Light management in nanostructured solar cells

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Outline

1. Light coupling
2. Light trapping
3. Current collection
4. Solving $V_{oc} < E_g$
5. Towards 70% efficiency
The scattering solar cell

• Integrate nanoscattegrers in the solar cell

• Couple incident light to in-plane waveguide modes or localized modes
Light scattering from nanoparticles

Large scattering cross section

Strong forward scattering

air \( (n=1.0) \)

Si \( (n=3.5) \)

4%

96%
Light scattering from nanoparticles

Large scattering cross section

All light captured
Ag nanoparticles; scattering vs. Ohmic losses

Albedo $\rightarrow 1$ for D $> 150$ nm

For Ag particles $>150$ nm nearly all light is scattered

For 50 nm particles 50% of the light is absorbed in the metal

Absorption $\sim r^3$
Scattering $\sim r^6$
Flexible rubber on thin glass
Conform to substrate bow and roughness
No stamp damage due to particles
Total reflectivity (specular+diffuse)

Experimental data

![Graph showing reflectivity vs. wavelength](image)

- **bare Si substrate**
- **67 nm Si$_3$N$_4$ on Si**
- **Ag nanoparticles on 67 nm Si$_3$N$_4$**

Wavelength (nm)

Total Reflectivity

Piero Spinelli
Ag nanoparticle coated thin-film a-Si cells

350 nm i-a-Si:H
120 nm ZnO, 80 nm ITO
Cell area: 0.13 cm²

Ag particles:
pitch 500 nm
height 120 nm
diameter 240 nm

10% enhanced photocurrent
Transparent resonant conductive plasmonic networks

Ag wire network fabricated with e-beam lithography
width: 45-110 nm
height: 60 nm

Jorik van de Groep, Piero Spinelli
Optical transmission measurements

- **Localized plasmons**
- **Surface plasmons**
- **Metal-insulator-metal plasmons**

![Graph showing normalized transmission vs. wavelength (nm) with labels for LSPR, SPP, and MIM plasmons.](image)
Optical transmission measurements

Thin wire networks are better than 80 nm ITO.
Electrical resistance measurements

- Four-Point-Probe
- Ohmic behavior

$w=45 \text{ nm}$

- $R_s=17.2 \text{ } \Omega/\text{sq}$
- $R_s=27.0 \text{ } \Omega/\text{sq}$
- $R_s=38.7 \text{ } \Omega/\text{sq}$

$V \text{ (mV)}$

$I \text{ (mA)}$

- 1000 nm
- 700 nm
- 500 nm

Jorik van de Groep, Piero Spinelli
Tradeoff between transmission and resistance

- Dilute network better than ITO
- Optimum for smallest $w$ and small pitch
Combining light trapping and current collection
Metallic vs. dielectric scatterers

- Metal NP: plasmonic resonance
- Dielectric NP: Mie (geometrical) resonance

\[ Q_{scat} = \frac{C_{scat}}{C_{geom}} \]
Si surface Mie scatterers

In cylindrical particles light leaks into the substrate and resonance broadens

Light incoupling using Si nanoparticle array

Weakly coupled Mie scatterers

Near-perfect anti-reflection coating!

radius = 125 nm
height = 150 nm
pitch = 450 nm
Si$_3$N$_4$ thickness = 45 nm

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Black silicon using leaky Mie resonances

Average reflectivity: 1.3%

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Piero Spinelli
The scattering solar cell

- Integrate nanoscatterers in the solar cell
- Couple incident light to in-plane waveguide modes or localized modes
Back contact nanopatterns on ultrathin a-Si:H solar cells

90-160 nm thick a-Si:H cells

Vivian Ferry, Claire van Lare
Nano Lett. 11, 4239 (2011)
Ultra-thin Si solar cell: 90 nm $i$-layer light enhanced red and blue response
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Thermodynamic energy losses in PV energy conversion

Problem
- Energy loss in Carnot cycle
- Entropy loss in absorption or emission
- Entropy loss due to non-reciprocity
- Energy loss due to thermalization or lack of absorption
- Entropy loss due to lack of angle restriction
- Entropy loss to incomplete light trapping and reduced QE
- Conventional single-junction solar cell

Solution
- Intrinsic loss
- Multi-junction solar cell
- Surface light directors
- Light-trapping structures, density of states engineering

\[
E_g \left(1 - \frac{T}{T_{sun}}\right) - kT \left[\ln \left(\frac{\Omega_{emit}}{\Omega_{sun}}\right) + \ln \left(\frac{4n^2}{I}\right) - \ln(QE)\right]
\]
Light management structures for reaching ultra-high efficiency

Nature Mater. 11, 174 (2012)
Multi-junction solar cell
Triple-junction tandem solar cell layer geometry

Record efficiency: 43.5 %

From: Richard King (Spectrolab)
Integrated parallel multi-junction solar cell

Light management

Spectrum splitting
Scalable inexpensive large-area layer transfer and nanofabrication techniques

a
Si wafer → H implant → Wafer splice → Wafer polish

b
GaAs wafer → AlAs CVD → GaAs CVD → Chemical etch

c
Wafer → Sol-gel spin-coat → Imprint stamp → Remove stamp → Reactive ion etch → Remove mask
Outline

1. Light coupling
   ![Light coupling diagram]

2. Light trapping

3. Current collection
   ![Current collection diagram]

4. Solving $V_{oc} < E_g$
   ![Energy level diagram]

5. Towards 70% efficiency
   ![Efficiency chart]
commentary

Photonic design principles for ultrahigh-efficiency photovoltaics

Albert Polman and Harry A. Atwater

For decades, solar-cell efficiencies have remained below the thermodynamic limits. However, new approaches to light management that systematically minimize thermodynamic losses will enable ultrahigh efficiencies previously considered impossible.