Sharing research experiences on nano-technologies for photovoltaics

Zi Ouyang (September 2013)

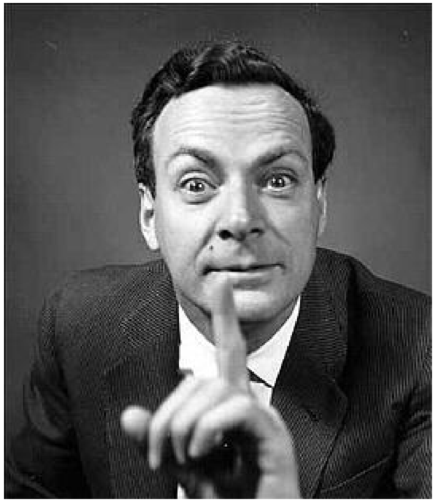
Outline 1

- Nanotechnologies and PV
  - The smaller the better?
  - Why nano for solar cells?
- Nano-photonics light management
- Metal nano-networks for transparent electrodes
- Nano-patterns for local contacts

The smaller the better?

- *"There's Plenty of Room at the Bottom."* – *Richard Feynman 1959*

- We don't understand what happens at small scales very well.
  - Hard to characterise (detection)
  - Hard to calculate (computing power intensive)
  - Hard to understand (non-intuitive)

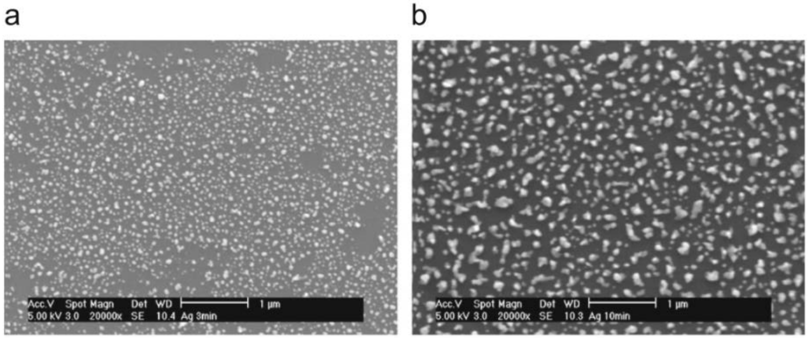


- Inspired by unknown – chance for a leap!

- It is so powerful, but so complex
  - Optimisation lies when we are able to manipulate individual atoms.
  - Nano-scale to micro-scale: 10^3 finer in1-D, 10^6 finer in 2-D and 10^9 finer in 3-D – degrees of complexity!
  - Nano-fabrication: simplicity vs. accuracy

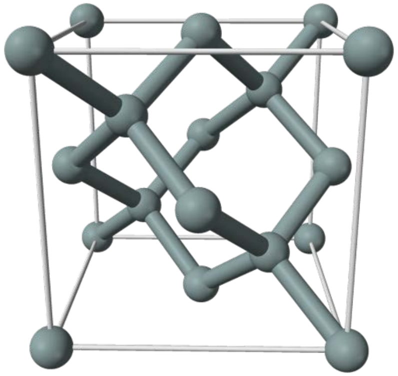
Nano is everywhere

- Almost all the deposition processes start from nano-structures (nuclei), e.g., plating, sputtering, crystal growth, chemical synthesis,



Blackwood, SOLMAT 94 (2010) 1201

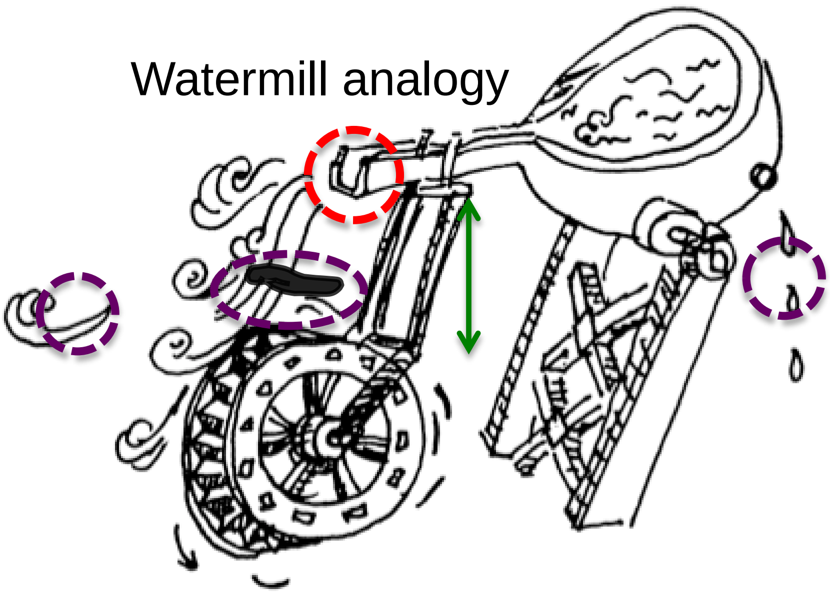
- All the crystals are repeating structures of nano-scale units



Why nano for solar cells?

- High performance: J_{sc} x V_{oc} x FF
  - New physics: nano-photonics, nano-electronics, quantum dots bandgap engineering, etc.

Watermill analogy



- Enabling solar cell fabrication
  - New material features: melting point, viscosity, conductivity, etc.
  - Example: DuPont™ Innovalight™ Silicon Inks, melting point reduction from 1400 ºC to below 500 ºC. Very high specific surface area!

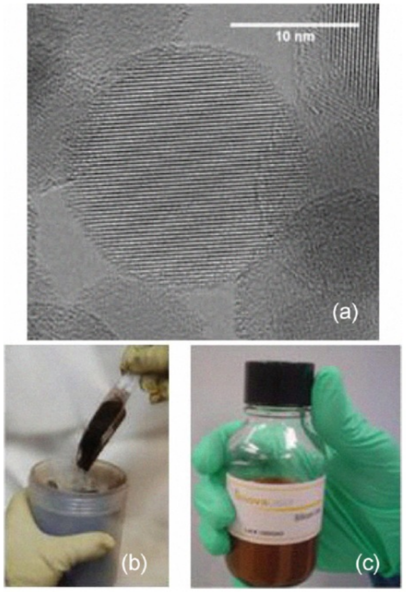


Fig. 1: TEM image of Innovalight's silicon nanoparticles (a), Silicon nanoparticle powder (b), Silicon Ink (c).

Antoniadis, IEEE PVSC (2009) 650

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Outline 2

- Nanotechnologies and PV
- Nano-photonics light management
  - What is nano-photonics?
  - Plasmonics and PV applications
  - Chances and challenges of nano-photonic strategies
- Metal nano-networks for transparent electrodes
- Nano-patterns for local contacts

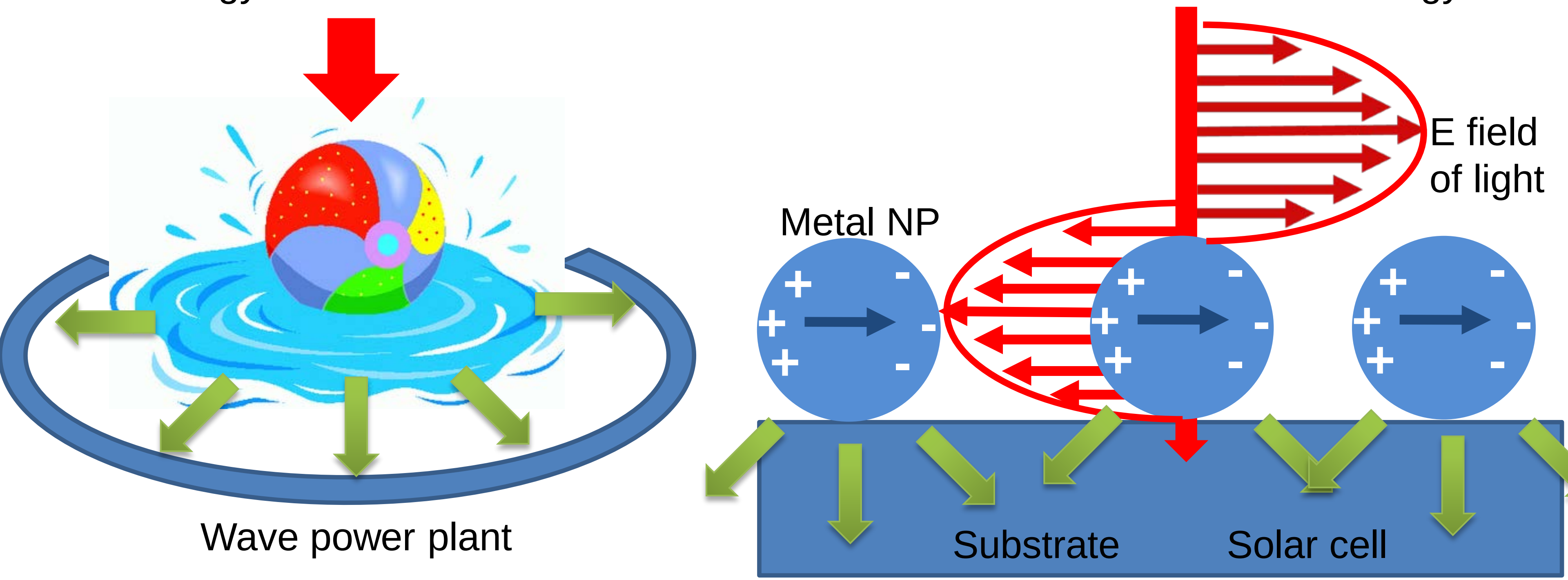
What is nano-photonics?

- Common definition:
  1. incident light in the nano-scale, or
  2. **illuminated materials in the nano-scale**
- What is unique to be in the nano-scale?
  - The feature sizes of the materials are equal to or smaller than the wavelengths of the light;
  - the light cannot be considered as a ray any more – classical ray tracing model & refractive index model may be INVALID;
  - Treating light as electromagnetic wave is needed – kind of *first principle* but computing power intensive (e.g., Finite-difference time domain (FDTD) method based on solving the Maxwell equations in partial differential form at local grids);
  - Classical electrodynamics is usually enough but quantum mechanics may be needed when the light is confined in semiconductors, e.g., optical bandgap, photonic crystals, etc.
- Popular nano-photonic technologies for PV:
  - Plasmonics, photonic crystals, whispering gallery mode, etc.

Plasmonics: how it works

- Throw a ball in water
- The ball moves up and down
- The energy propagates as wave in the water (with higher density)
- Build a wave power plant and collect the energy!!

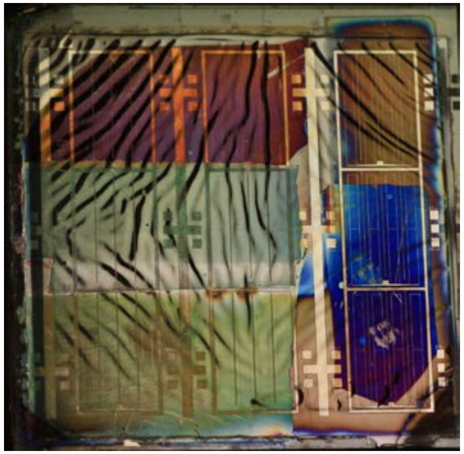
- Light strikes on metal nano-particles (NPs)
- Electrons in the NPs oscillate collectively
- The oscillations re-radiate electromagnetic waves that propagate to the substrate (with higher optical density)
- Put a solar cell and collect the energy!!



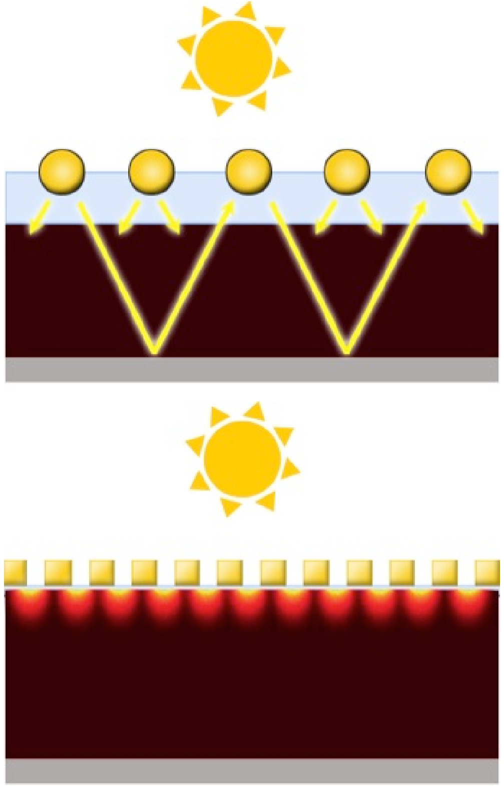
Water polo analogy (inspired by Catchpole's balloon analogy)

Plasmonics: attraction for PV

- Three attractive features (water polo analogy):
  - Anti-reflection (front surface)
  - Scattering (front and rear surfaces)
  - Near-field concentration (trapped mode)



- UNSW is a pioneer for plasmonic solar cell research that first experimentally demonstrated light trapping benefits. *S. Pillai et al., JAP 101 (2007) 093105*

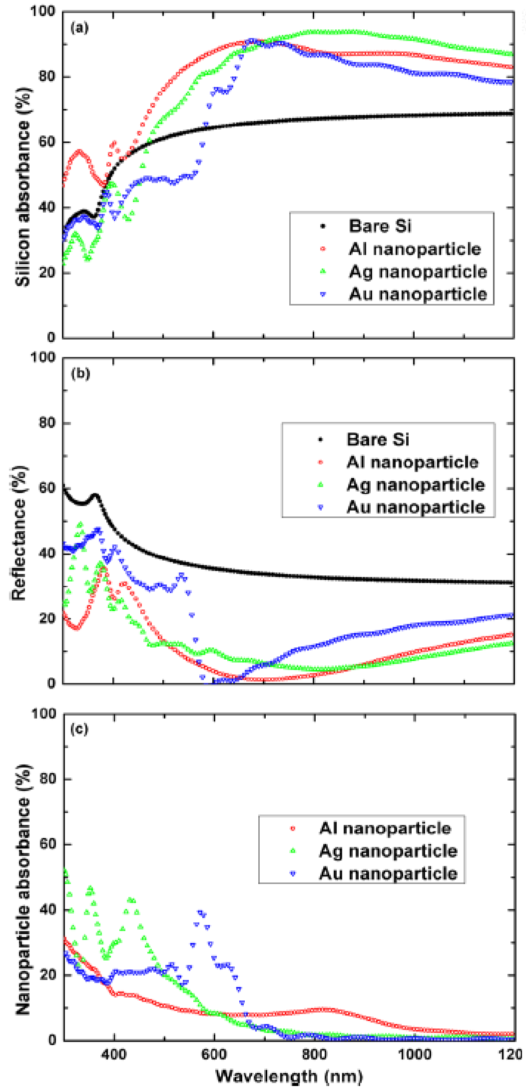


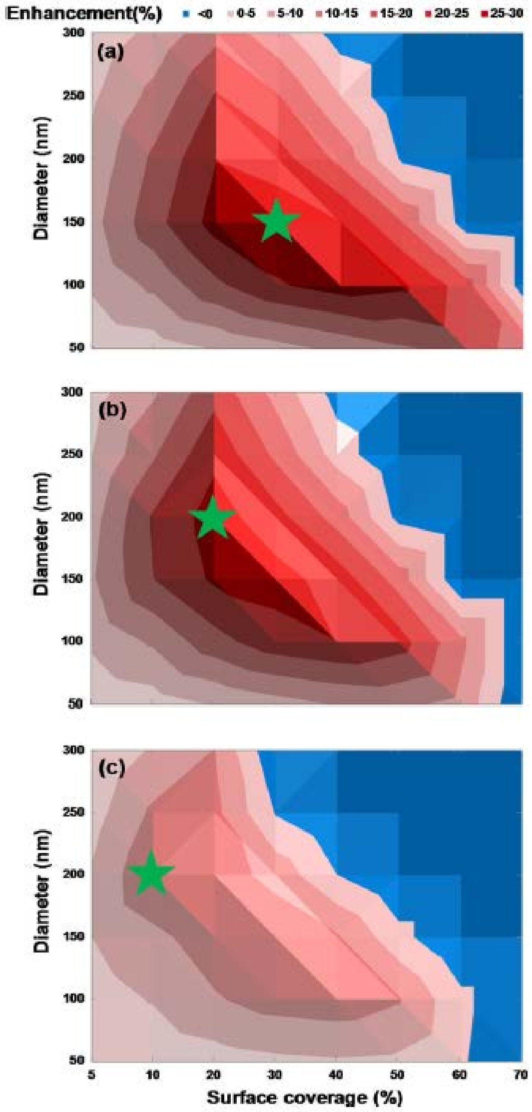
M. Gu, Z. Ouyang, et al., Nanophotonics (2012)18

Plasmonics: design considerations (1)

1. Metal material to use
   – Different materials have different scattering, absorption properties at distinctive resonance wavelengths
   – Most metals result in a transmission dip at short wavelengths due to (i) destructive interference between the scattered and incident light and (ii) parasitic absorption.
   – Ag and Au had been the “standard” plasmonic materials until recently we found Al!
   – Al suffers from fabrication difficulties
   – Very good practice

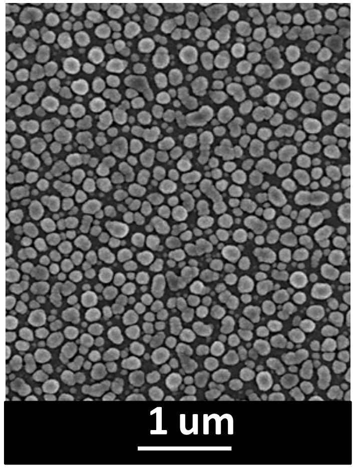
Y. Zhang, Z. Ouyang, et al., APL100 (2012) 151101



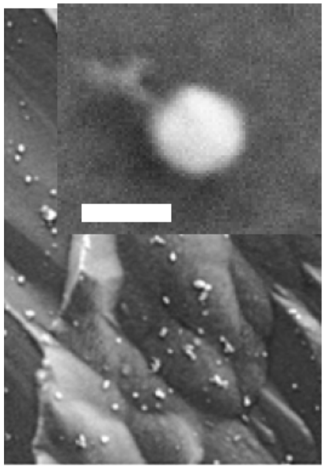


Plasmonics: design considerations (2)

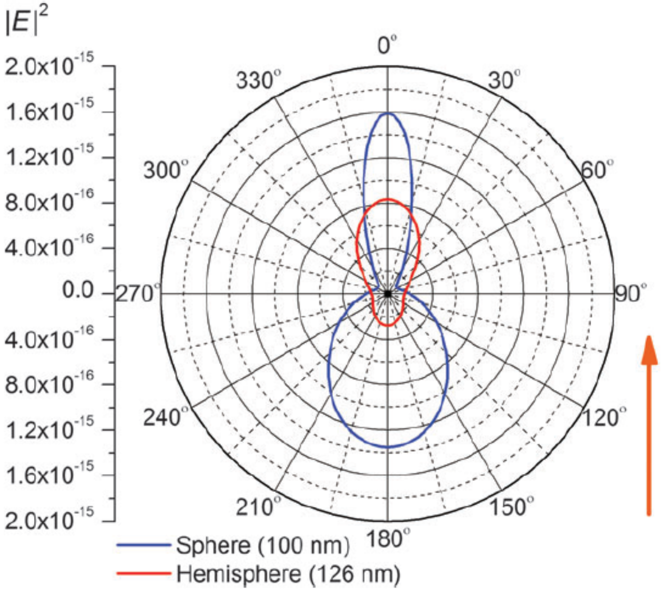
2. Fabrication methods: physical vs. chemical
   - Control fineness
   - Fabrication cost
   - Shape limits (sphere vs. hemisphere)
   - Material limits (oxidation rate?)



Z. Ouyang, S. Pillai, et al., APL 96 (2010) 261109



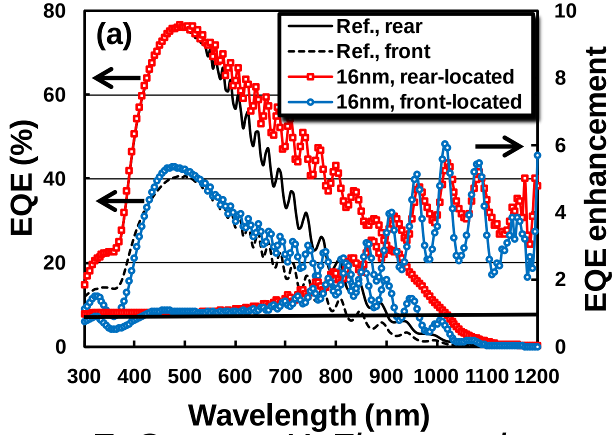
Y. Zhang, Z. Ouyang, et al., APL 100 (2012) 151101



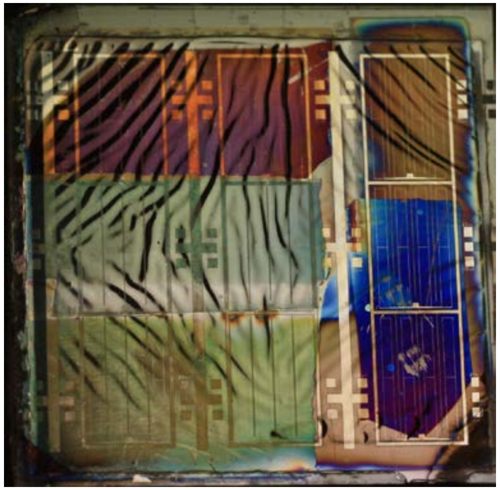
M. Gu, Z. Ouyang, et al., Nanophotonics (2012)18

Plasmonics: design considerations (3)

3. Rear-located, front-located or embedded?
   - Depending on the material and fabrication methods
   - Embedded is very challenging due to recombination
4. Dielectric environment
5. NP size



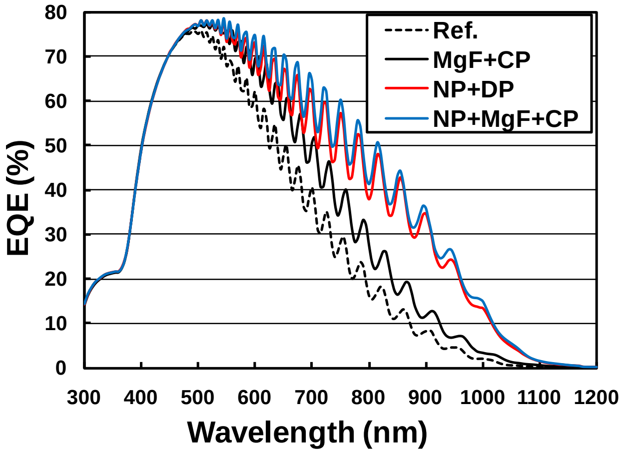
Z. Ouyang, X. Zhao, et al., PIP 19 (2011) 917



S1 *Jsc* enh. -3% small Ag thin nitride	**S2 *Jsc* enh. -2%** small Ag thin nitride	**S3 *Jsc* enh. -3%** reference
S4 *Jsc* enh. 17% large Ag thin nitride	**S5 *Jsc* enh. 19%** large Ag thin nitride	**S6 *Jsc* enh. -6%** small Ag thick nitride
S7 *Jsc* enh. 9% large Ag thick nitride	**S8 *Jsc* enh. 17%** large Ag thick nitride	**S9 *Jsc* enh. -3%** small Ag thick nitride

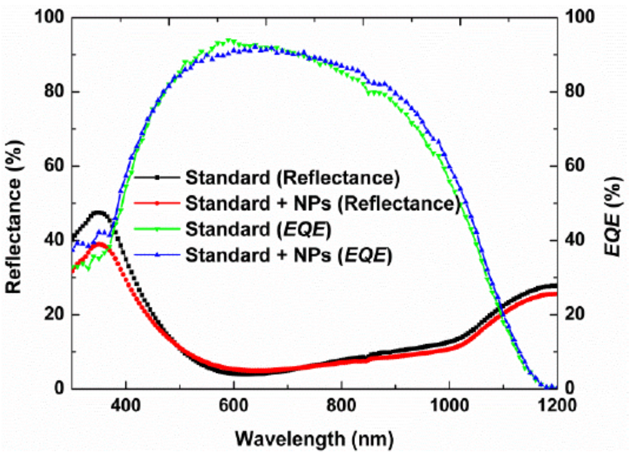
Plasmonics: design considerations (4)

6. Hybrid structures with other light trapping schemes
   - Polycrystalline Si thin-film solar cells: rear NP + BSR paint: J_{sc} from 14.85 to 21.42 mA/cm^2 (enhancement of 44%)
   - Multicrystalline Si wafer solar cells: texturing + ARC + front NP: 35 to 35.5 mA/cm^2. (Calculated to be more than 1 mA/cm^2 enhancement)



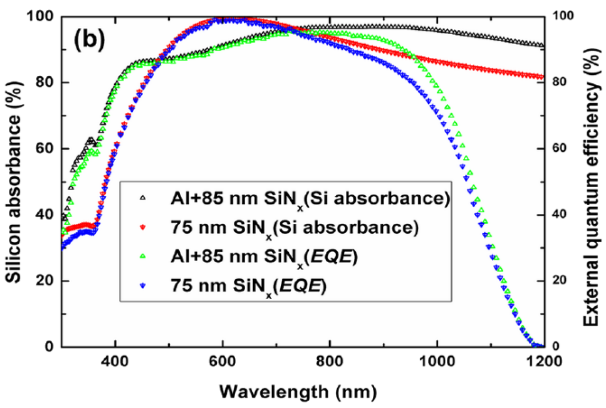
Poly-Si thin-film experimental

Z. Ouyang, X. Zhao, et al., PIP 19 (2011) 917



Multi-Si wafer experimental

Z. Ouyang, X. Zhao, et al., PIP 19 (2011) 917

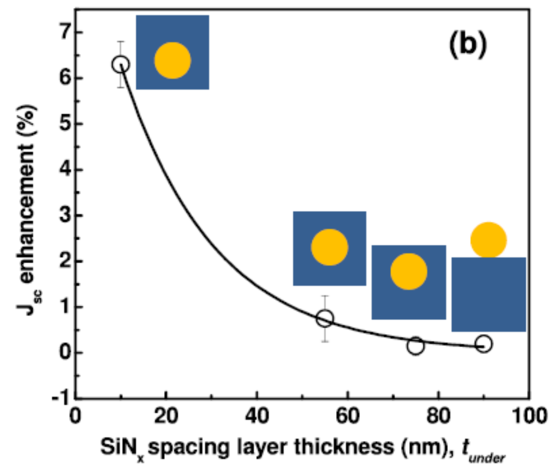


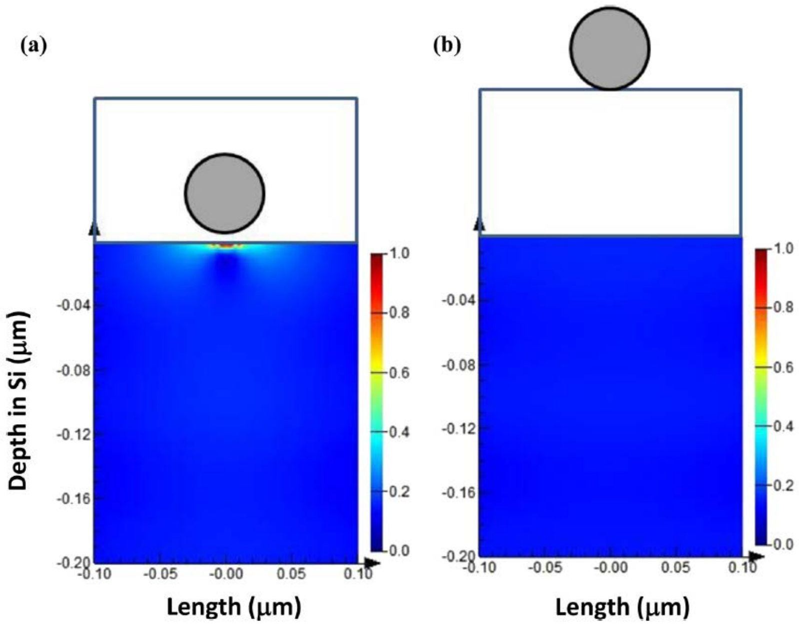
Planar Si wafer simulated

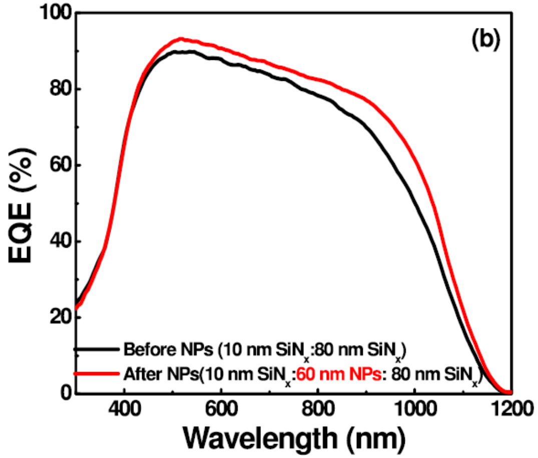
Y. Zhang, Z. Ouyang, et al., APL100 (2012) 151101

Plasmonics: design considerations (5)

7. Possible near-field enhancement
   - Experiment on the c-Si/ SiN_x/ NP system.
   - As moving further away from Si, lower J_{sc} enhancement observed, exponentially decay
   - Absorption competition between NP and Si in the near-field? Further study needed!





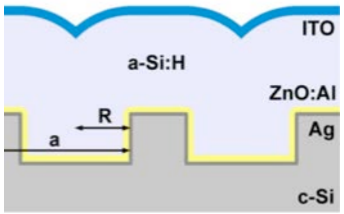


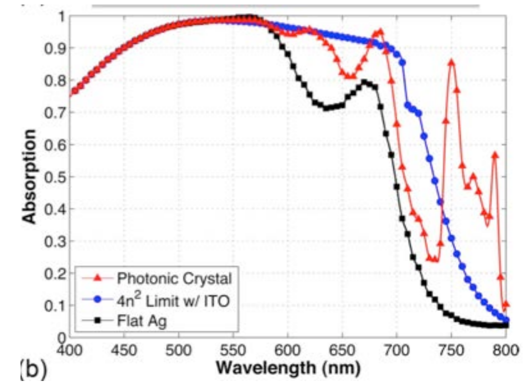
N. Fahim, Z. Ouyang et al., APL 101 (2012) 261102

Other nano-photonic designs

- Photonic crystals
  - Using quantum confinement to control the propagation of the light
- Whispering gallery mode

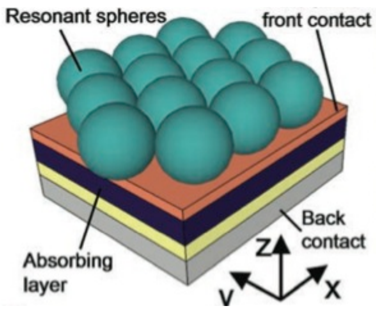
Photonic crystal

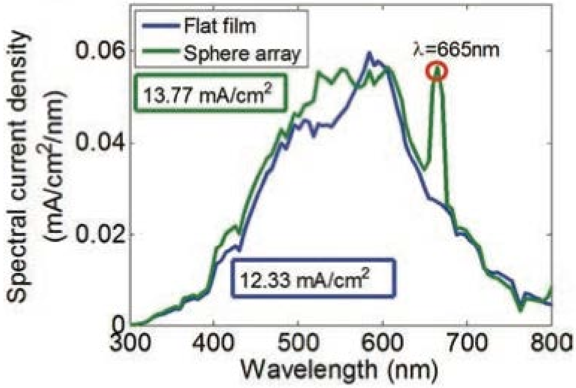




B. Curtin, APL 96 (2009) 231102

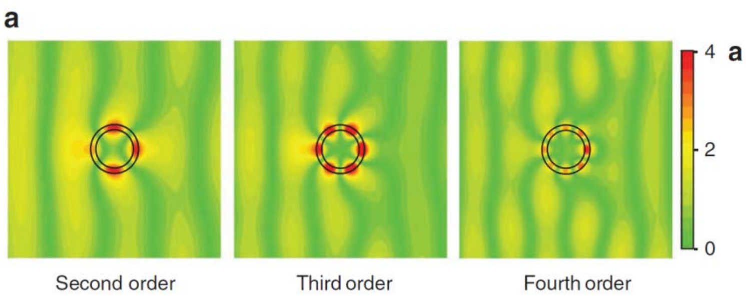
St Paul's Cathedral

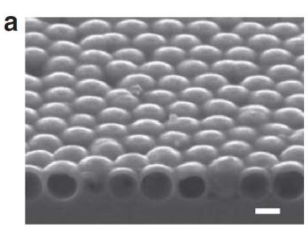


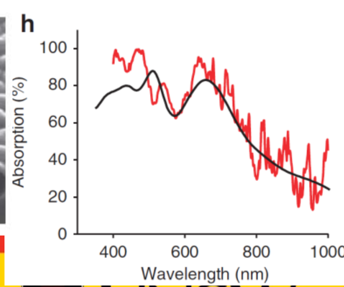


J. Grandidier, D. Callahan, et al., Advanced Materials 23 (2011) 1272

Temple of Heaven



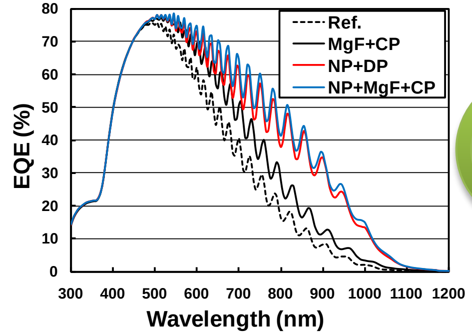


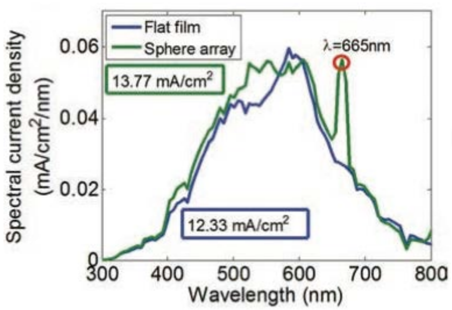


Y. Yao, J. Yao, et al., Nature Communications 3 (2012) 664

Nano-photonics: chances and challenges

- Broadband: most of the designs only respond to a narrow frequency band, which is more for sense, less for PV





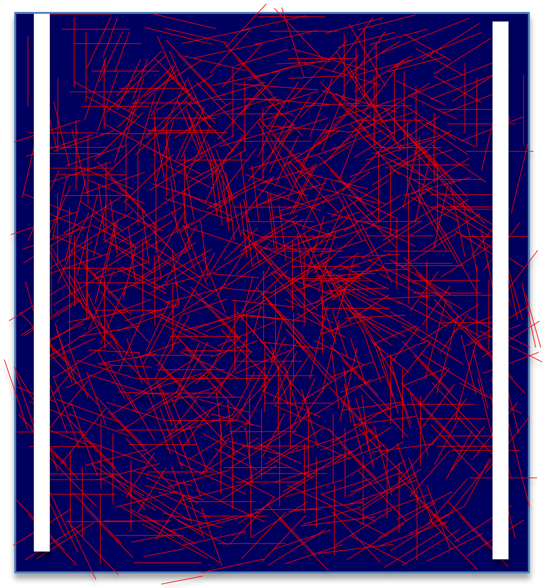
- Down-conversion and photonic crystal?
- Homogeneous enhancement over the entire surface: how many “channels” can you put on the surface?
- Strong coupling of the light: quality factor trade-off
- Easy integration to solar cells
- Low cost, easy fabrication, scalable. The add-on cost of every $1\%_{abs}$ efficiency enhancement should be much lower than $\$10/m^2$. (key factor but not fundamental)
- More smart ideas!

Outline 3

- Nanotechnologies and PV
- Nano-photonics light management
- Metal nano-networks for transparent electrodes
  - Why metal nano-networks?
  - Some simulation results and design principles
  - Initial experimental results
  - Chances and challenges
- Nano-patterns for local contacts

Why metal nano-networks?

- Inspired by plasmonic research: absorption enhancement.
- Inspired by the finger-busbar design for the commercial c-Si wafer solar cells: narrower and more closely-packed metal wires.
- A dream of one-step spray-on metal contact at low temperature.
- Plasmonic metal nano-wires (NWs)?



PlasFingers?

NanoNest?

(Back to the end of 2010.)

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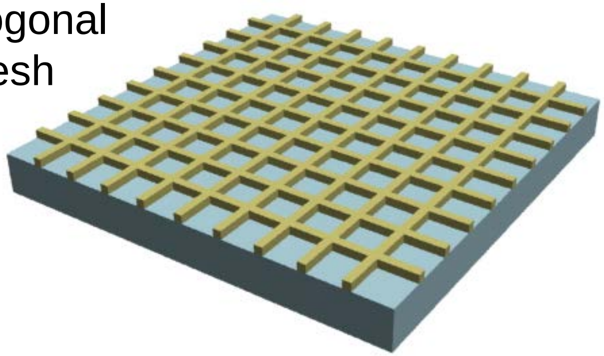
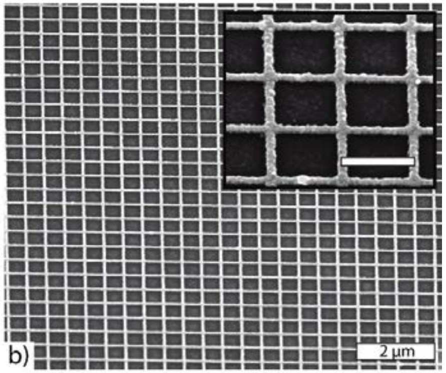
Metal NWs: iterature

- People have considered using NWs as alternative transparent electrodes.

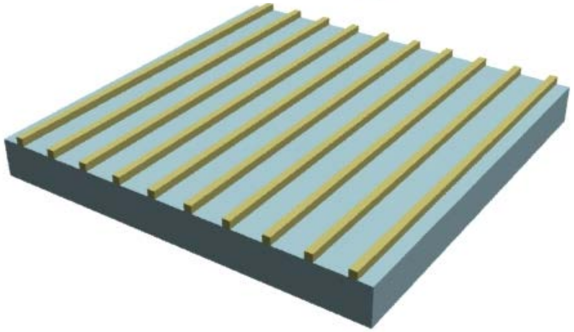
Orthogonal mesh

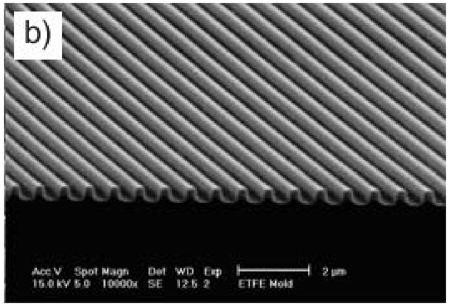




J. van de Groep, P. Spinelli, et al., Nano Letters (2012)

Gratings



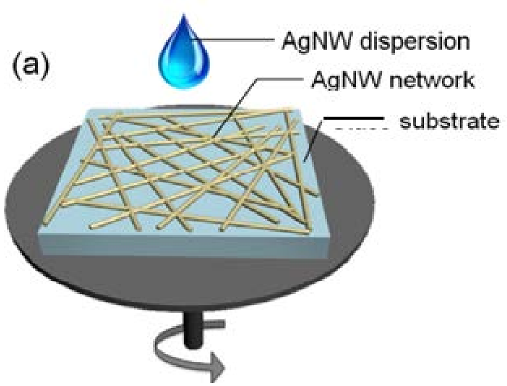


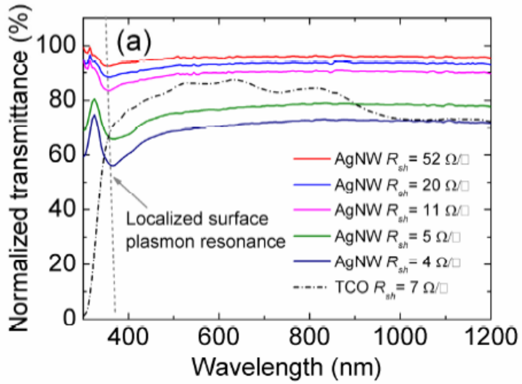
L. Guo, et al., Advanced Materials 19 (2007) 495

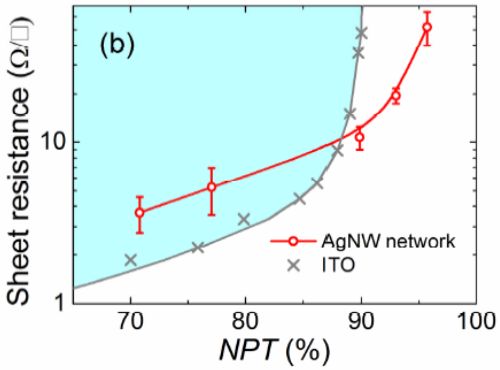
- We focused more on (i) easy processing (ii) fundamental limits.

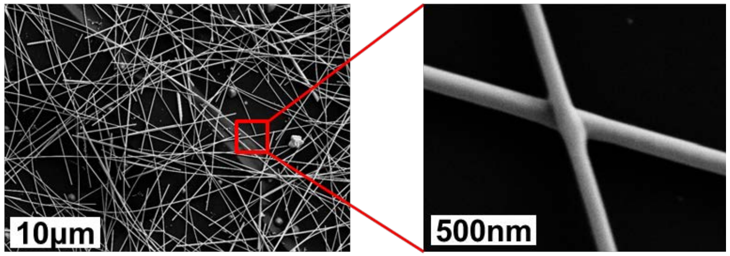
Metal NWs: experimental

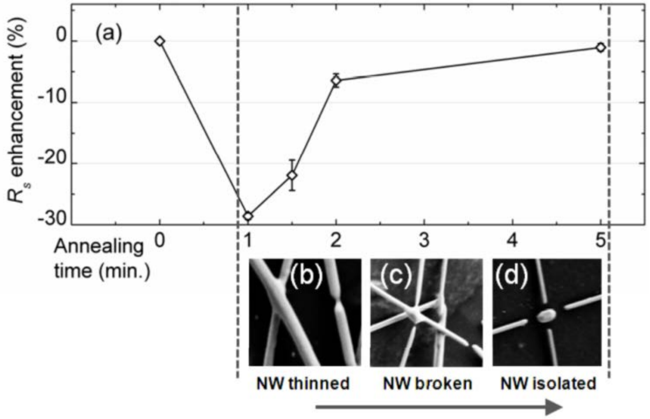
- Chemical synthesis + coating
- Optimising the NWs (100 nm D, 30 um L), coating conditions, post-deposition treatments, etc.
- Electrically improved, optically degraded still.











S. Xie, Z. Ouyang, et al., Optics Express (2013) A355

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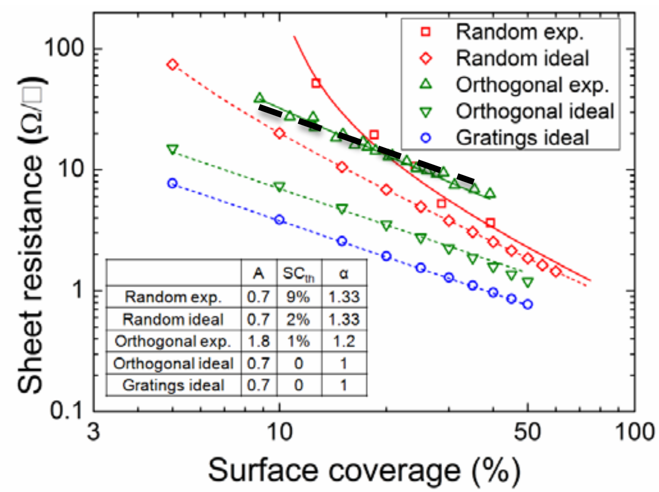
Metal NWs: conductance limits

- More electron scattering at the surface – lower resistivity than the bulk
- When reducing diameter by *n* times, conductance by n^2 times.
- For the random meshes, there is a surface coverage threthhold determined by percolation theory.



$$R_{sh} = A \cdot SC^{-1} \ ?$$

Percolation theory

$$R_{sh} = A \cdot (SC - SC_{th})^{-\alpha}$$

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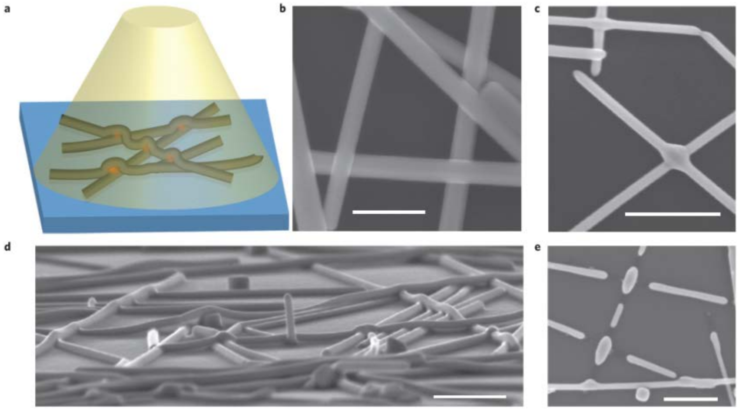
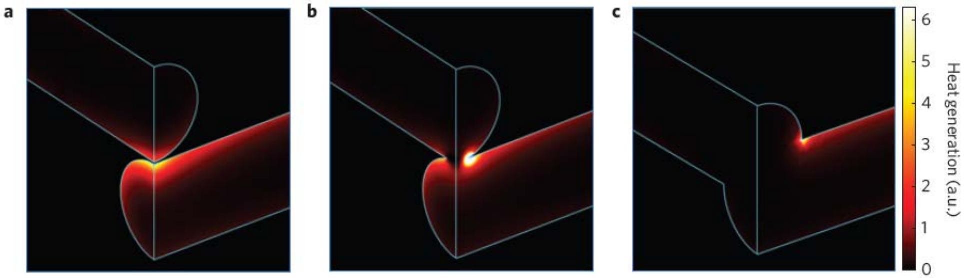
Metal NWs: conductance improvement

- Homogenous annealing – performance limited and process restricted;
- Plasmonic welding: localised heating at the contact regions;



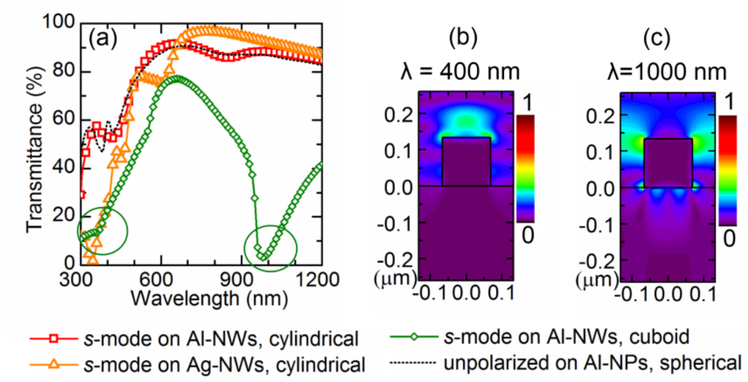


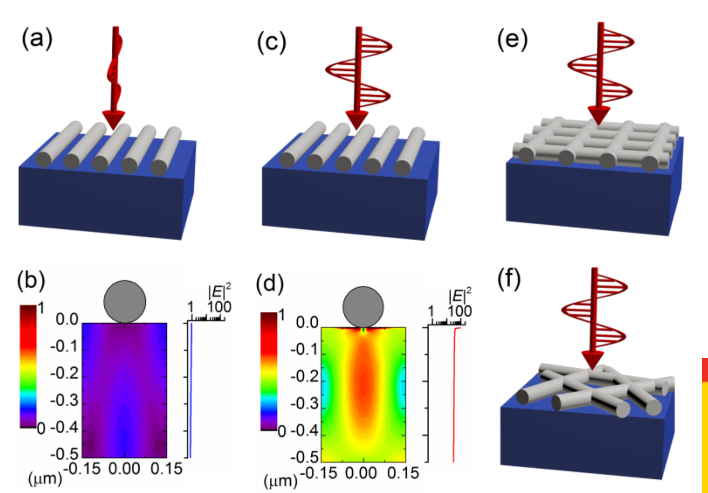
E. Garnett, W. Cai, et al., Nature Materials (2012) 3238

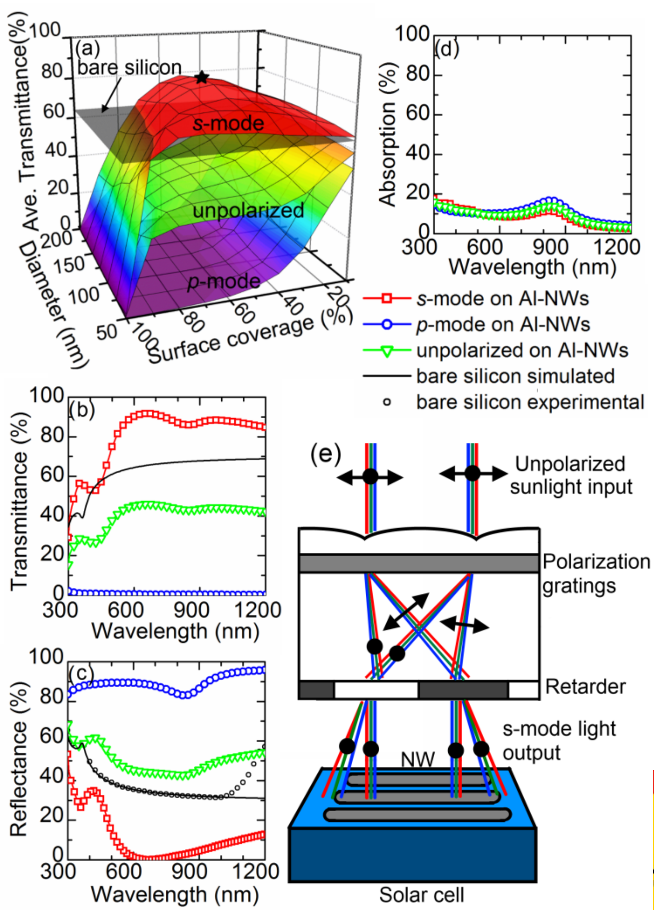
- Core-shell NWs: should be possible!

Metal NWs: transmittance limits

- Disappointingly, plasmonic light trapping is not found – optically, it is still a loss factor.
- The loss mechanisms are fundamental. (*Results unpublished.*)
  - P-mode polarisation, Fano effects, non-ideal geometry, etc.







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Outline 4

- Nanotechnologies and PV
- Nano-photonics light management
- Metal nano-networks for transparent electrodes
- Nano-patterns for local contacts

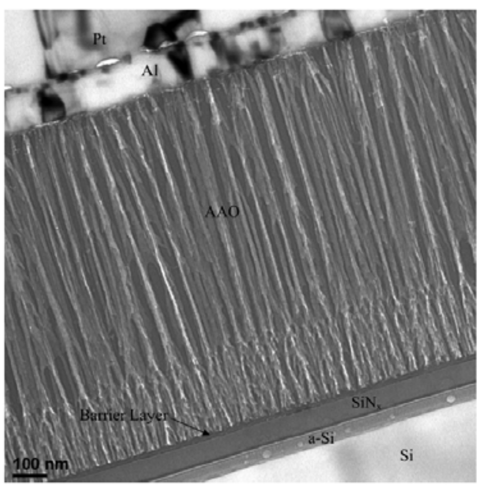
Nano-patterns for local contacts

- Self-patterning is the key because of the system complexity.

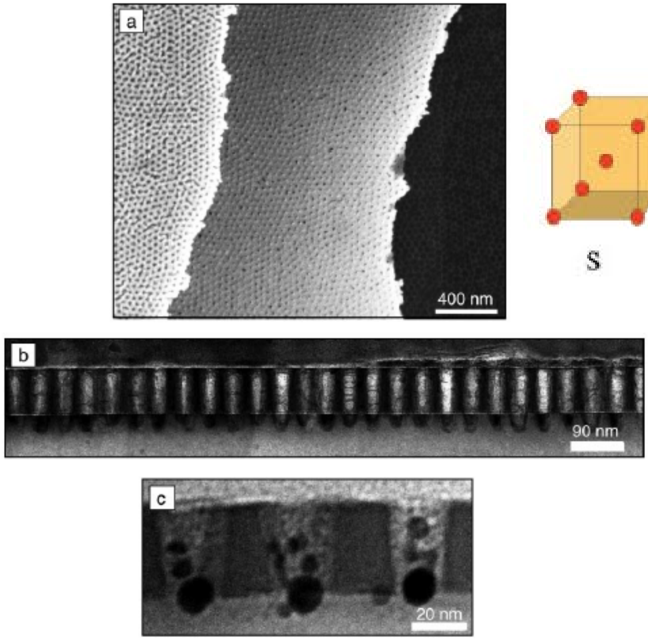
Wikipedia "Snowflake"

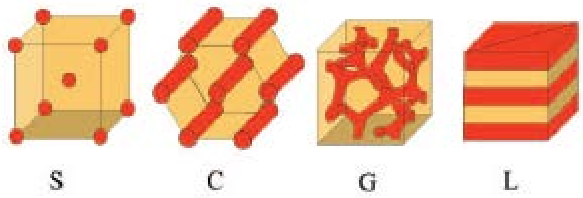
- Anodic aluminum oxide

Block copolymer lithography



P. Lu, K. Wang, et al., IEEE JPV (2012)





C. Hawker, MRS Bulletin 30 (2005)

Conclusion (opinion sharing)

- Most of the nano-technologies will NOT be useful for commercial PV products in a visible future.
- Necessary to distinguish nano-technologies that are limited fundamentally, technically, or financially.
- Nano is the future if you look back into the history.
- Have a to-do list and keep searching.
- Keeping generating ideas!

Thanks for your attention!!