

High efficiency solar cells by nanophotonic design



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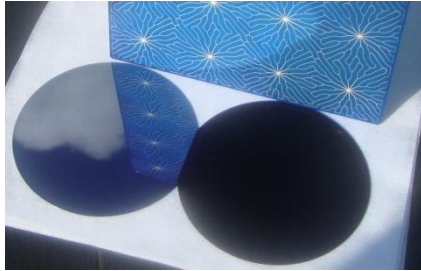
Guanchao Yin
Martina Schmid



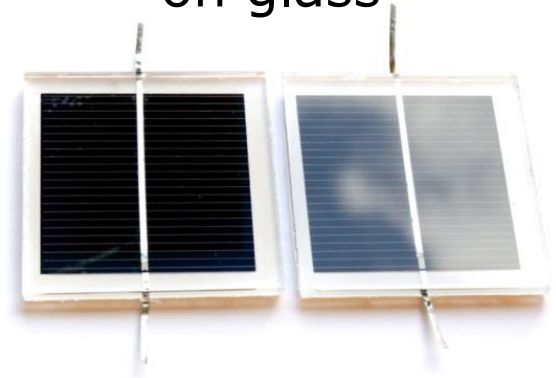
Vivian Ferry
Dennis Calahan
Matt Sheldon
Harry Atwater

Outline

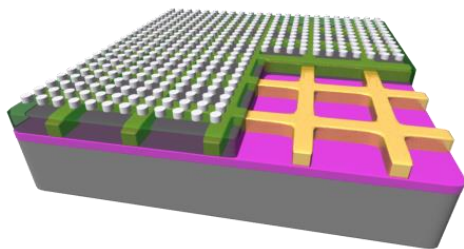
Light coupling
and trapping



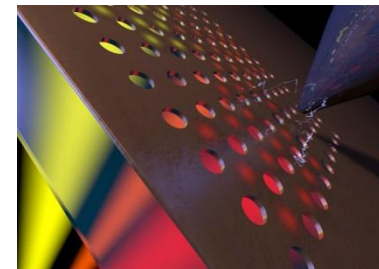
Nanopatterned ARC
on glass



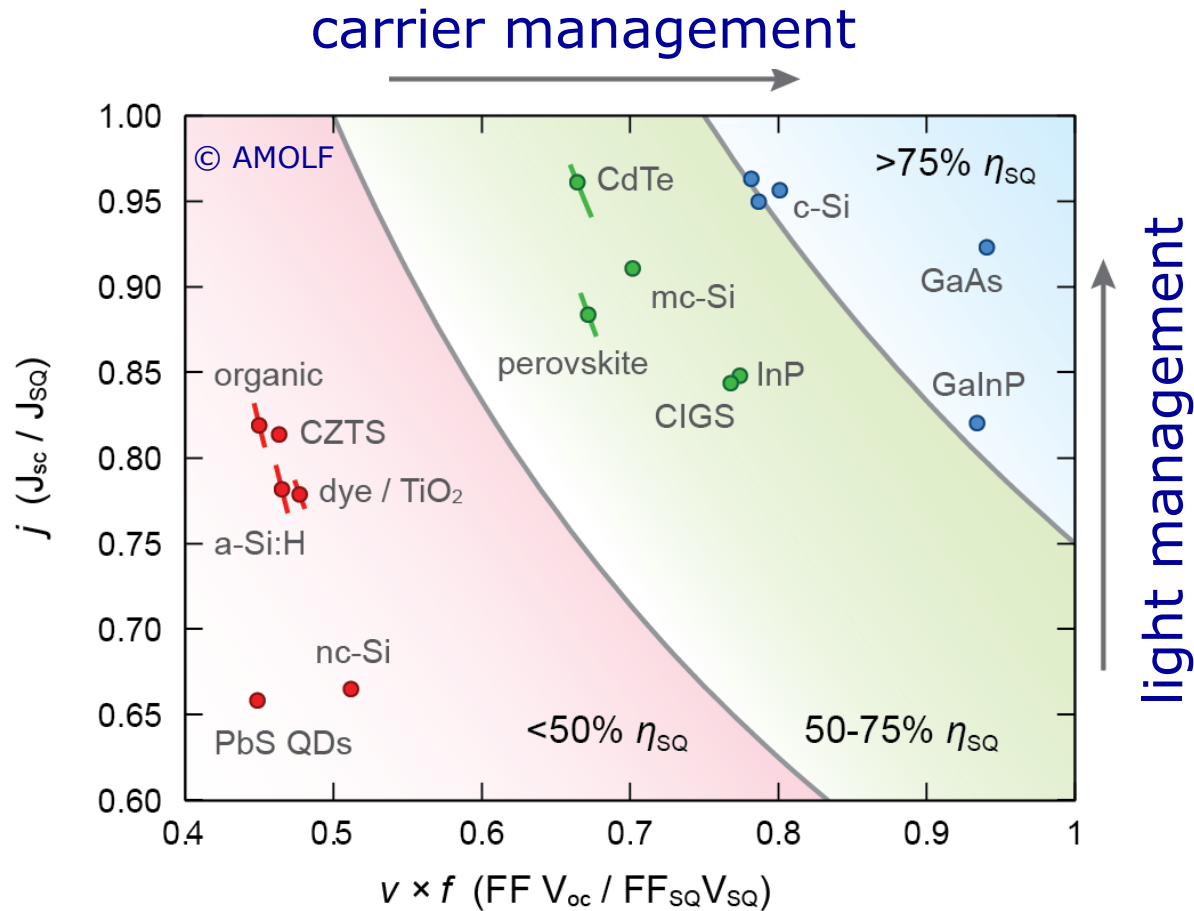
Transparent metal
nanowire networks



Plasmoelectric effect in
metal nanostructures

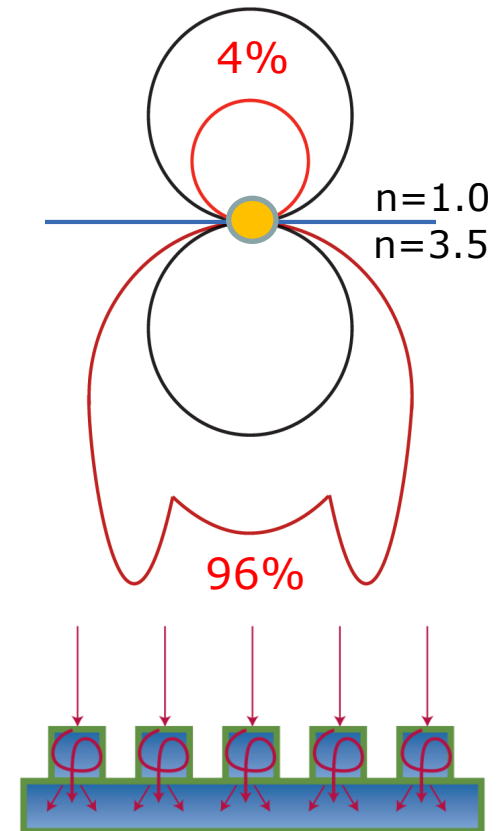
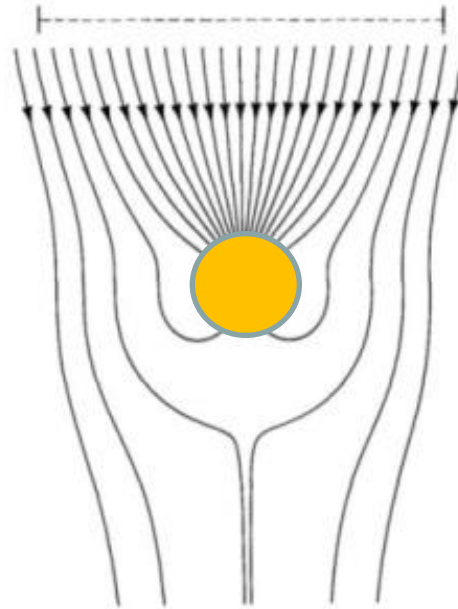
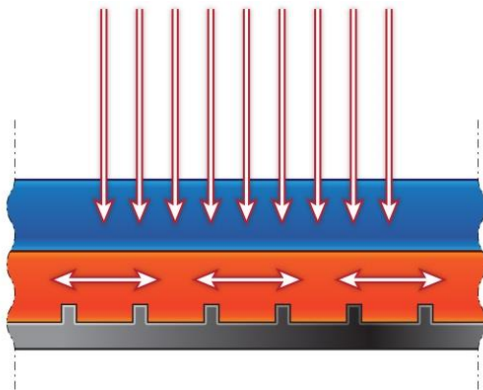
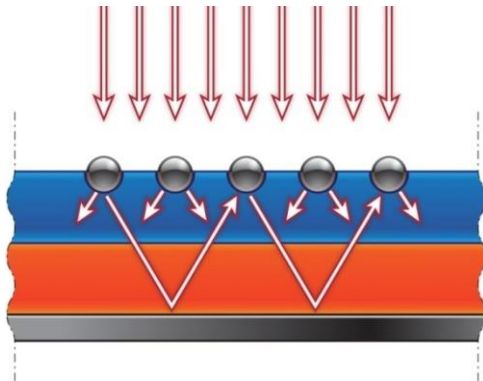


J_{sc} and V_{oc} relative to SQ limit (at given bandgap)

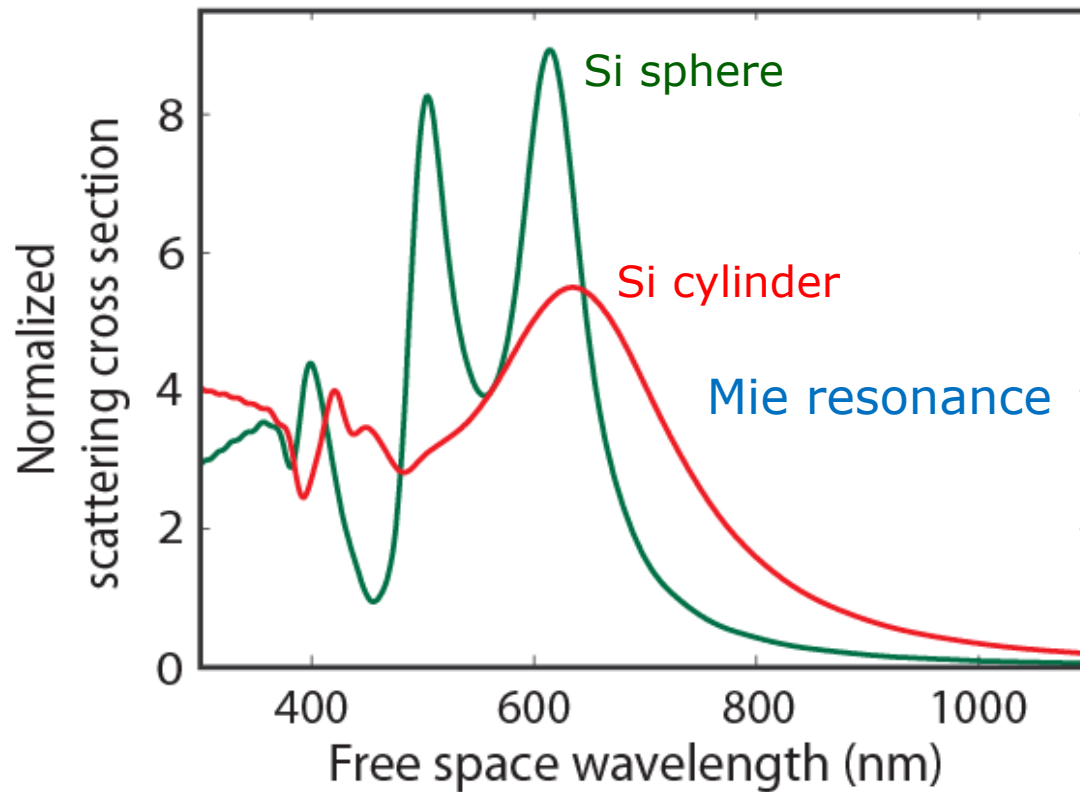


The scattering solar cell

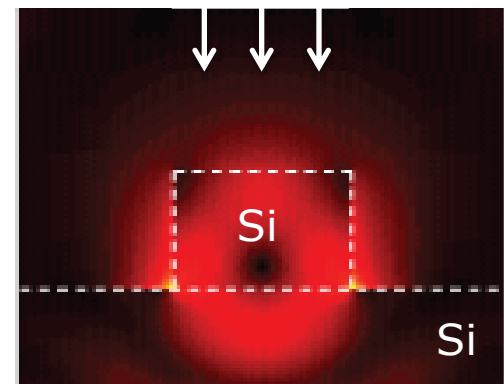
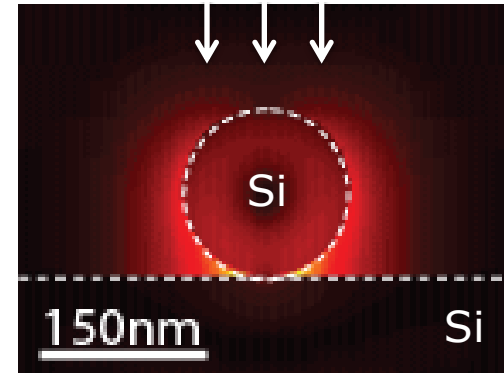
Light coupling and trapping by resonant light scatterers



Silicon Mie scatterer on a Si substrate

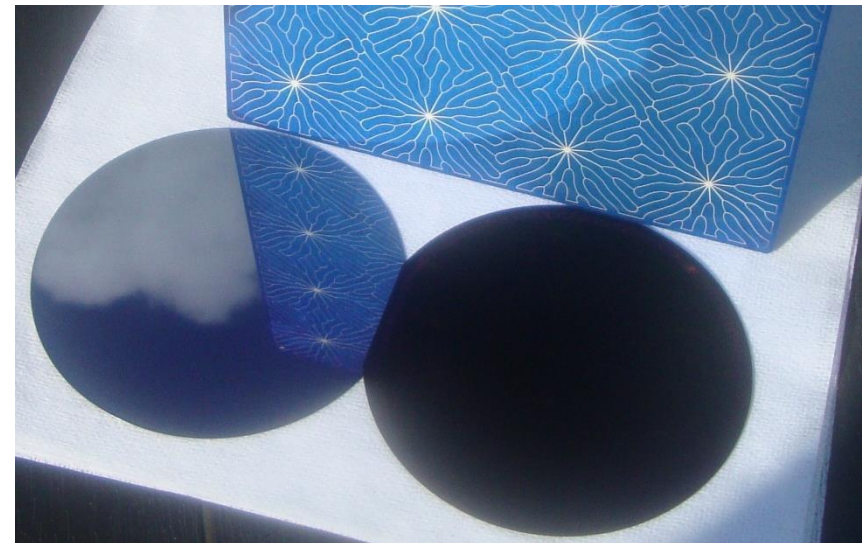
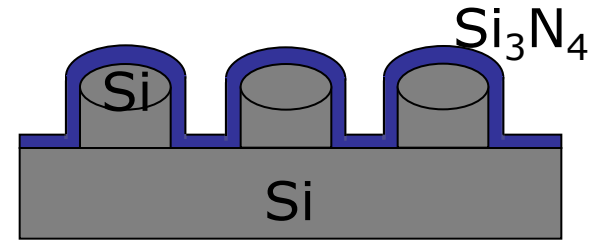
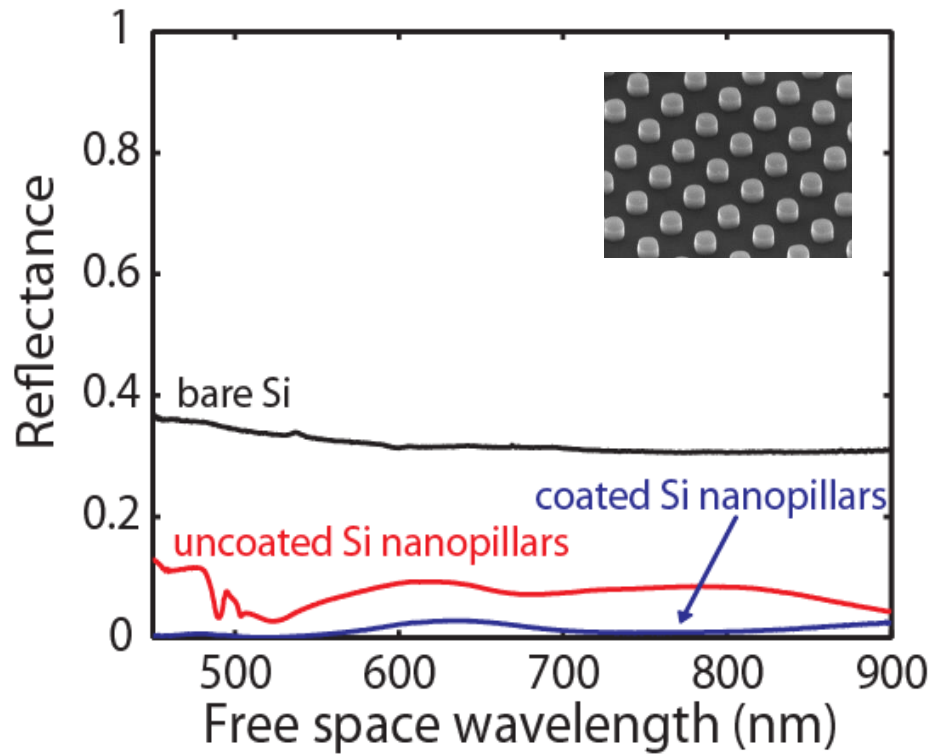


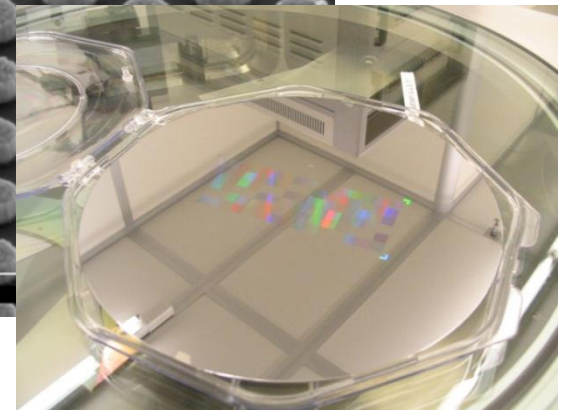
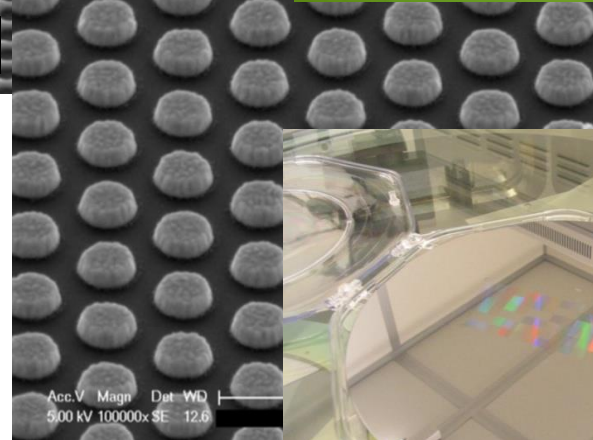
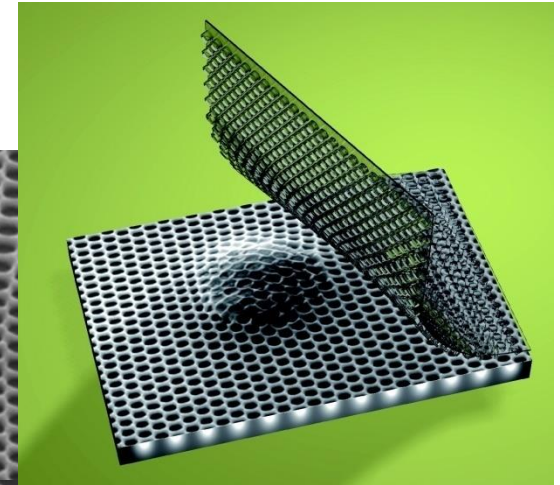
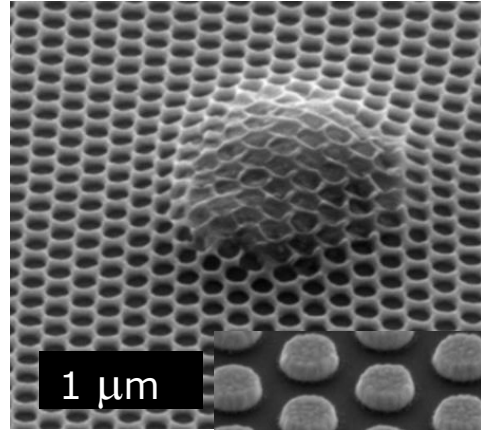
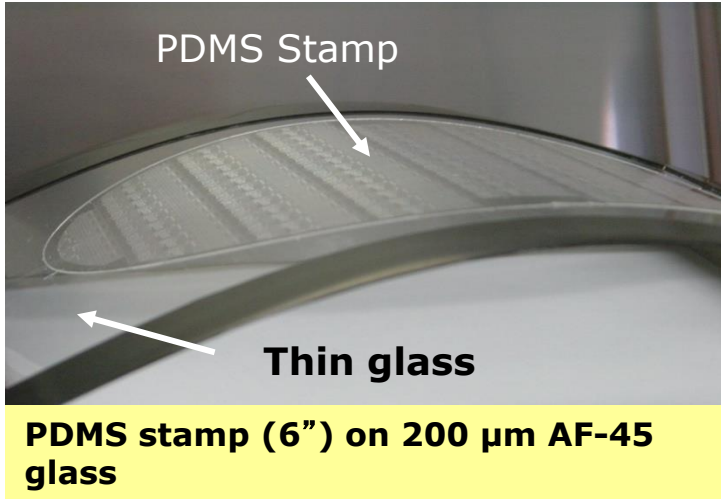
Silicon nano-cylinders act as cavities for light and direct light into the substrate



Black silicon using leaky Mie resonances

Average reflectivity: 1.3%

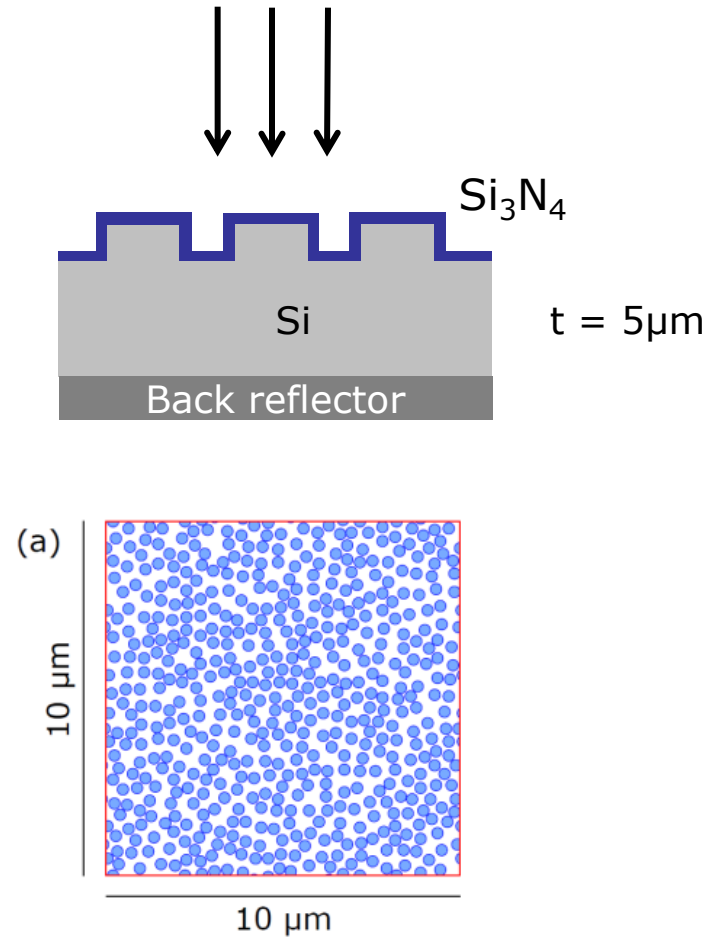
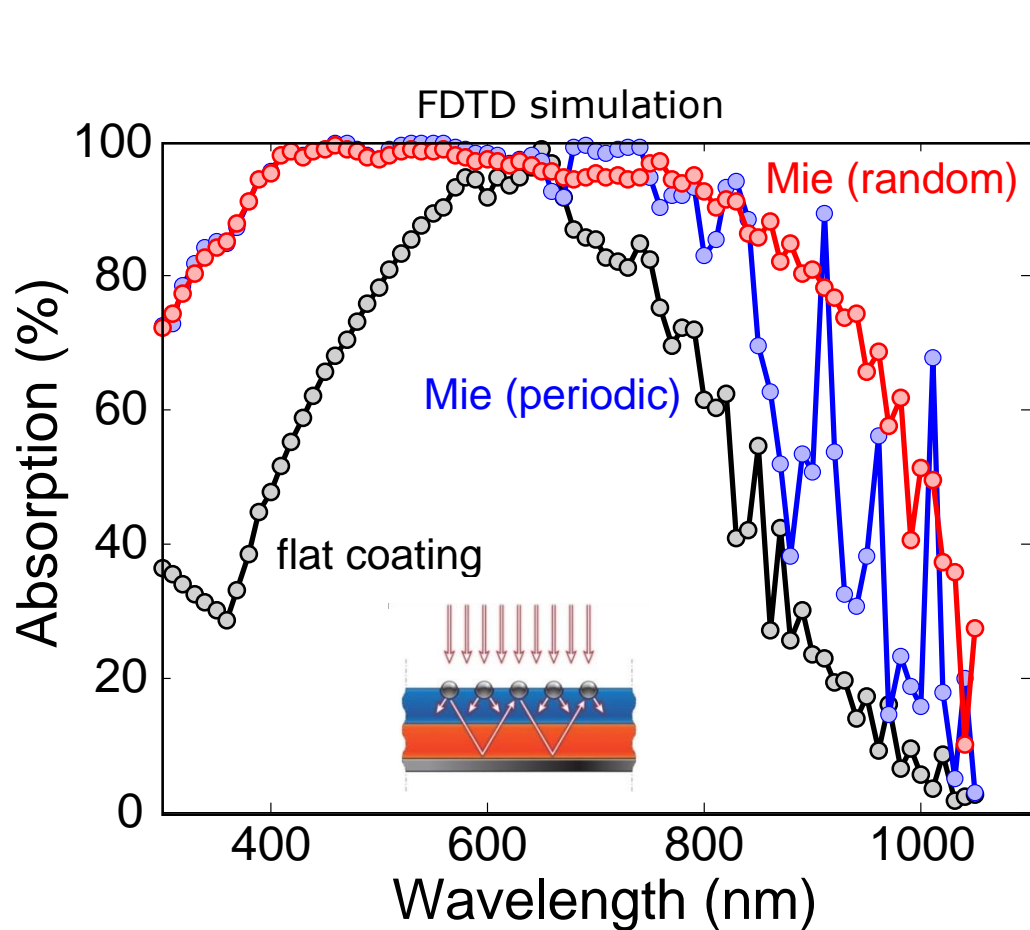




Full-wafer soft nano-imprint

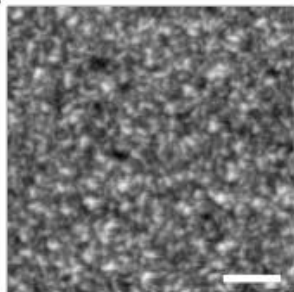
- Flexible rubber on thin glass
- Conform to substrate bow and roughness
- No stamp damage due to particles

Light trapping in 5 μm crystalline Si slab

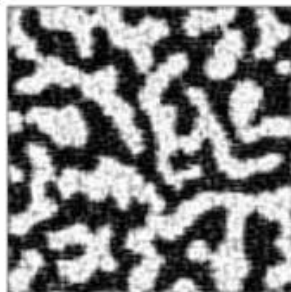


Optimizing spatial frequency of scattering pattern

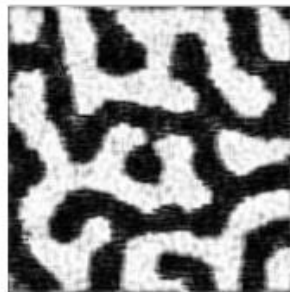
a Asahi U-type



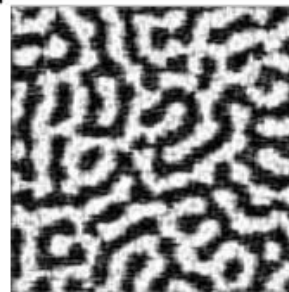
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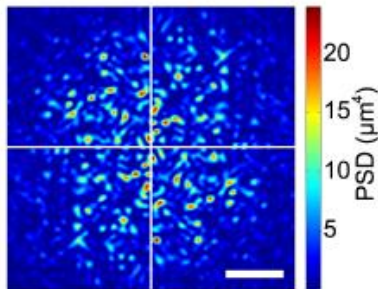
c



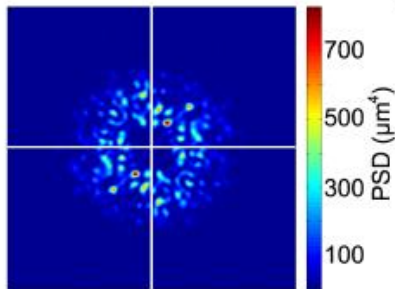
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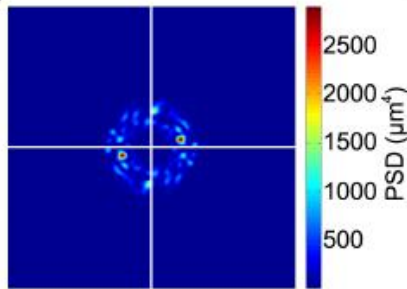
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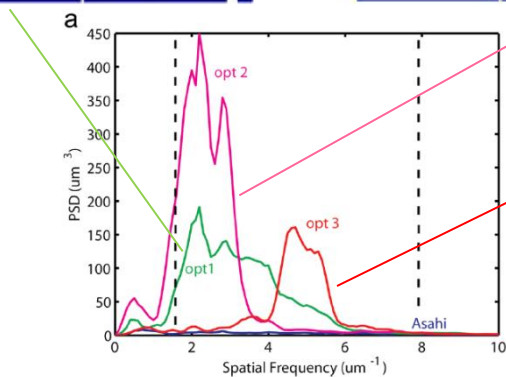
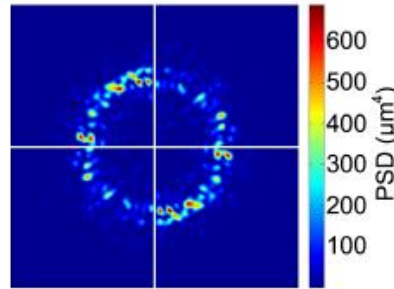
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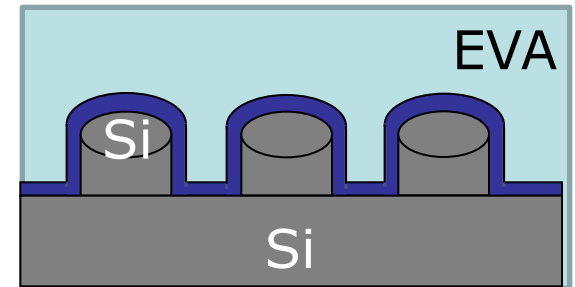
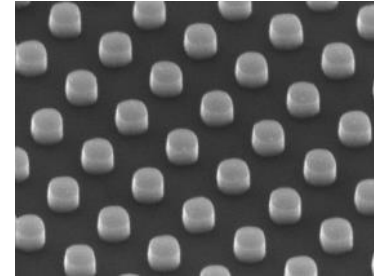
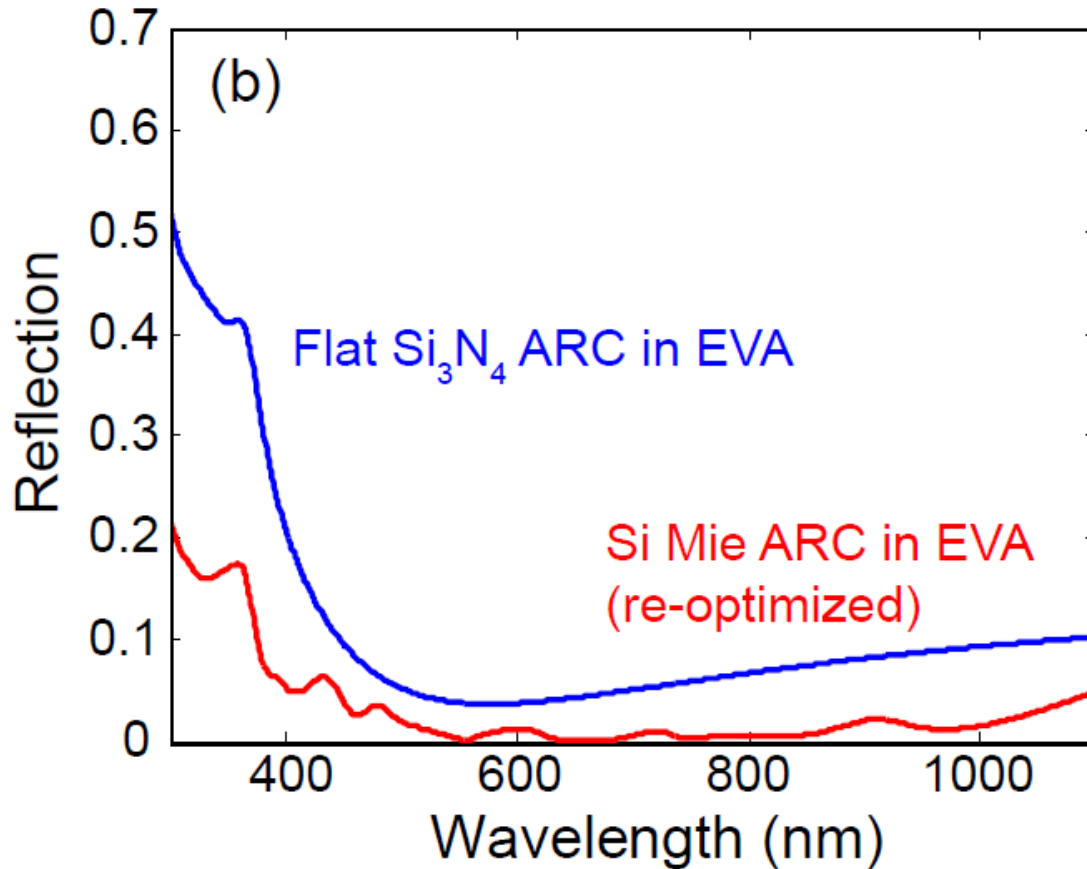
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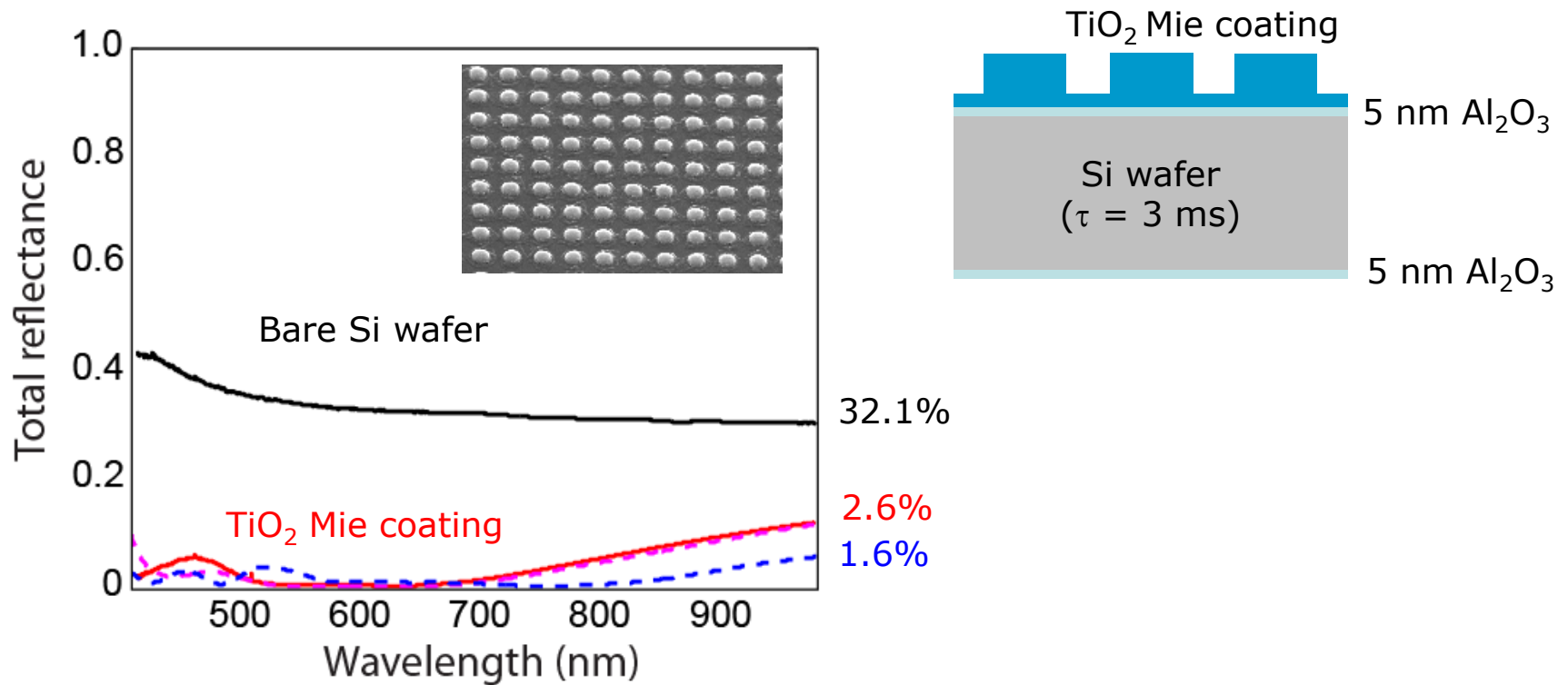
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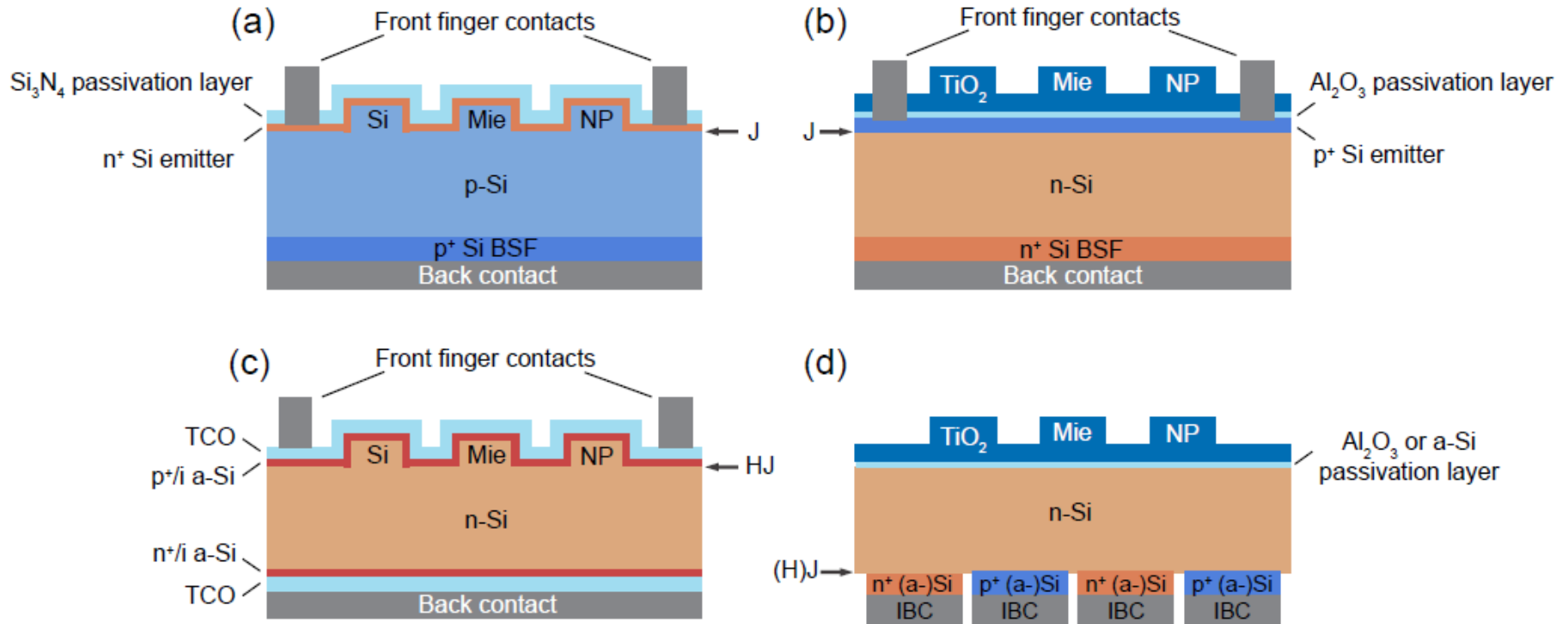
Effect of EVA encapsulation



TiO₂ nanoscatterers on Si Al₂O₃ surface passivation

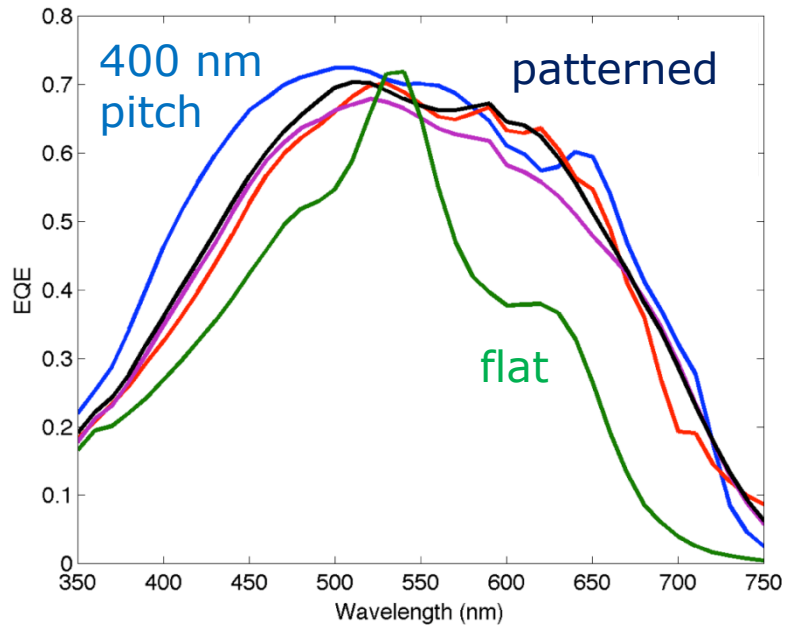


Nanopatterned Si solar cell designs

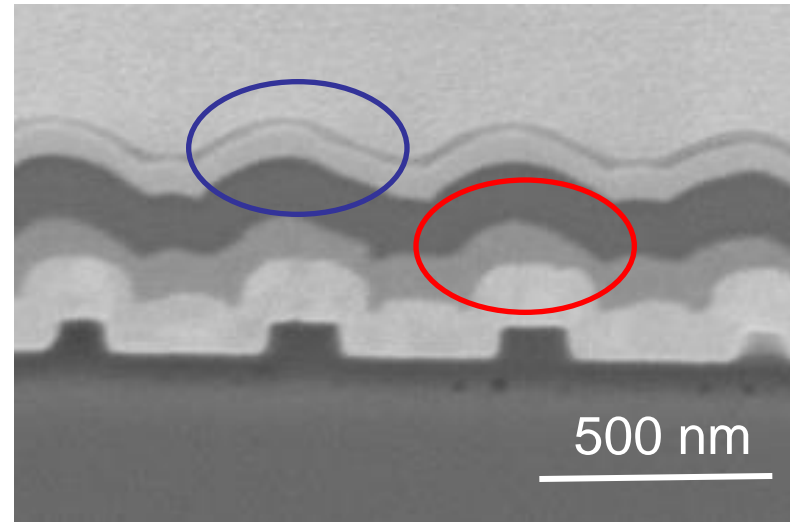


Ultra-thin a-Si:H solar cell: 90 nm *i*-layer

Experiment

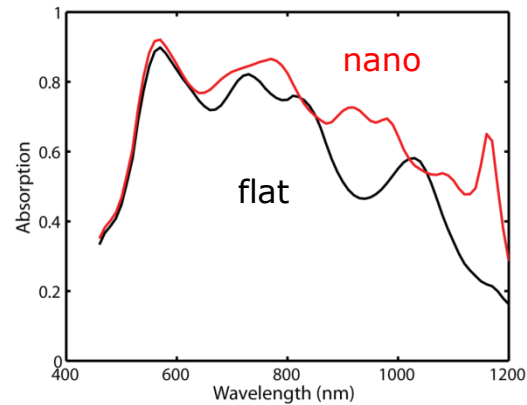
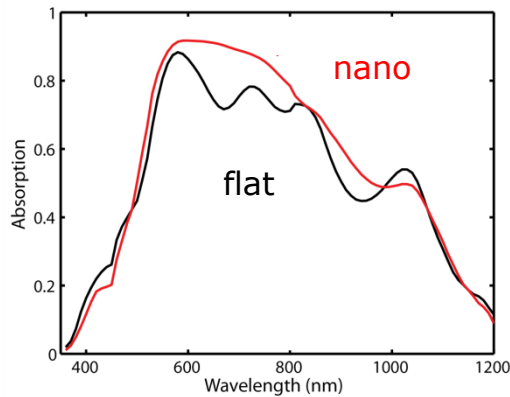
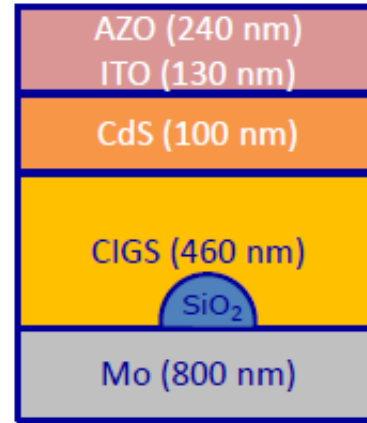
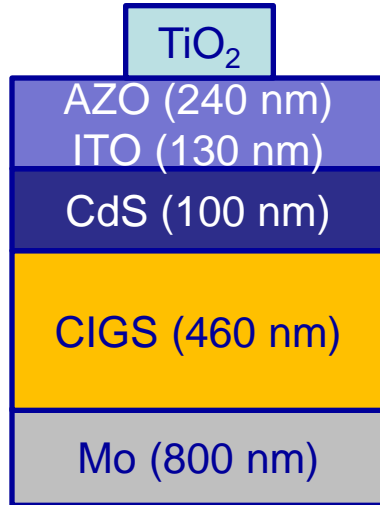


enhanced **red** and **blue** response by resonant dielectric scatterers



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

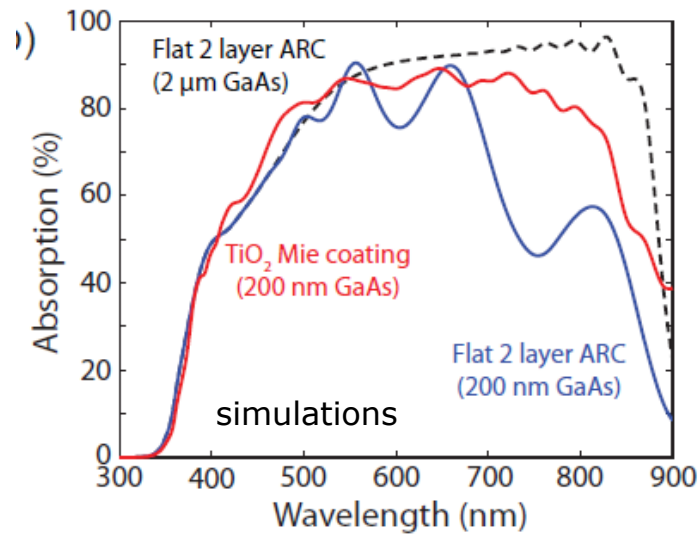
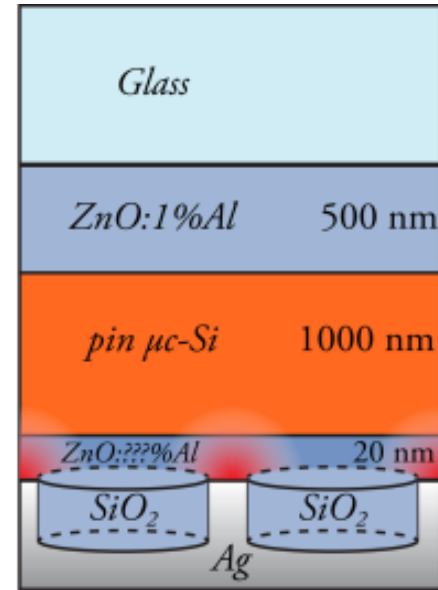
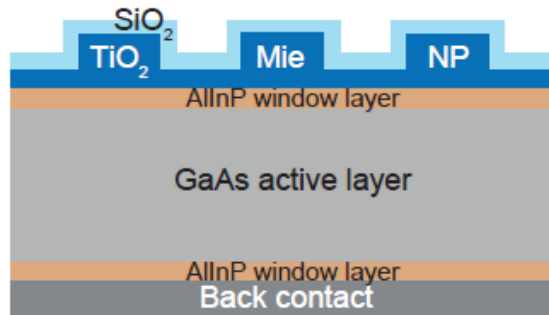
Nanopatterned CIGS solar cell designs



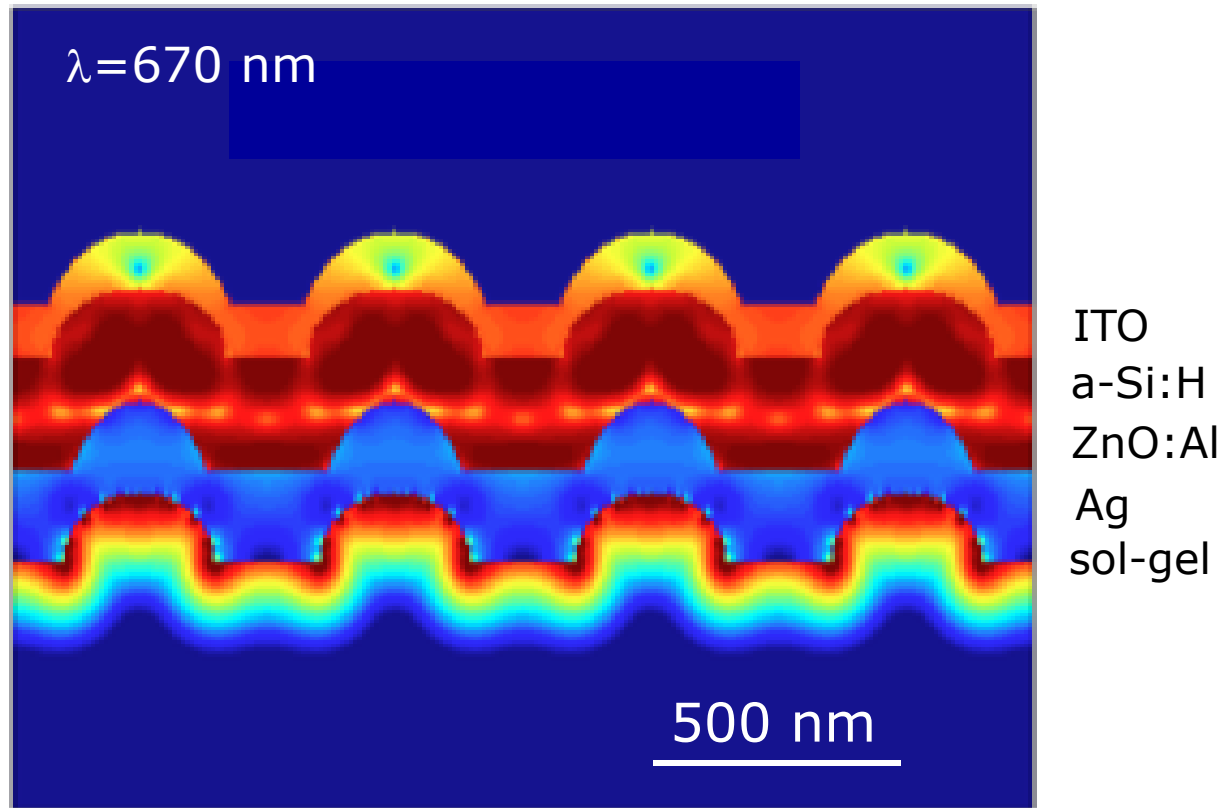
+ enhanced V_{oc}

reduced back-recombination

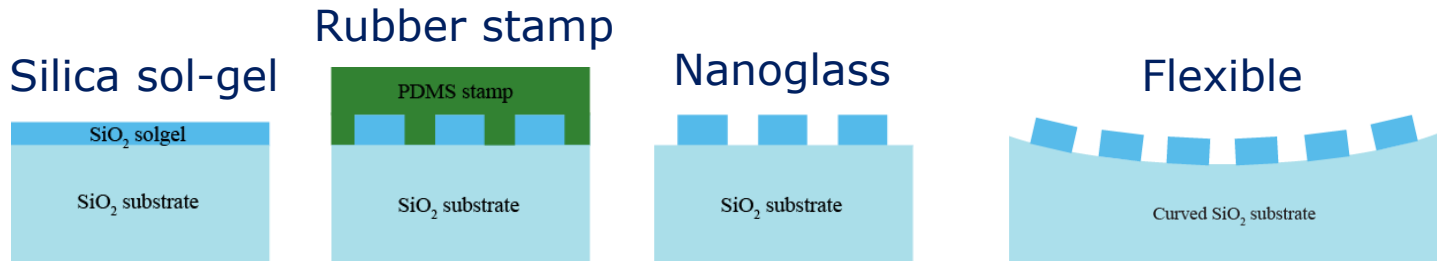
Nanopatterned GaAs, thin crystalline Si



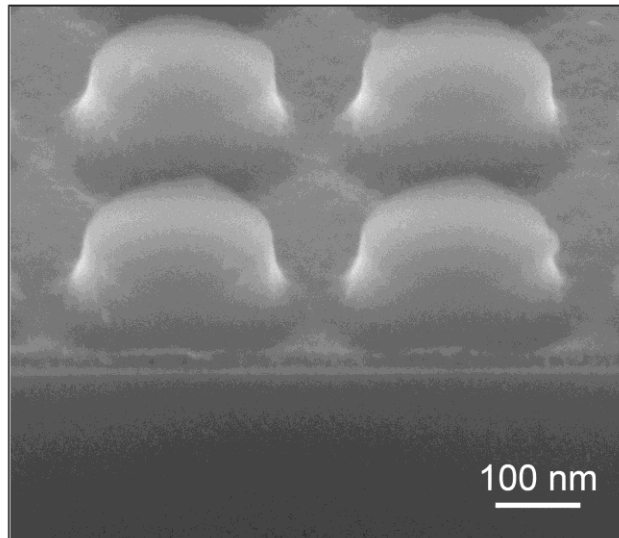
The solar cell as an optical integrated circuit



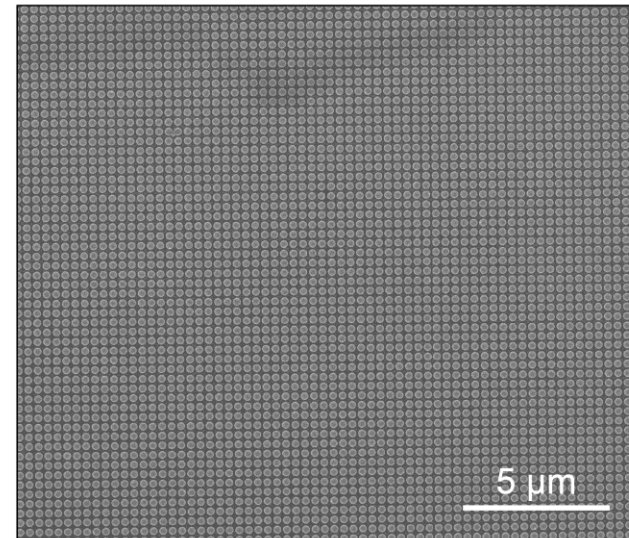
Soft-imprinted nanopatterned AR interference coating



Silica nanopattern with effective index $n=1.22$

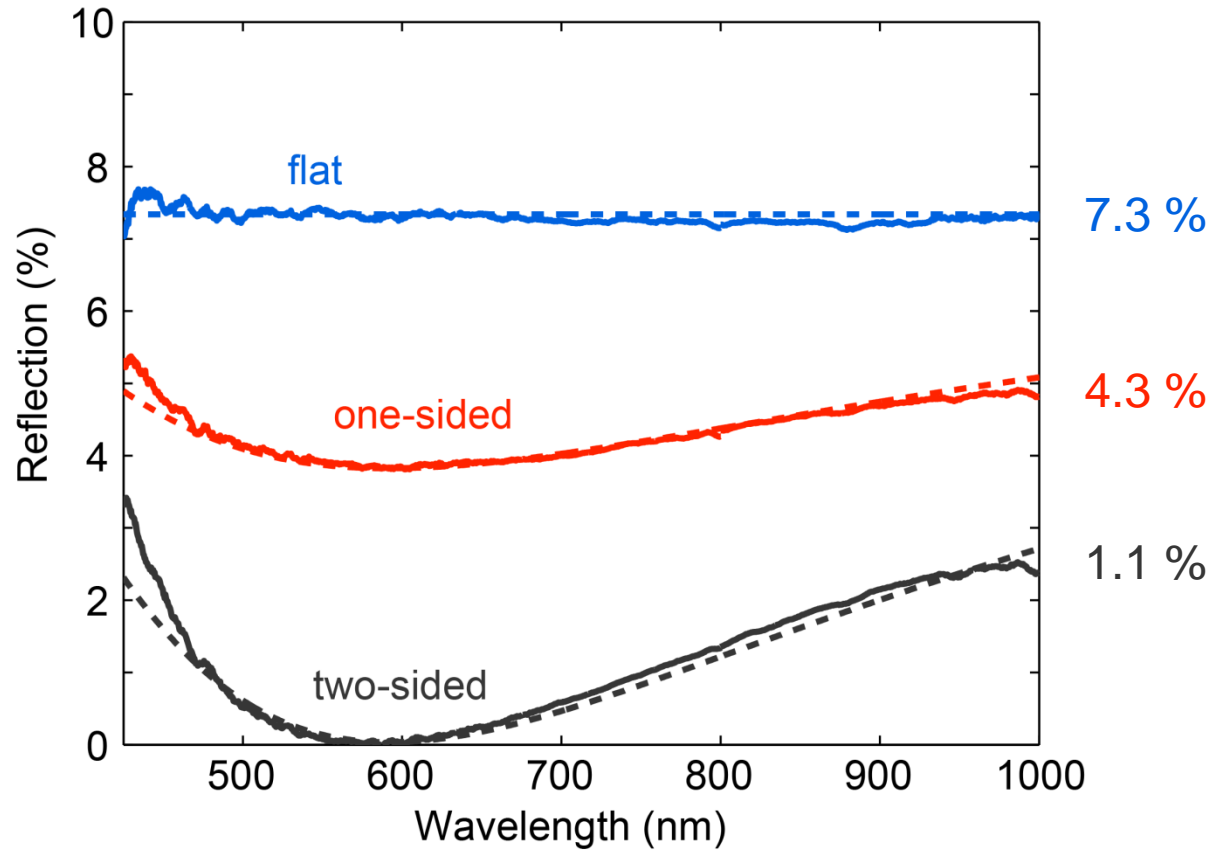


$d = 240 \text{ nm}$
 $h = 120 \text{ nm}$
 $p = 325 \text{ nm}$

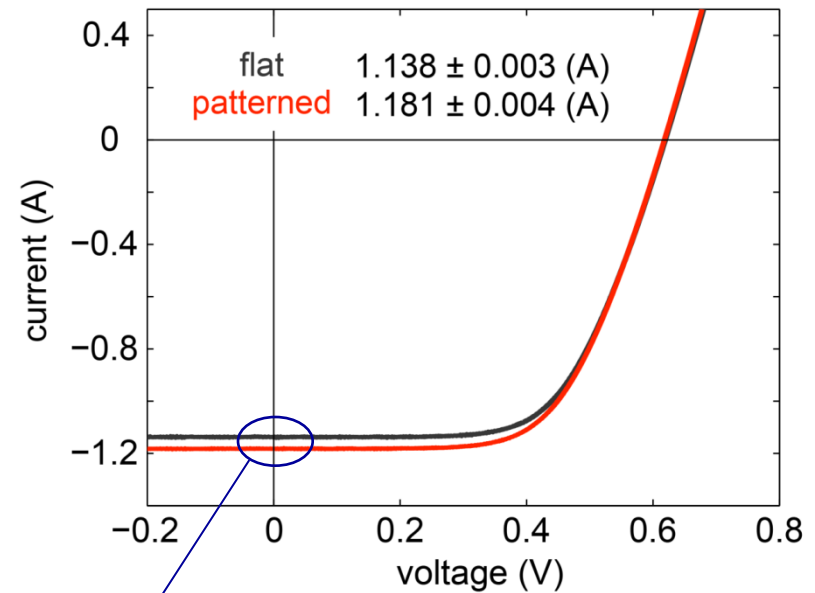
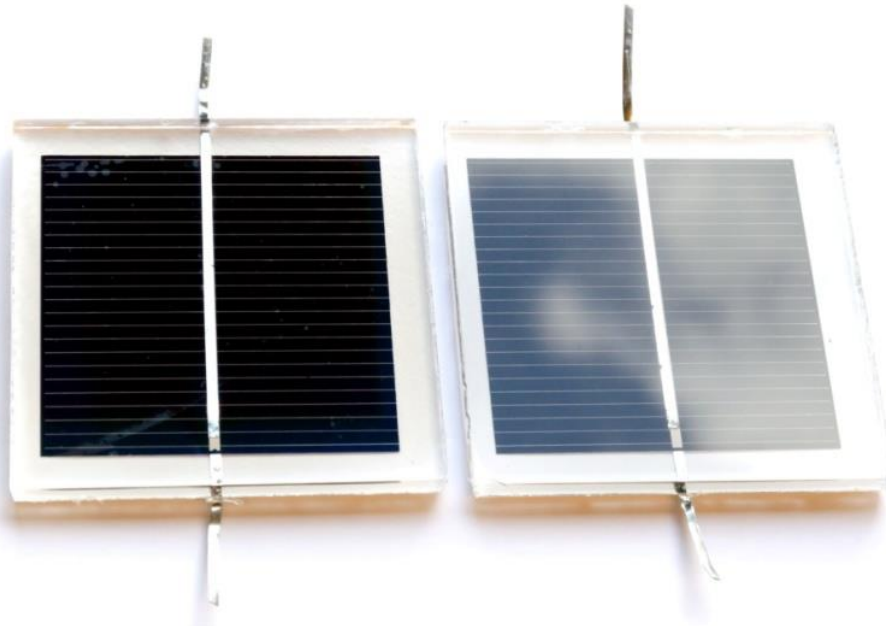


Measured total reflection

Silica nanopattern on glass substrate

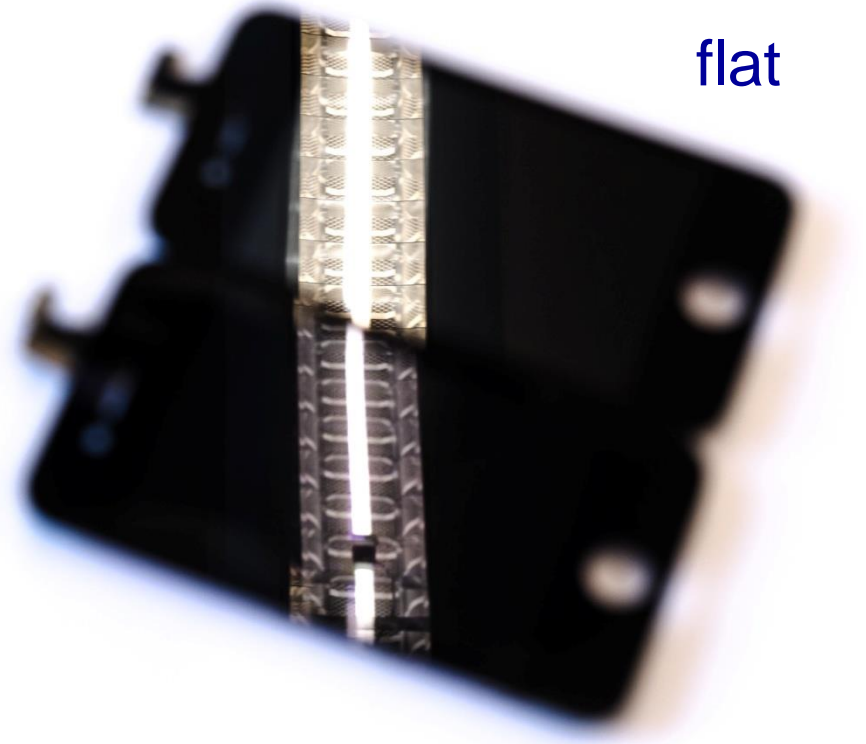


Nano-imprinted encapsulated Si solar cells



3.8% increase in photocurrent

Nano-imprinted smart phones

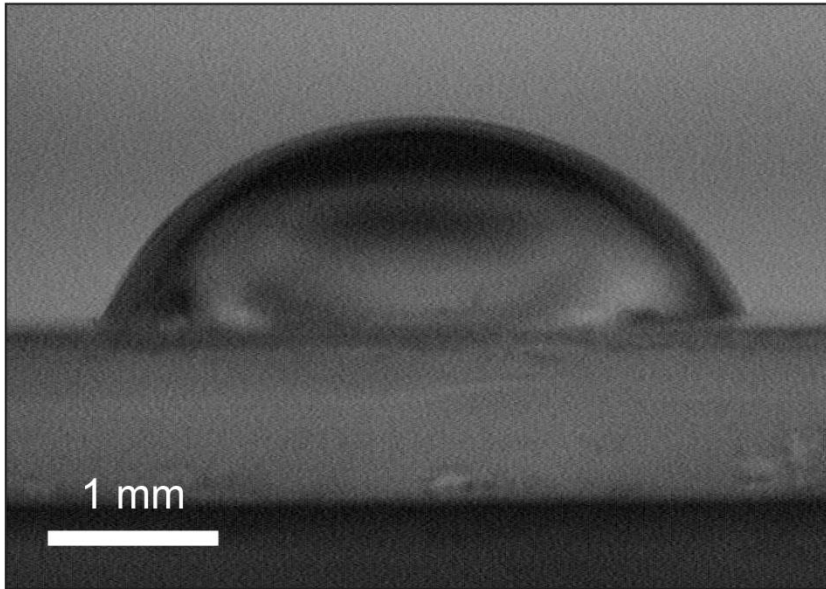


flat

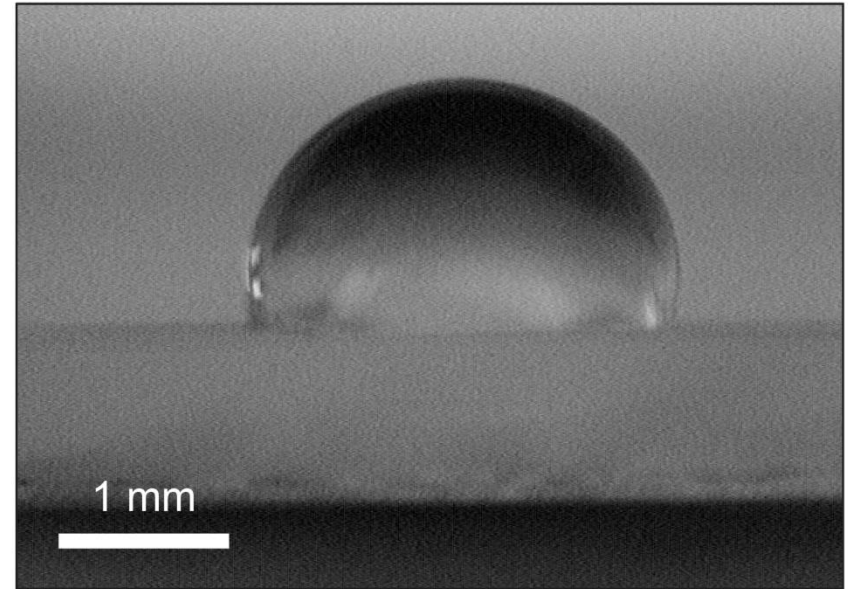
patterned

Hydrophobicity

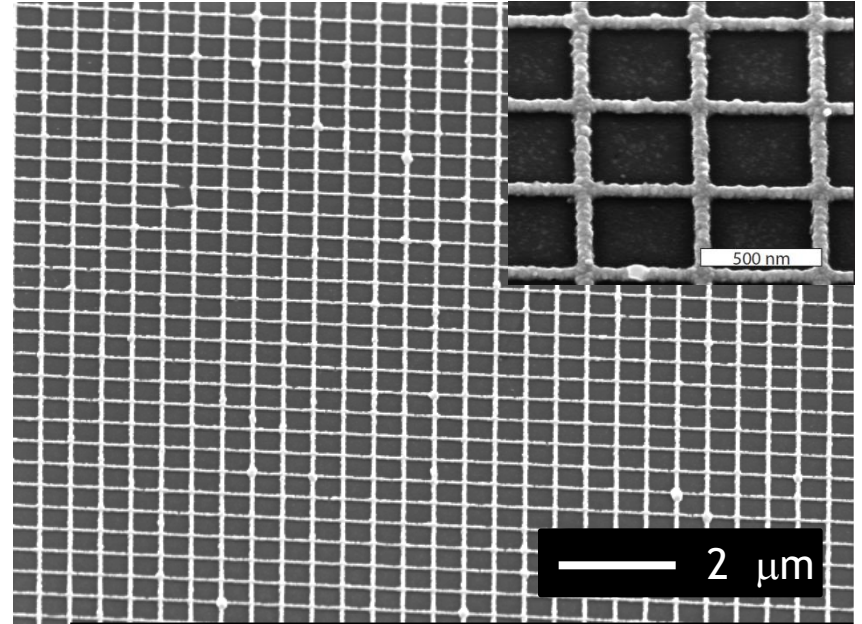
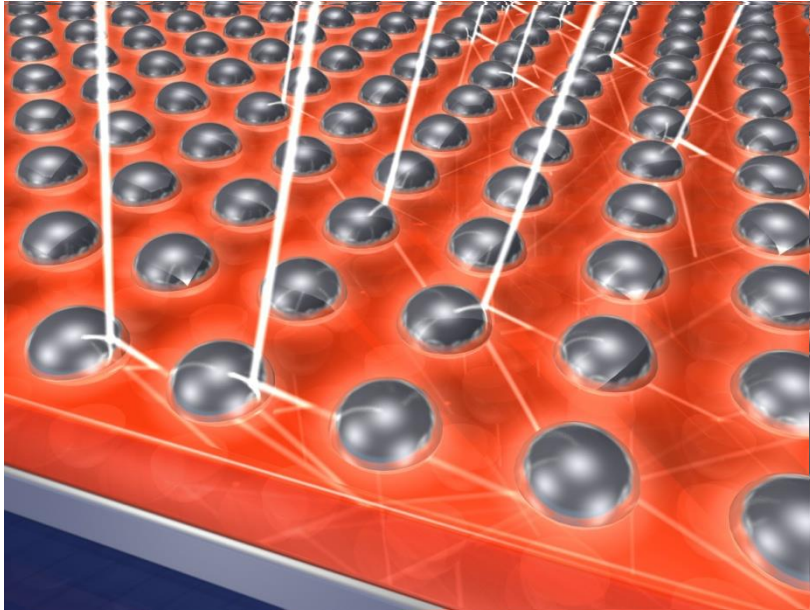
flat



patterned



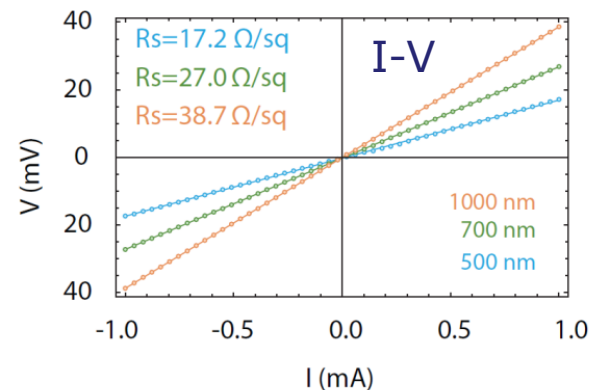
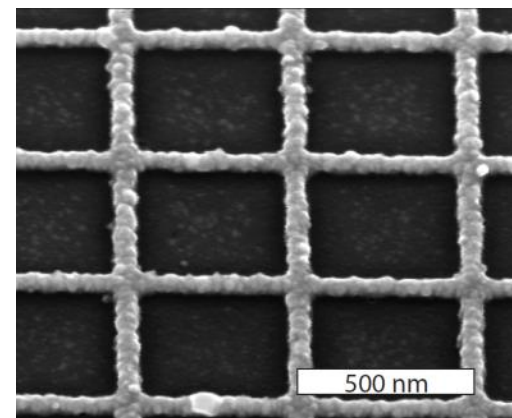
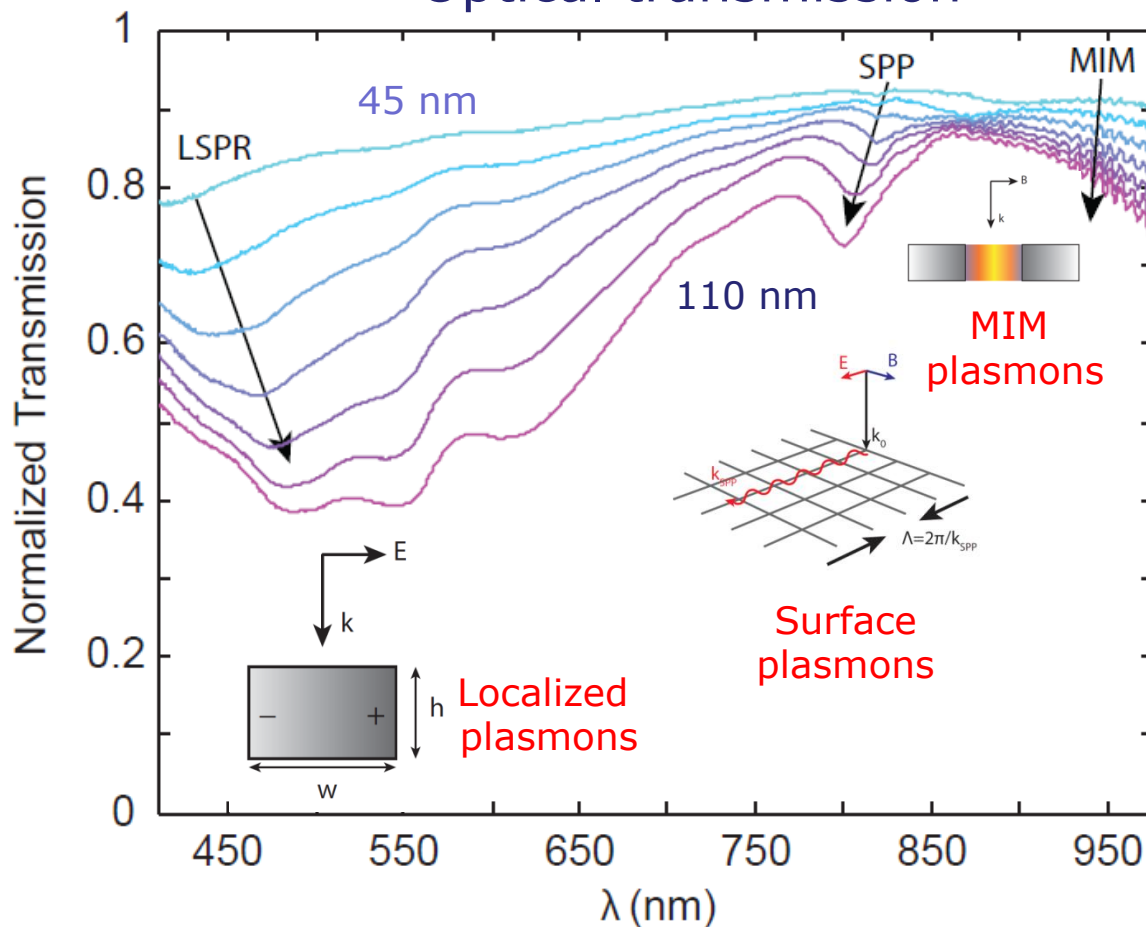
Transparent conductive silver nanowire network



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

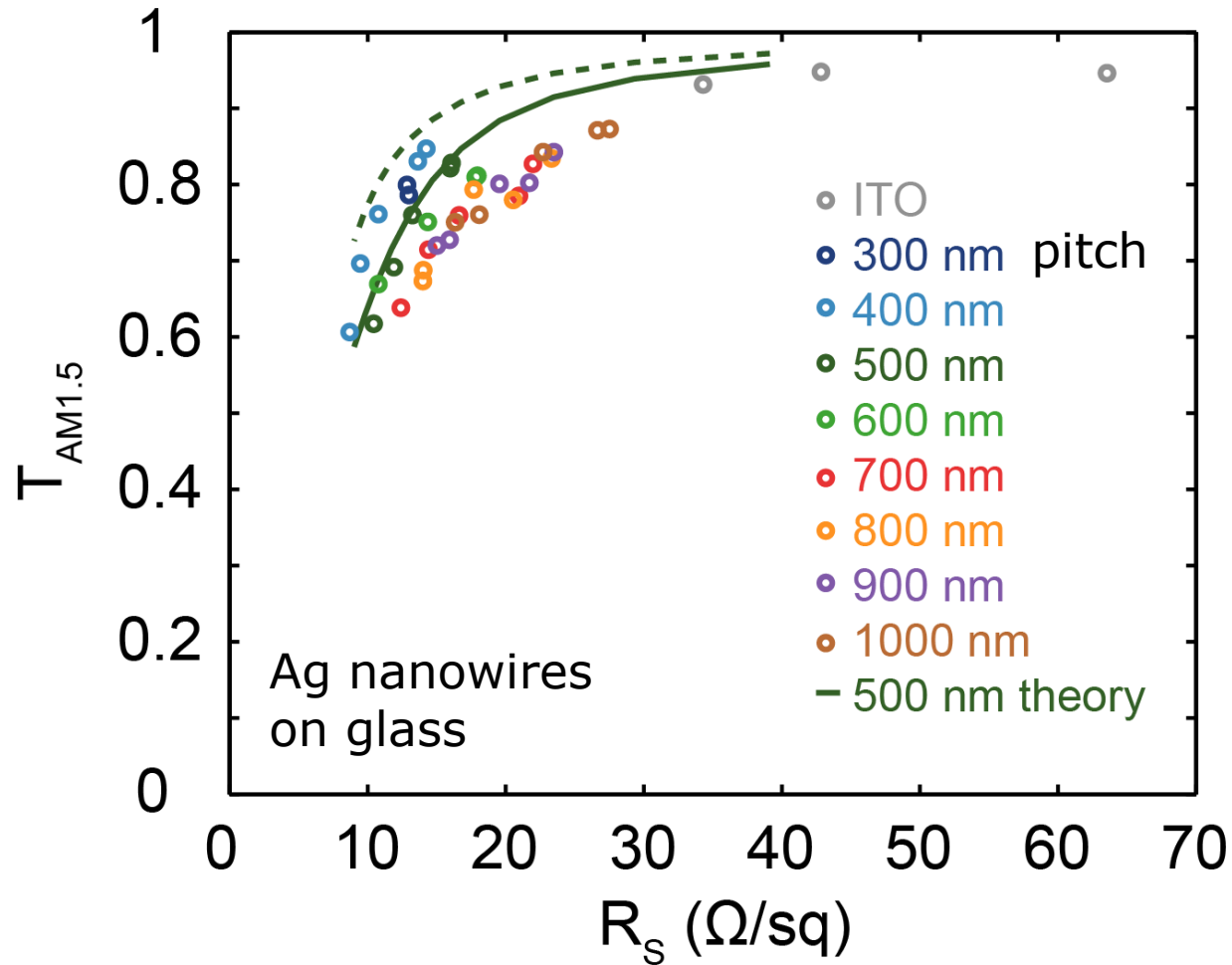
Transparent conductive silver nanowire network

Optical transmission



Ag nanowires
can replace ITO

Ag nanowire network transparent conductors

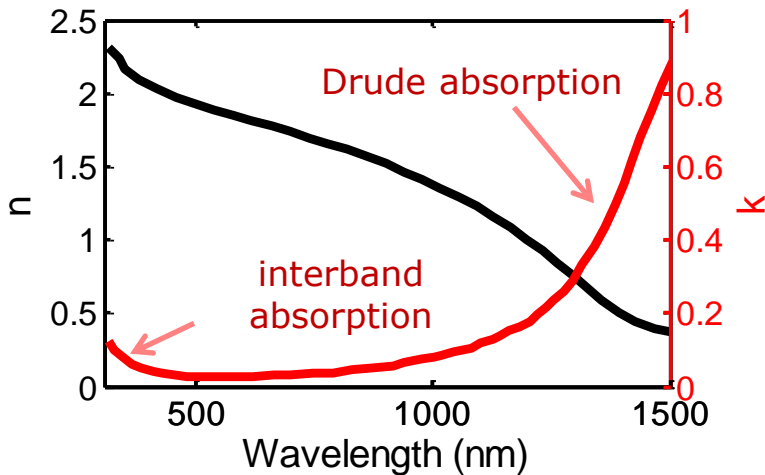


Metal nanowire printed Si HIT cells

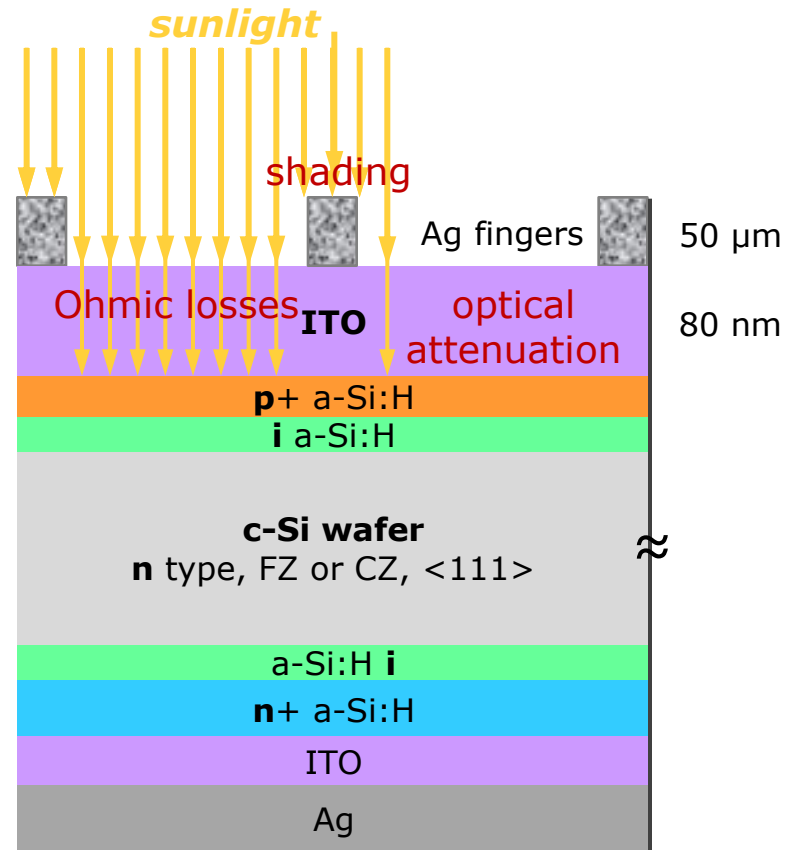
ITO: reduces J_{sc}

- Ohmic losses
- Shading by Ag fingers
- Optical absorption
- Light reflection

ITO dielectric function



Synowicki, Thin Solid Films **313**, 394 (1998)

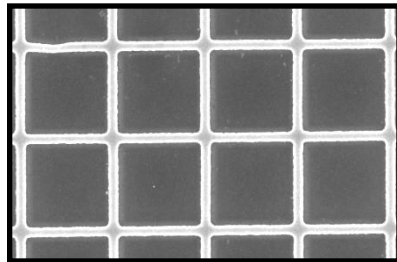


Metal nanowire printed Si HIT solar cells

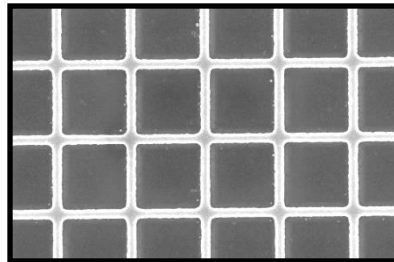
SCIL in silica sol-gel + Ag evaporation + lift-off

Varying array pitch

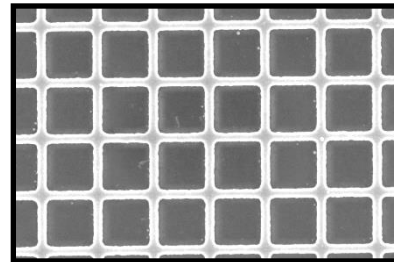
Width
~80 nm



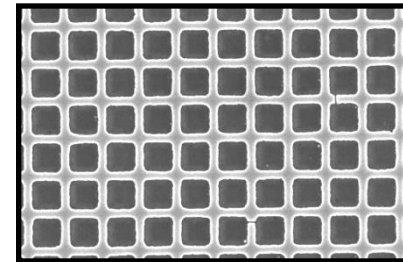
1000 nm



800 nm



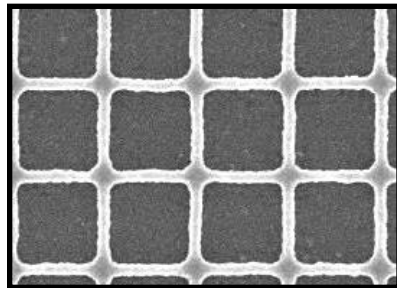
600 nm



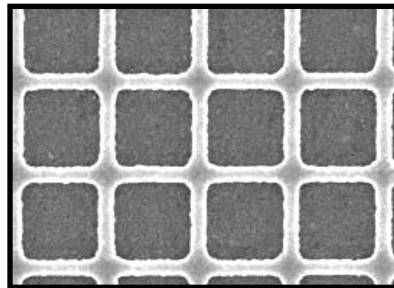
400 nm

Varying wire width

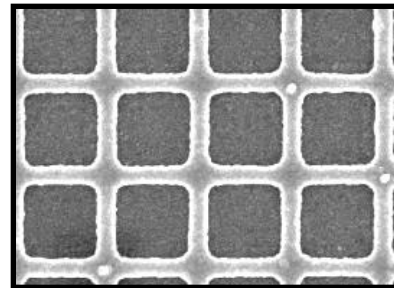
Pitch
500 nm



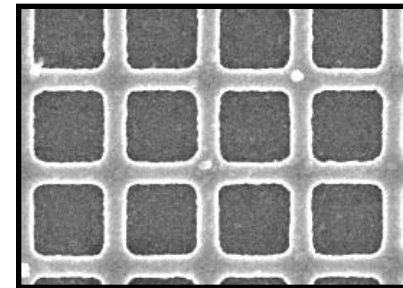
63 nm



82 nm



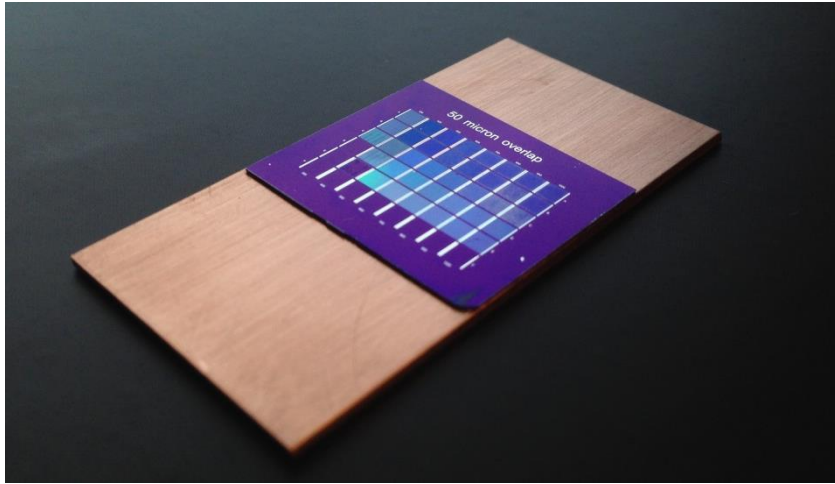
101 nm



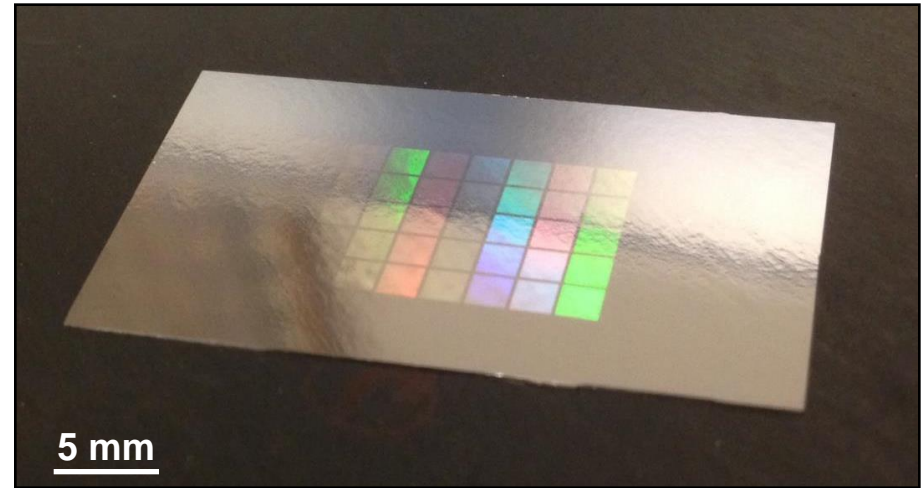
113 nm

SCIL on FZ and CZ Si wafers

Float-zone Si(100)
mechanically polished



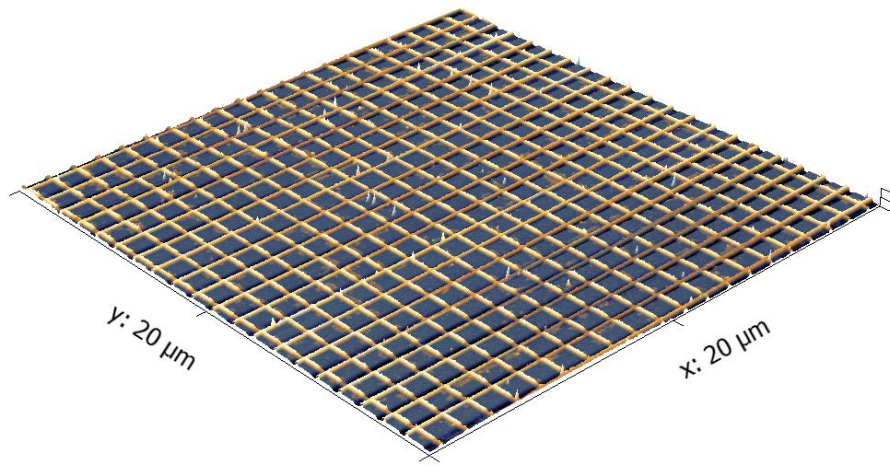
Czochralski-grown Si(111)
chemically polished



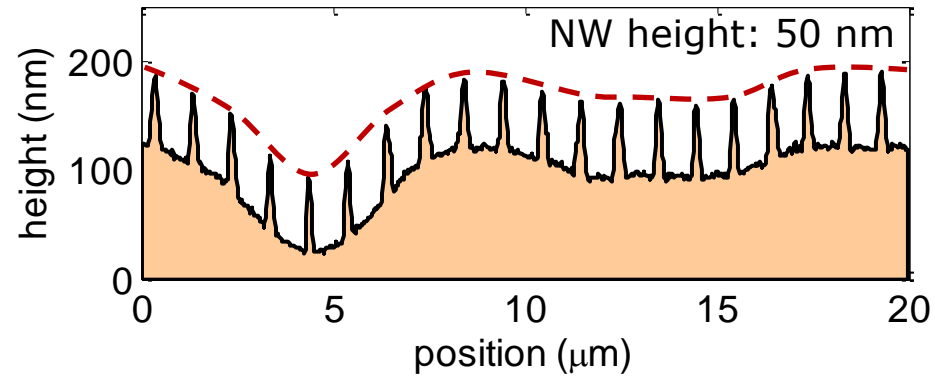
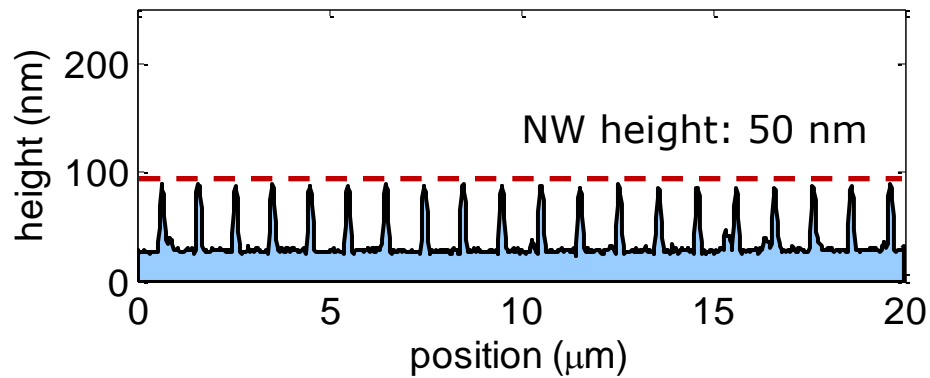
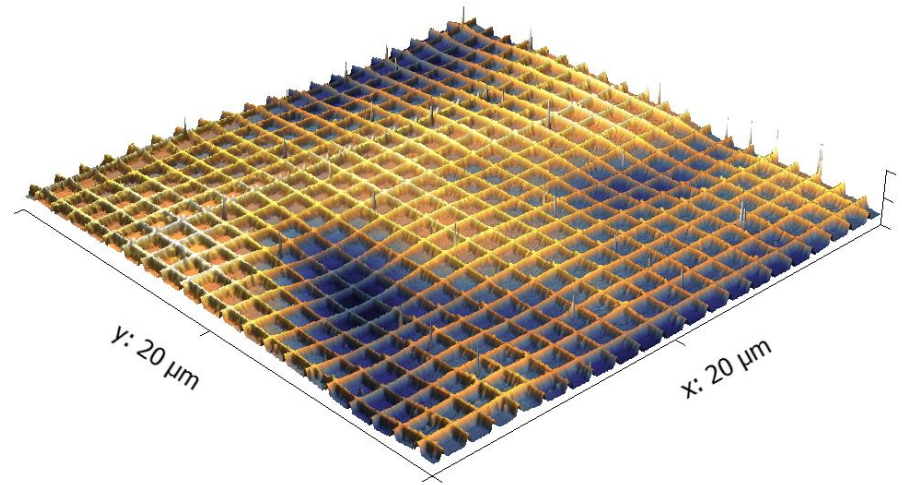
- Flexible PDMS stamp conforms to rough substrate
- No stamp damage due to dust, roughness

Nanoscale conformality of SCIL soft imprint

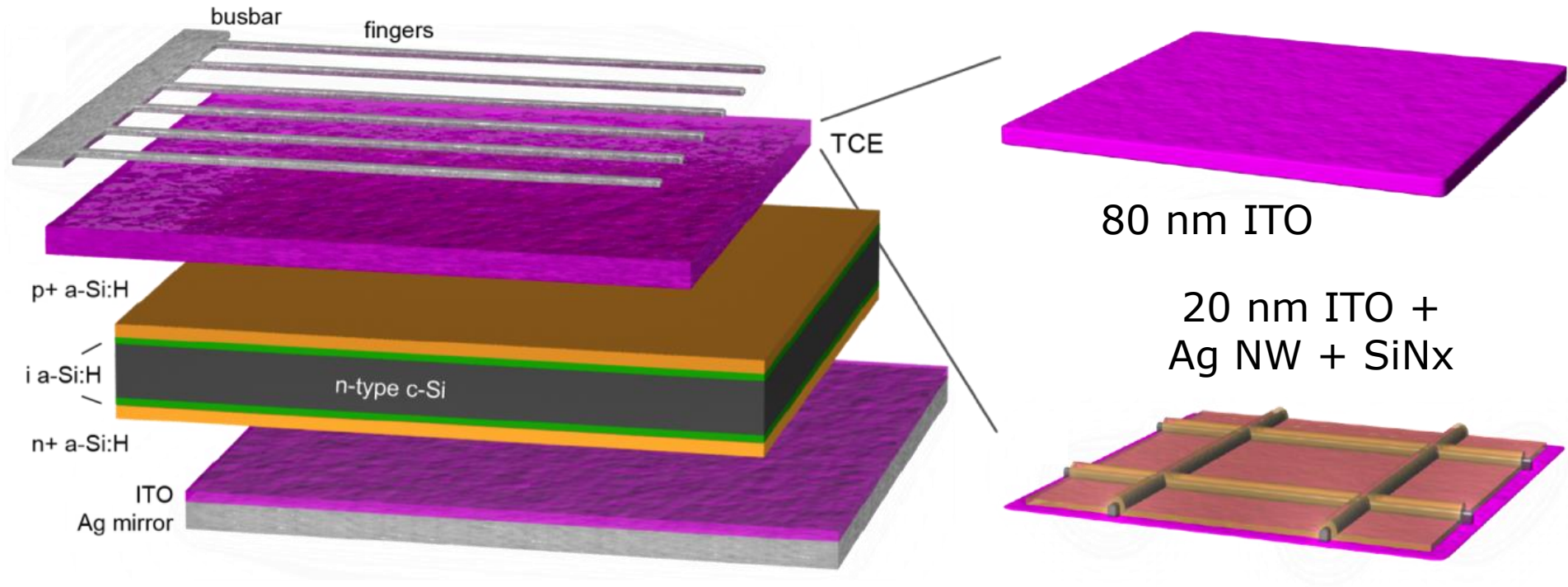
Polished FZ Si



Rough CZ Si



Ag nanowire patterned Si heterojunction solar cells



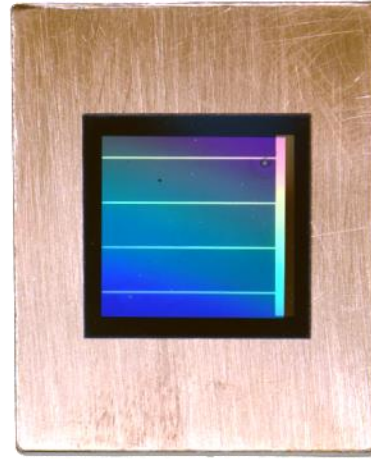
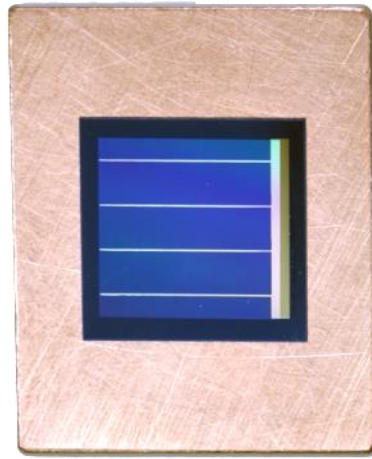
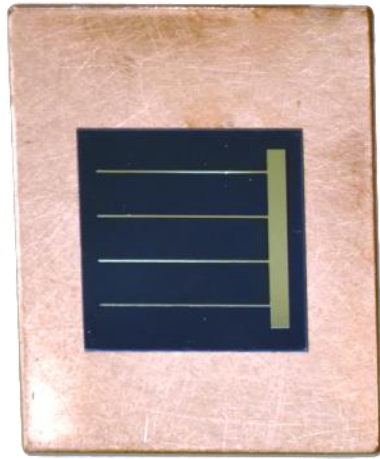
Ag nanowire patterned Si heterojunction solar cells

NW pitch : 1 μm

2 μm

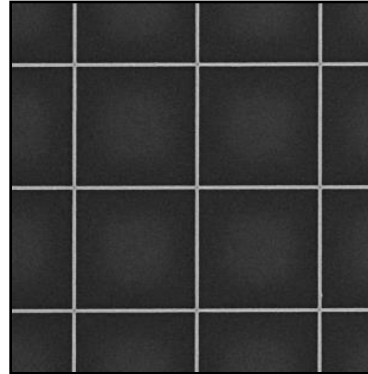
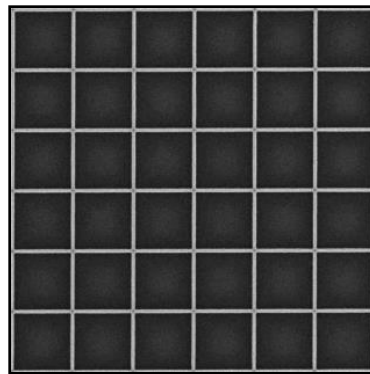
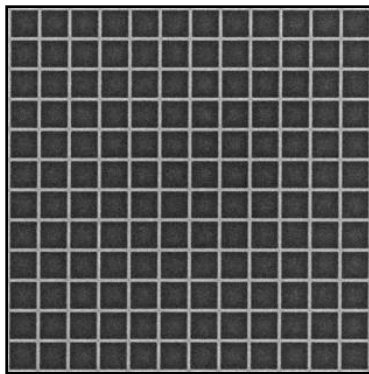
4 μm

ITO only

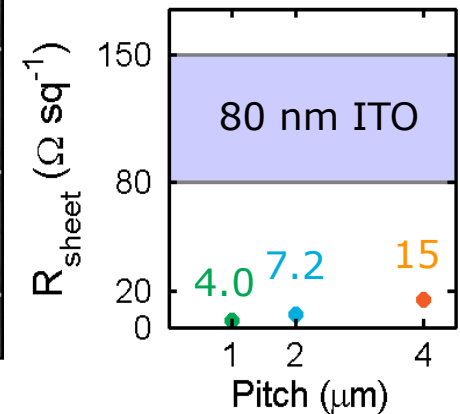


1 cm

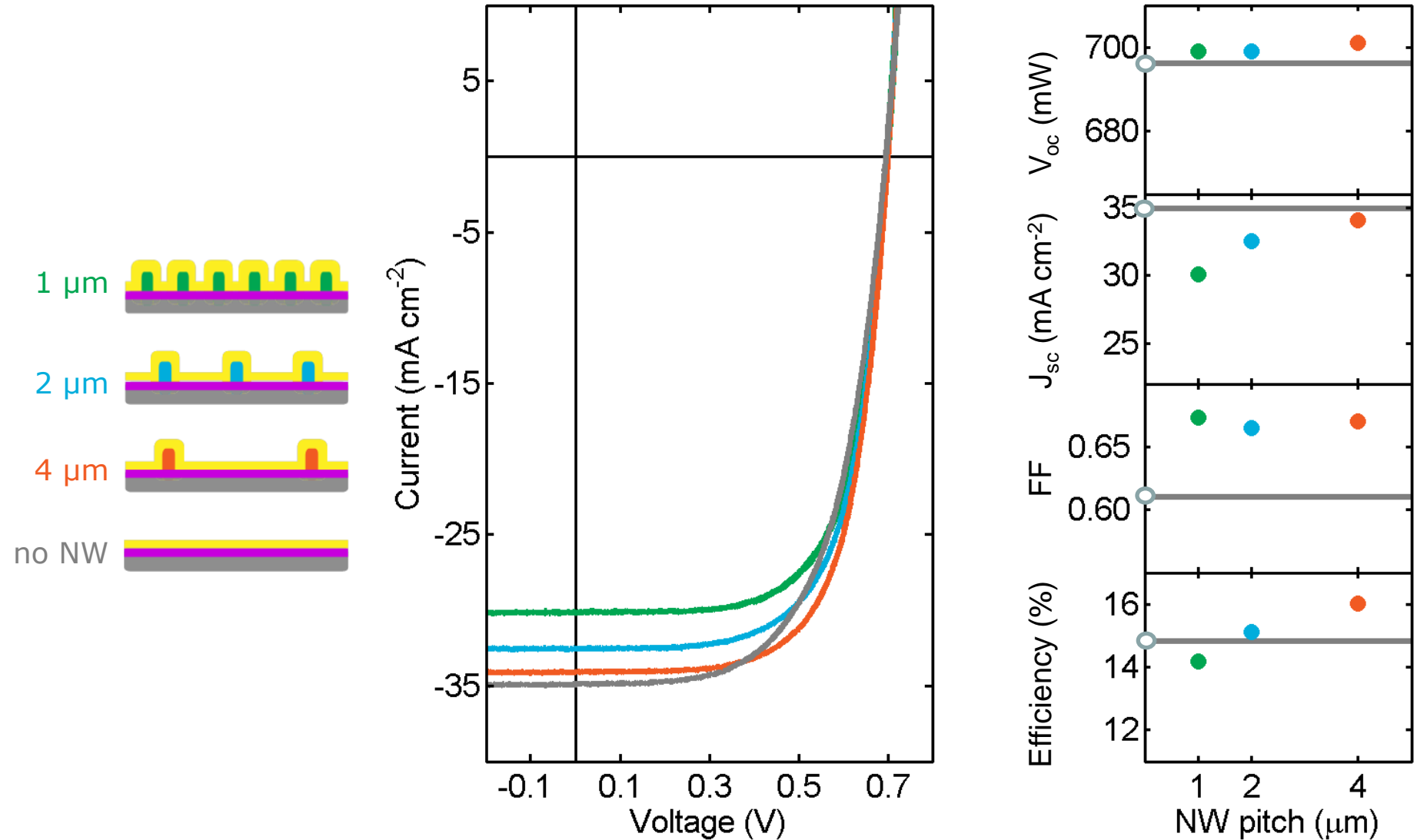
1 μm

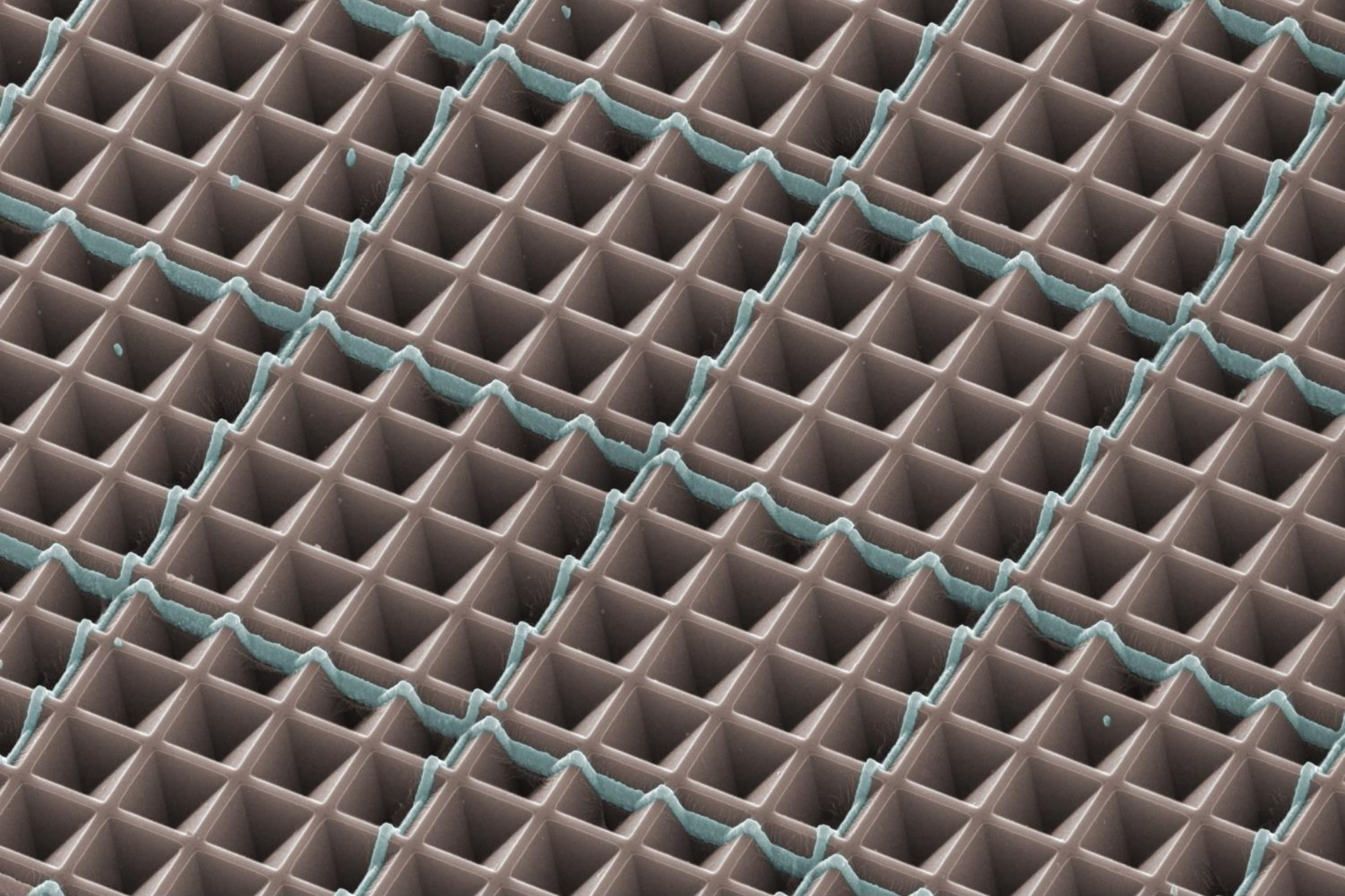



width: 80 nm
height: 120 nm



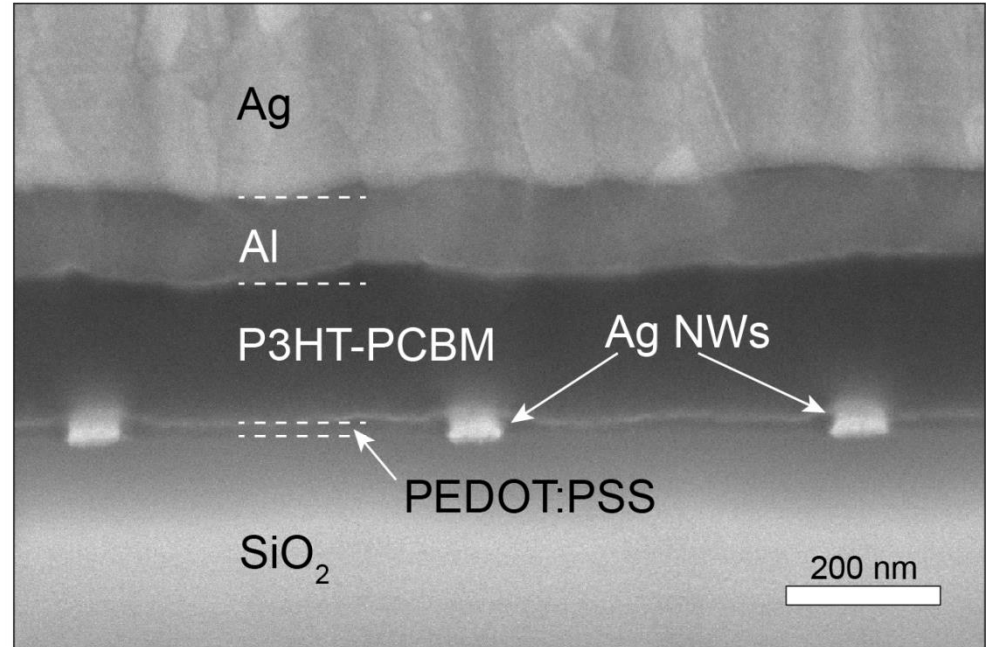
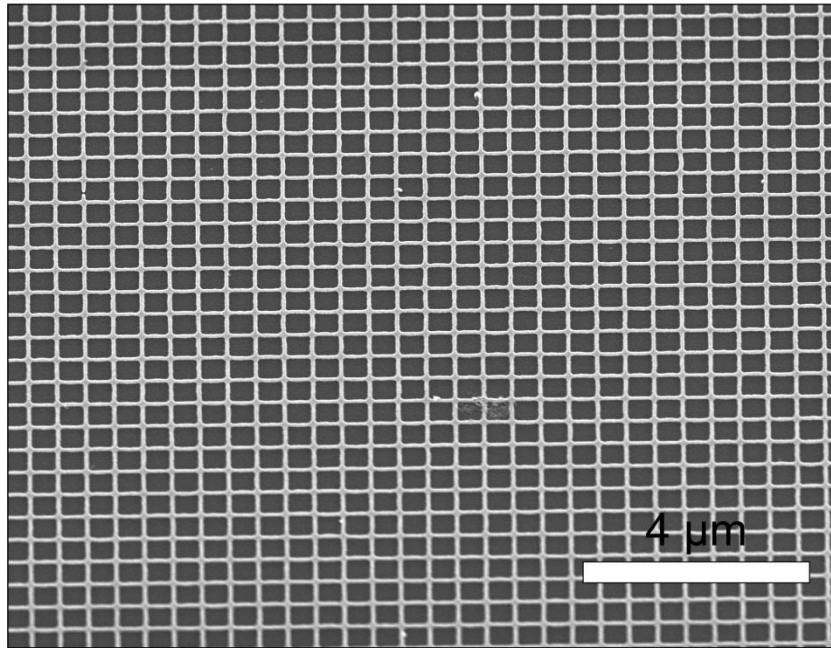
Ag nanowire patterned Si heterojunction solar cells





	11/18/2015	HV	WD	HFW	mag 	mode	det	tilt	3 μm
	11:06:23 AM	10.00 kV	4.0 mm	13.8 μm	15 000 x	SE	TLD	40 $^\circ$	

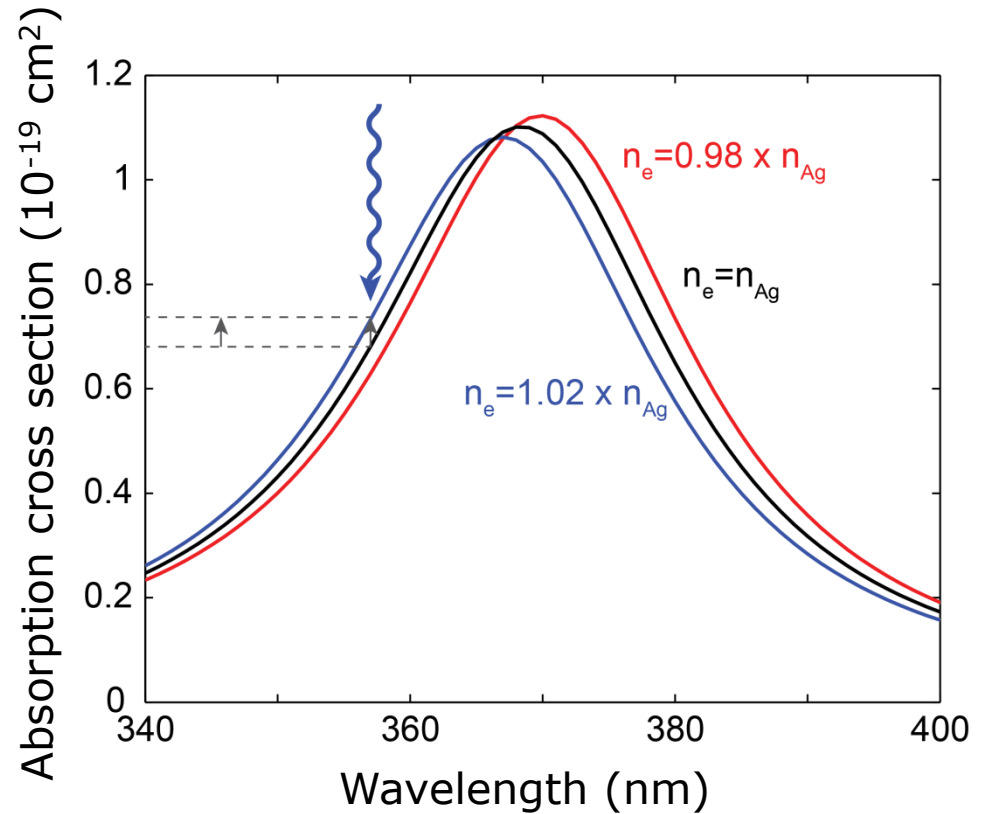
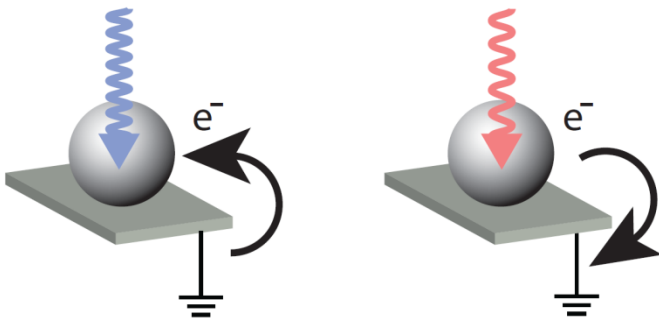
Soft imprinted nanowire networks



Plasmon resonance depends on charge density

20 nm Ag sphere in vacuum

$$\omega_R \propto \omega_p = \sqrt{\frac{n_e e^2}{m^* \epsilon_0}}$$



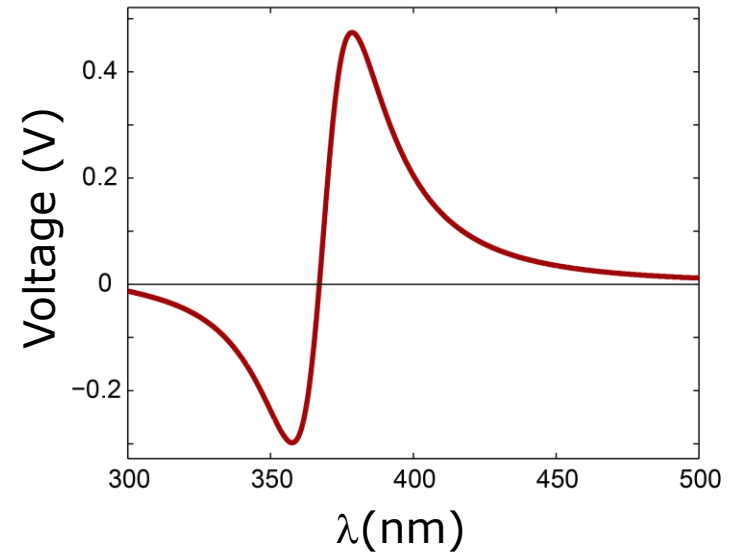
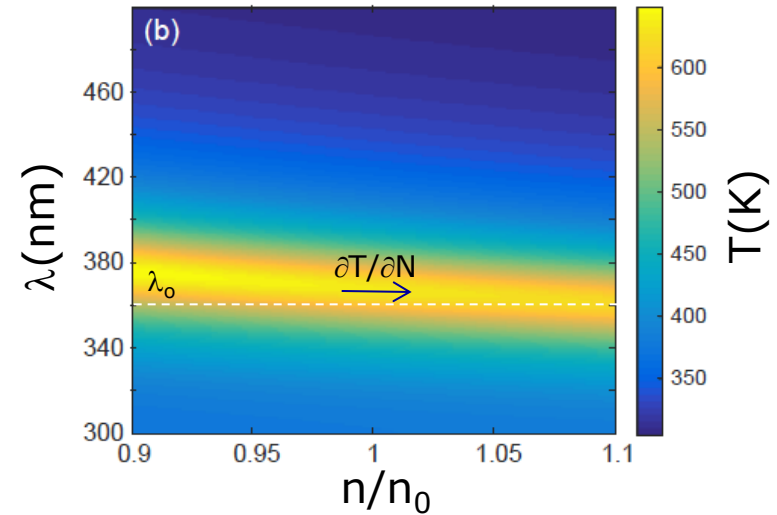
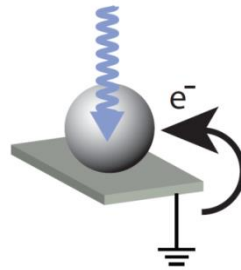
Plasmo-electric effect in metal nanostructures: thermodynamics

Minimize free energy $F(N, T)$

$$\frac{\partial F(N, T)}{\partial N} = \left(\frac{\partial F}{\partial N} \right)_T + \left(\frac{\partial F}{\partial T} \right)_N \frac{\partial T}{\partial N} = 0$$

$$= \mu - S \frac{\partial T}{\partial N} = 0$$

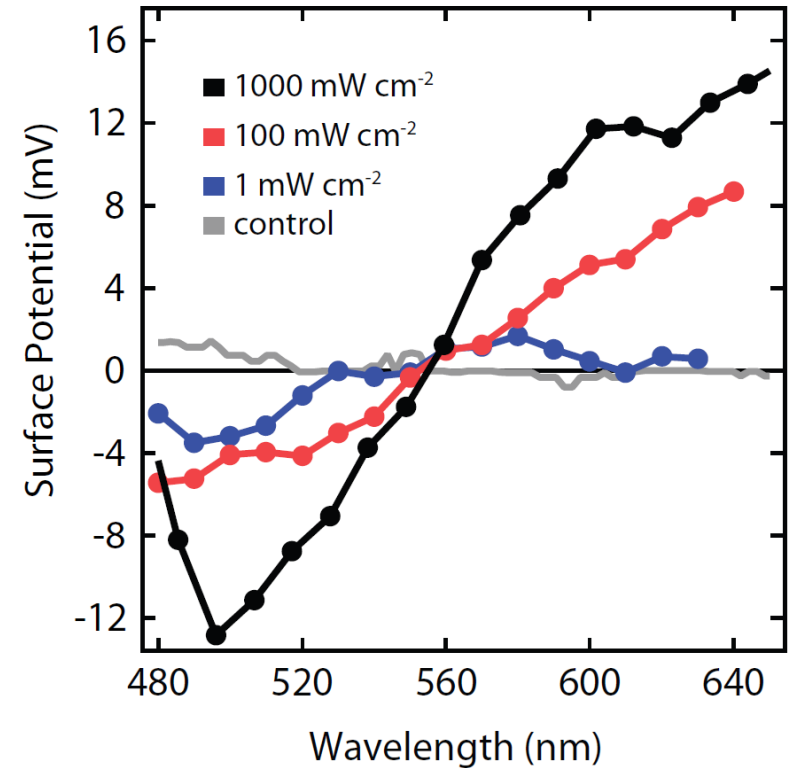
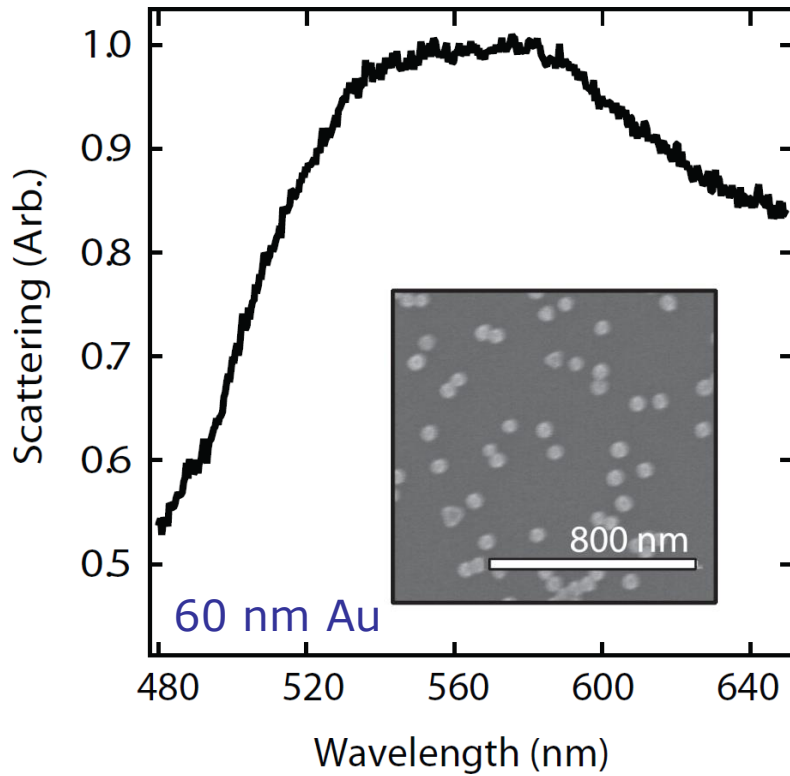
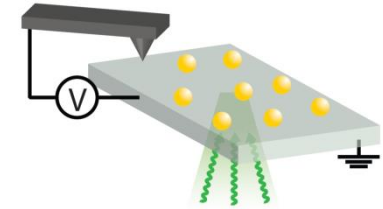
$$\mu(N, T) = S(N, T) \frac{\partial T}{\partial N}$$



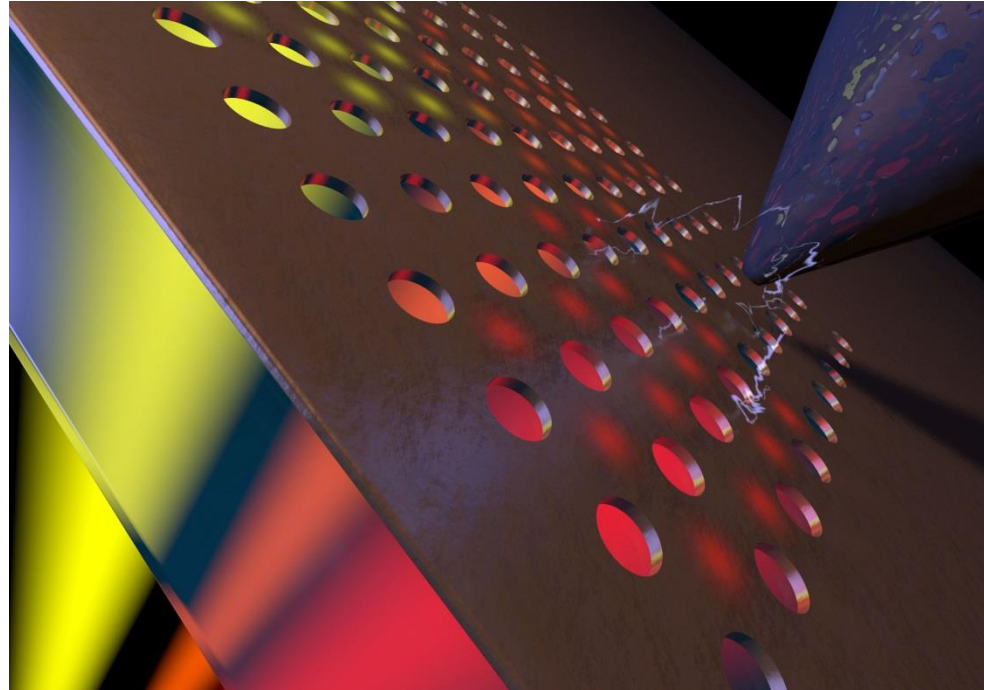
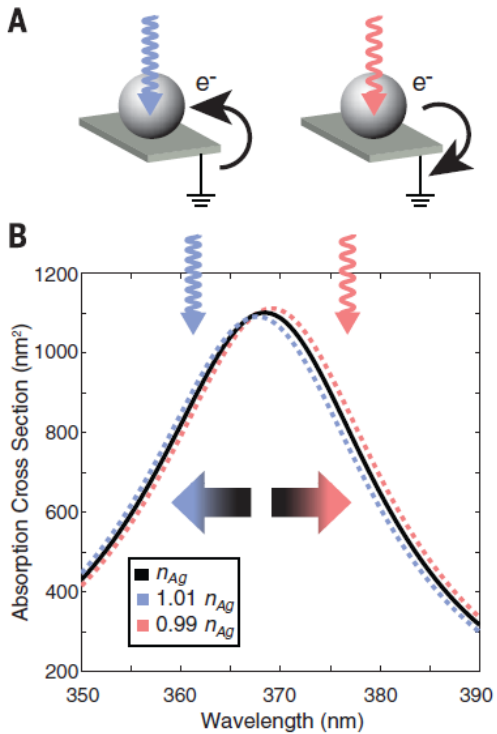
Plasmo-electric potential: experiments

Ag colloids on ITO

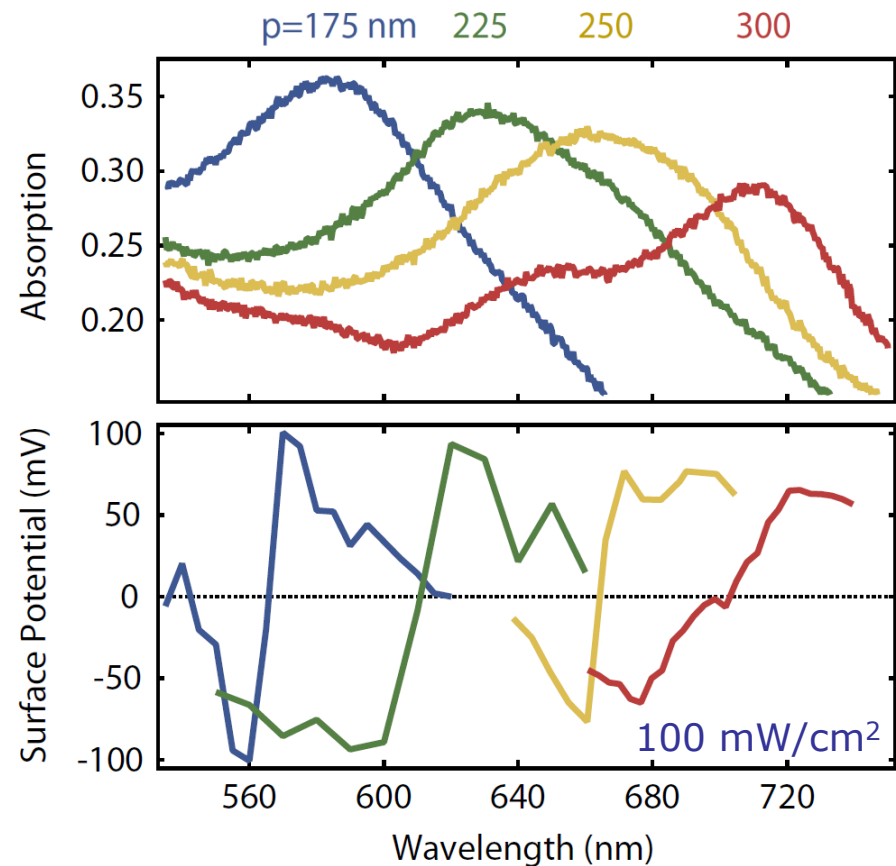
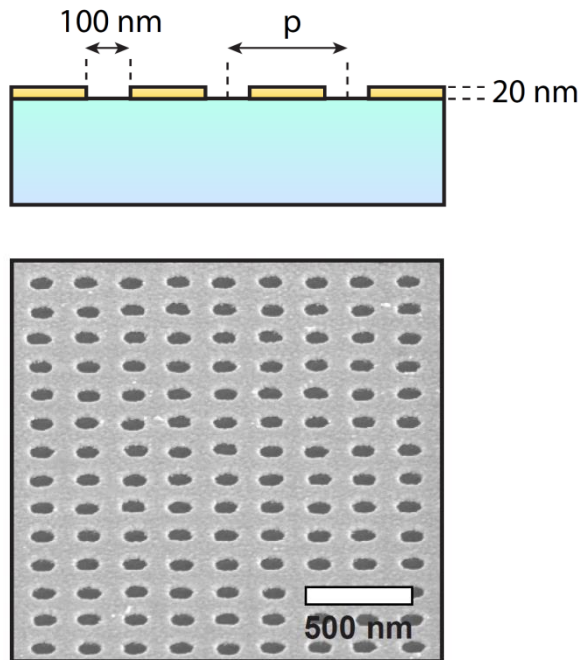
Kelvin probe
microscopy



Plasmo-electric effect in metal nanostructures

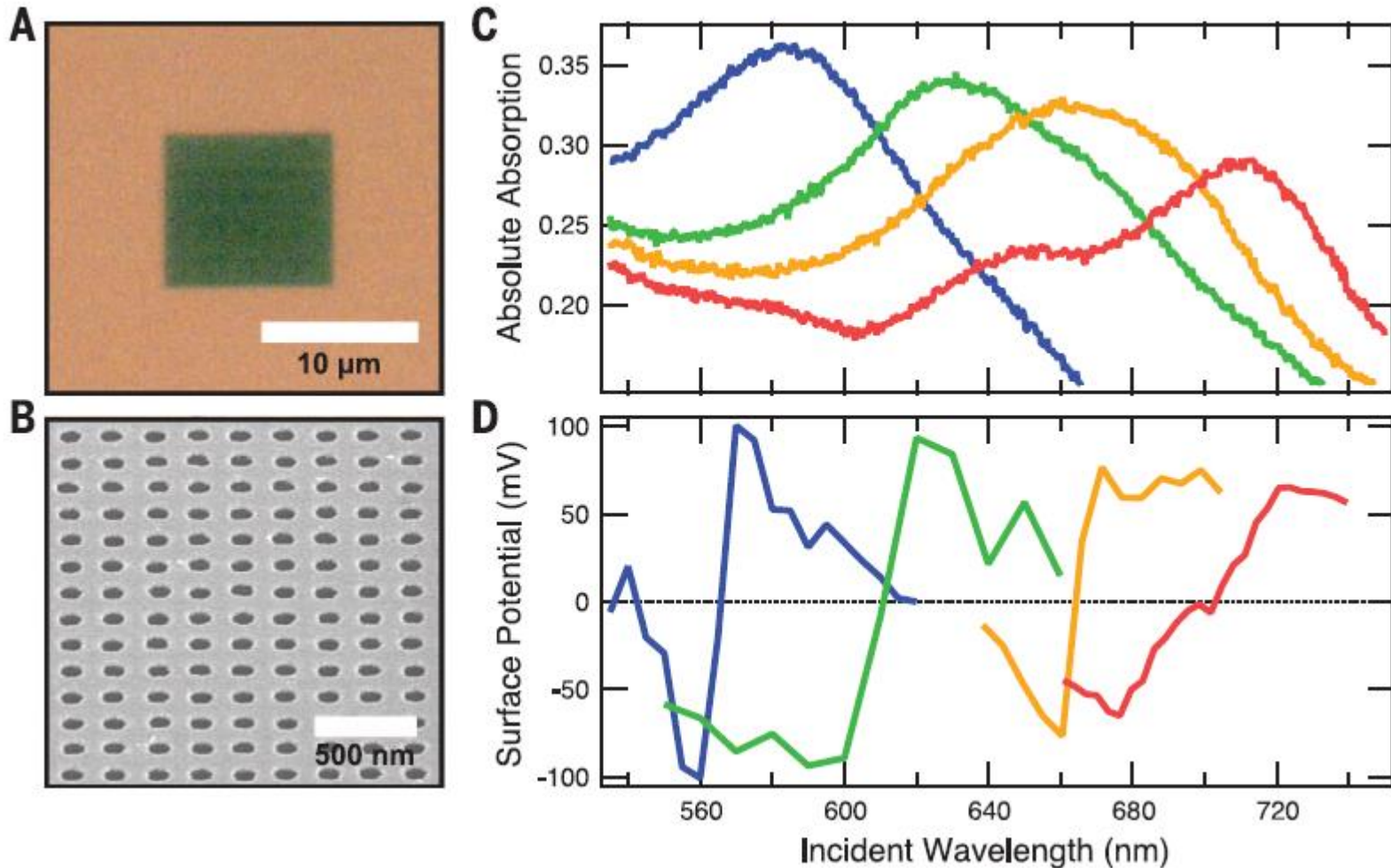


Plasmo-electric effect on resonant Au hole arrays



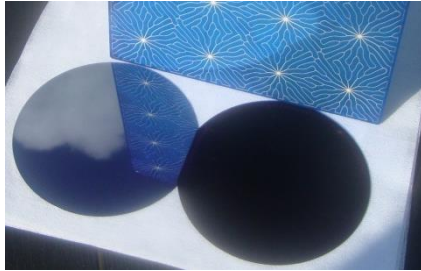
Plasmo-electric potential spectral dependence shifts with array resonance

Plasmo-electric effect in metal nanostructures

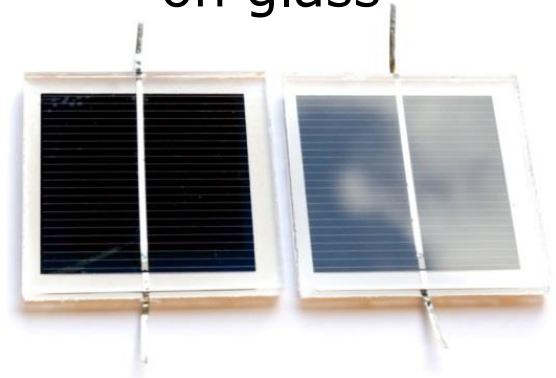


Conclusions

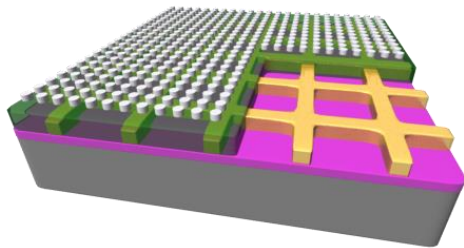
Light coupling
and trapping



Nanopatterned ARC
on glass



Transparent metal
nanowire networks



Plasmoelectric effect in
metal nanostructures

