Sharing research experiences on nano-technologies for photovoltaics

Zi Ouyang (September 2013)
• 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 in 1-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,

\[ \text{Blackwood, SOLMAT 94 (2010) 1201} \]

• All the crystals are repeating structures of nano-scale units
Why nano for solar cells?

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

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

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
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
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

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Jsc enhancement (%)</th>
<th>Material Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>-3%</td>
<td>small Ag, thin nitride</td>
</tr>
<tr>
<td>S2</td>
<td>-2%</td>
<td>small Ag, thin nitride</td>
</tr>
<tr>
<td>S3</td>
<td>-3%</td>
<td>reference</td>
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<tr>
<td>S4</td>
<td>17%</td>
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<tr>
<td>S5</td>
<td>19%</td>
<td>large Ag, thin nitride</td>
</tr>
<tr>
<td>S6</td>
<td>-6%</td>
<td>small Ag, thick nitride</td>
</tr>
<tr>
<td>S7</td>
<td>9%</td>
<td>large Ag, thick nitride</td>
</tr>
<tr>
<td>S8</td>
<td>17%</td>
<td>large Ag, thick nitride</td>
</tr>
<tr>
<td>S9</td>
<td>-3%</td>
<td>small Ag, thick nitride</td>
</tr>
</tbody>
</table>

EQE enhancement vs. Wavelength (nm)

Z. Ouyang, X. Zhao, et al., PIP 19 (2011) 917
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/cm² (enhancement of 44%)

- Multicrystalline Si wafer solar cells: texturing + ARC + front NP: 35 to 35.5 mA/cm². (Calculated to be more than 1 mA/cm² 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
7. Possible near-field enhancement
   - Experiment on the c-Si/ SiNₓ/ 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!
Other nano-photonic designs

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

B. Curtin, APL 96 (2009) 231102

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

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 $1/\%_{\text{abs}}$ efficiency enhancement should be much lower than $10/\text{m}^2$. (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.)
Metal NWs: literature

- People have considered using NWs as alternative transparent electrodes.

- 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.

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 threshold determined by percolation theory.

\[
R_{sh} = A \cdot SC^{-1}
\]

Percolation theory

\[
R_{sh} = A \cdot (SC - SC_{ih})^{-\alpha}
\]
Metal NWs: conductance improvement

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


- 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.
Outline 4

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Nano-patterns for local contacts

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

- Anodic aluminum oxide

Wikipedia “Snowflake”


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!!