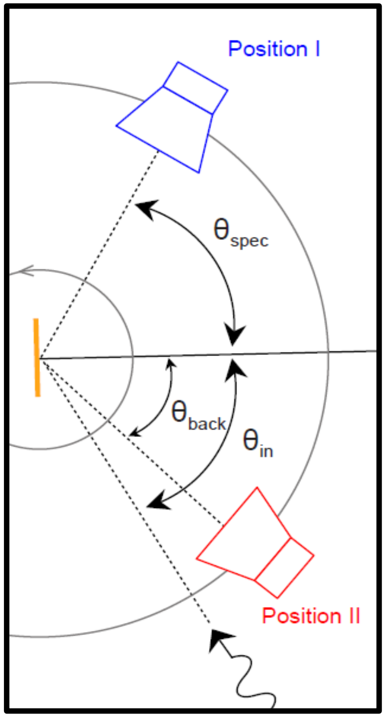
Measured backreflection of fabricated metasurface





λ= 700nm

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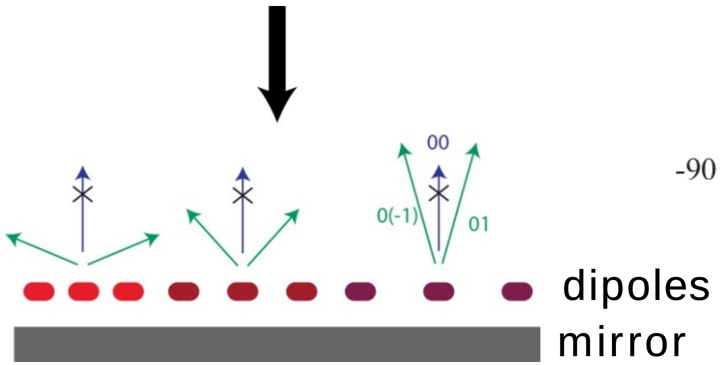
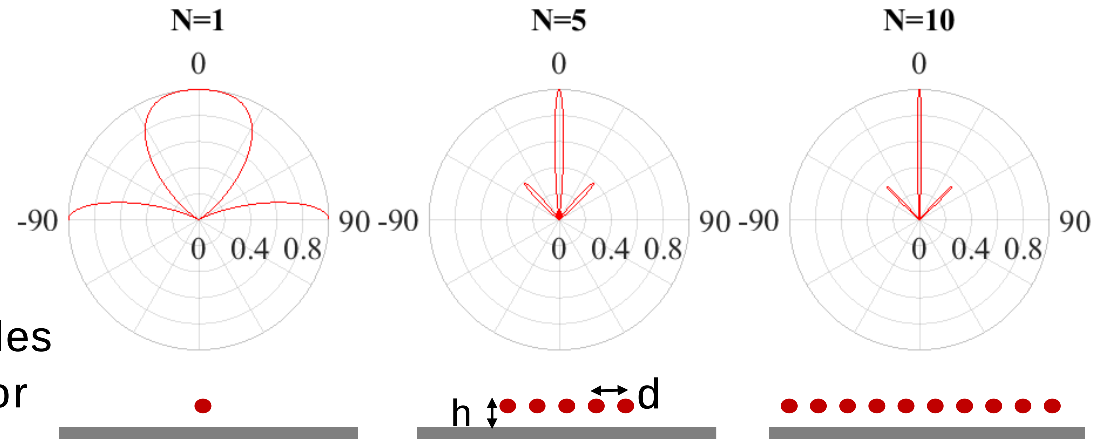
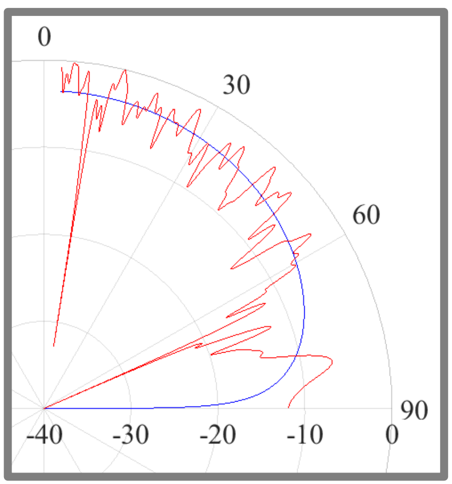
Metagratings for light management in PV



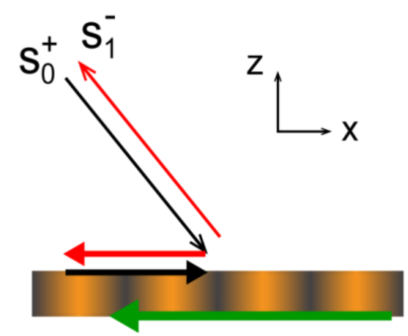




Unit cell: 40 µm

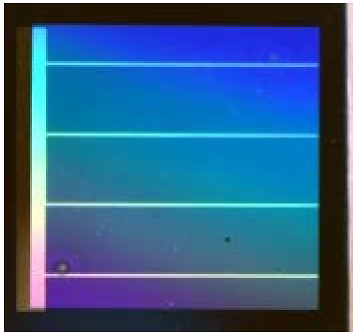
Lambertian
angular scattering profile
for colored PV

Optimizing light trapping
for Si/(III-V, perovskite)
tandem solar cells

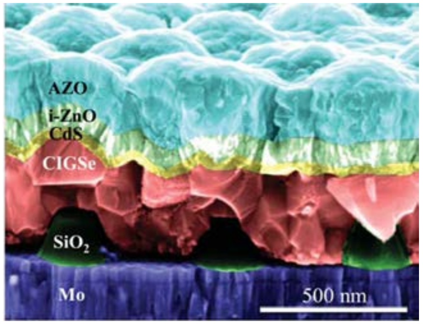


Summary

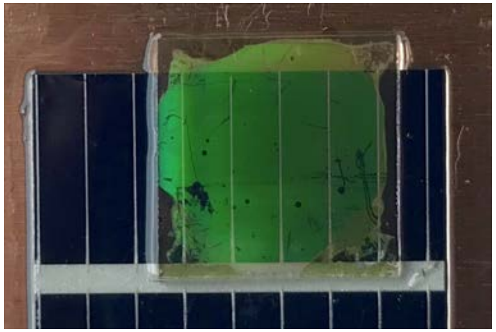
Plasmonic solar cells
transparent conductors



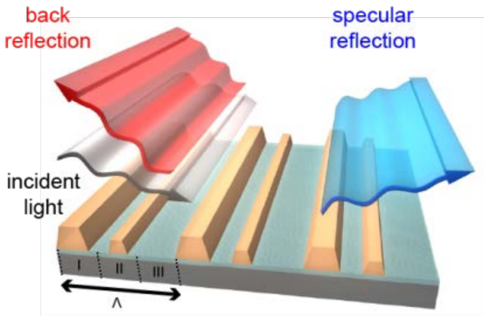
Scattering solar cells
light trapping



Colored solar cells
BIPV



Metasurfaces for PV
new designs



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Abel Tasman: the first Dutchman trying to find Australia (1642)