Plasmonic Photovoltaics

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Abstract

Thin-film solar cells offer the benefits of reduced materials and fabrication costs as well as the advantages of light-weight, flexible devices. For these geometries to exhibit efficient current generation, light trapping schemes are essential to capture the full solar spectrum in the cell. We have investigated the use of metallic (plasmonic) and dielectric light scattering geometries, integrated on the top, bottom or inside the solar cell to enhance the incoupling and trapping of light into ultra-thin solar cells. The following five key results were achieved:

<u>Ultra-thin highly efficient solar cells with nanoscale light trapping structures</u>

Plasmonic backreflectors were studied on ultrathin amorphous Si solar cells and short circuit current densities exceeding that of planar cells by 26 % are achieved due to near-field coupling to waveguide modes of the a-Si:H layer. By using engineered random scattering patterns the mode coupling of infrared light scattered from the backreflector is optimized. The cell efficiency is further enhanced by effective forward scattering of light from weakly coupled Mie resonators integrated at the front surface of the cell. In optimized geometries the cell efficiency is found to exceed that of cells made using commercial Asahi-type substrates. We present the first silicon solar cell with an active layer thickness less than 100 nm with an efficiency close to 10%. We also demonstrate a 3-fold reduction of the a-Si active layer thickness (from 260 to 90 nm), while maintaining cell efficiency, using plasmonic light trapping. The nanopatterns are fabricated via an inexpensive and scalable imprinting technique that could be adopted into standard large-area solar cell production.

<u>Metallic and dielectic nanoscatterer arrays are highly effective antireflection coatings</u>

We carried out a systematic study of the coupling of light into semiconductor substrates covered with metallic and dielectric nanoscatterers. We find that suitably engineered Ag nanoparticle arrays (diameter 200 nm, height 125 nm, pitch 450 nm) can serve as effective antireflection

coatings, with an overall reflectivity (averaged over the AM1.5 solar spectrum) of only 2%, better than a standard Si_3N_4 antireflection coating. The efficient light coupling is due to the efficient forward scattering of light from the plasmonic resonators. We made a detailed study of all physical parameters that determine this coupling effect, including the effect of Fano interference and the effect of particle shape on the near-field coupling. Inspired by our work on metallic nanoscatterers we investigated the effect of dielectric scatterers on light coupling into a silicon substrate. Silicon cylinders (250 nm diameter, 150 nm height, 450 nm pitch) etched into the surface of a Si wafer posses geometric Mie resonances, that mediate the preferential coupling of light into the Si wafer. The "black" silicon made this way has an overall reflectivity (averaged over the solar spectrum) of only 1.3 %, less than any other interference coating or surface texture. A key advantage of using dielectric Mie resonators as scattering structures is that they do not suffer from ohmic losses as is the case for plasmonic structures.

Metal nanoparticles are poor antennas in semiconductors

Next, we carried out a systematic study of the use of metallic nanoantennas embedded in semiconductor materials with the aim to achieve enhanced near-field coupling to the semiconductor. We find that while metal nanoparticles are effective antennas of light, most of the light is lost to ohmic dissipation in the metal, rather than by near-field absorption in the semiconductor. We conclude that there is only very limited practical application of metallic nanoparticle antenna's to sensitize thin solar cell materials, despite many claims of the contrary in the literature.

Metal nanowire arrays are effective transparent conductors

Periodic two-dimensional networks of silver nanowires (diameters of 45-110 nm, pitch 500-1000 nm) show anomalous optical transmission, with an solar-spectrum-averaged transmission up to 91% and a sheet resistances as low as 6.5 Ω/sq. The most dilute networks show lower sheet resistance and higher optical transmittance than a 80 nm thick layer of ITO sputtered on glass, the standard transparent conductor used in many solar cell materials. We identify four distinct physical phenomena that govern the transmission of light through the networks, all related to the excitation of localized surface plasmons and surface plasmon polaritons on the wires. The insights given in this project provide the key guidelines for designing high-transmittance and low-resistance nanowire electrodes for thin-film solar cells.

Photonic design principles for ultrahigh-efficiency photovoltaics

Finally, we derive new design principles for ultra-high efficiency solar cells, based on the insights derived from this GCEP project. By integrating suitably engineered nanostructures in and on the solar cell the Schockley-Queisser limit, which has long been considered as a fundamental limit to the maximum achievable solar cell efficiency, can be overcome. Moreover, by using a parallel multijunction architecture, solar cell efficiencies of 50-70% may be achieved. These ideas may serve as guidelines for future work on advanced solar cells with nanophotonic design with ultra-high photovoltaic conversion efficiency.

The project has lead to 13 publications in the international refereed literature, including a review article in Nature Materials (2010) that has been cited over 500 times in the first two years since it appeared, and a Perspective Article in Nature Materials (2012). Several prototype solar cell devices were made. Two main collaborators on this project, Albert Polman and Harry Atwater were awarded the 2012 ENI Renewable and Non-conventional Energy Prize.

Introduction

Conventionally, photovoltaic absorbers must be "optically thick" to enable nearly complete light absorption and photocarrier current collection. Figure 1 shows the standard AM1.5 solar spectrum together with a graph that illustrates what fraction of the solar spectrum is absorbed upon a single pass through a 2 µm thick crystalline Si film.

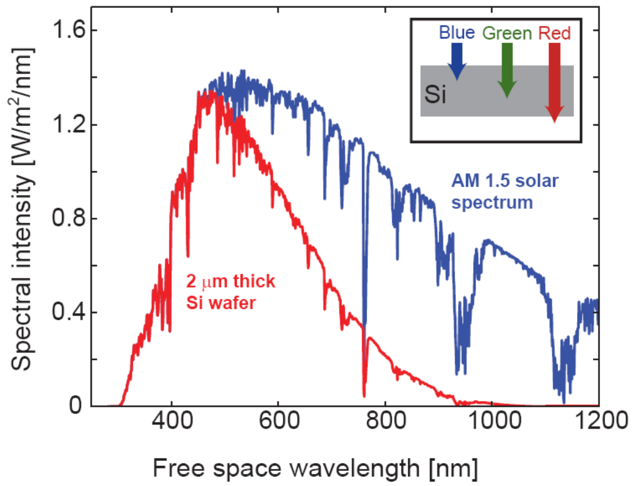


Figure 1 | AM1.5 solar spectrum, together with a graph that indicates the solar energy absorbed in a 2-µm-thick crystalline Si film (assuming single-pass absorption and no reflection). Clearly, a large fraction of the incident light in the spectral range 600–1.100 nm is not absorbed in a thin crystalline Si solar cell.

Clearly, a large fraction of the solar spectrum, in particular in the intense 600-1100 nm spectral range is poorly absorbed in a thin Si film. This is the reason why, for example, conventional wafer-based crystalline Si solar cells have a much larger thickness of typically 180-300 µm. An additional requirement for high efficiency solar cells is that they must have minority carrier diffusion lengths several times the material thickness in order for all photocarriers to be collected, a requirement which is most easily met for thin cells. Thus solar cell design and material synthesis considerations are strongly dictated by these opposing optical absorption thickness and carrier collection length requirements. Plasmonic and dielectric nanostructures offer the possibility of reducing the physical thickness of the photovoltaic absorber layers while keeping their 'optical thickness' constant, in at least three ways:

1) Metallic or dielectric nanoparticles can be used as subwavelength scattering elements to couple and trap freely propagating plane waves from the sun into an absorbing semiconductor thin film, by "folding" the light into a thin absorber layer (see Fig. 2(a)).

2) Metallic nanoparticles can be used as subwavelength antennas in which the plasmonic near field is coupled to the semiconductor, enhancing its effective absorption cross section (see Fig. 2(b)).

3) A corrugated metallic film on the back surface of a thin photovoltaic absorber layer can couple sunlight into surface plasmon polariton modes supported at the metal-semiconductor interface

as well as guided modes in the semiconductor slab; whereupon the light is converted to photocarriers in the semiconductor (see Fig. 2(c)).

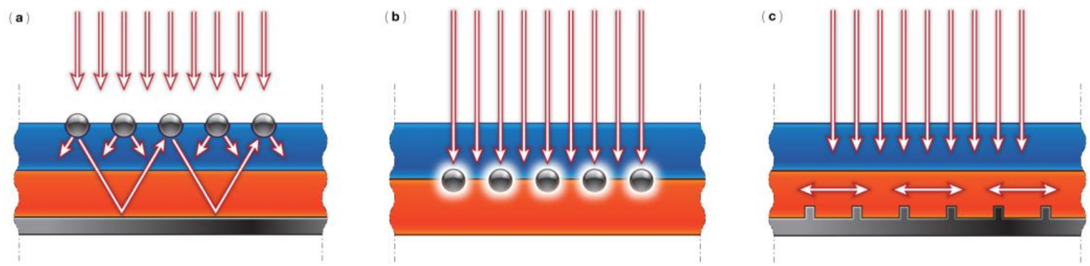


Figure 2 | Plasmonic light trapping geometries for thin-film solar cells (a) Light trapping by scattering from metal nanoparticles at the surface of the solar cell. Light is preferentially scattered and trapped into the semiconductor thin film by multiple and high-angle scattering, causing an enhancement of the effective optical path length in the cell. (b) Light trapping by the excitation of localized surface plasmons in metal nanoparticles embedded in the semiconductor. The excited particle's near field causes the creation of electron-hole pairs in the semiconductor. (c) Light trapping by the excitation of surface plasmon polaritons at the metal-semiconductor interface. A corrugated metal back surface couples light to surface plasmon polariton or photonic modes that propagate in the plane of the semiconductor layer. From Polman and Atwater, Nature Mater. **9**, 205 (2010).

These three light trapping techniques may enable a large shrinkage (possibly 10 to 100 fold) of the photovoltaic layer thickness, while keeping the optical absorption (and thus efficiency) constant. This GCEP project has focused on all three light trapping schemes described above.

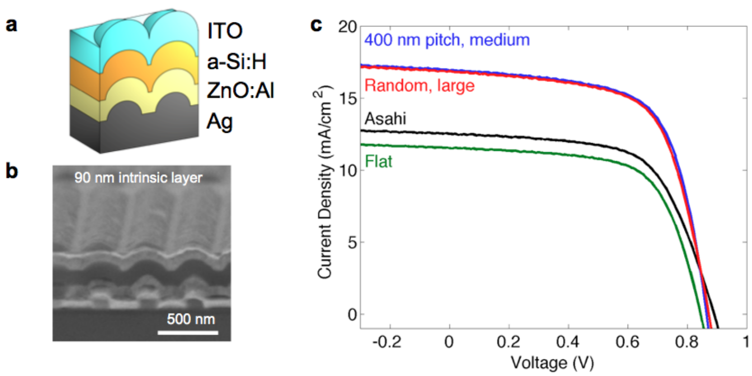
Project 1: Light trapping in ultra-thin a-Si:H solar cells

We investigated the design, fabrication, and simulation of ultrathin film n-i-p a-Si:H solar cells incorporating light trapping plasmonic back reflectors which exceed the performance of n-i-p cells on randomly textured Asahi substrates. The periodic patterns are made via an inexpensive and scalable nanoimprint method, and are structured directly into the metallic back contact. Compared to reference cells with randomly textured back contacts and flat back contacts, the patterned cells exhibit higher short-circuit current densities and improved overall efficiencies than either reference case. Angle-resolved photocurrent measurements confirm that the enhanced photocurrents are due to coupling to waveguide modes of the cell. Electromagnetic modeling is shown to agree well with measurements, and used to understand further details of the device. We developed several new insights into the nature of light trapping in a highly efficient ultra-thin amorphous Si:H solar cell. The three key new developments are:

<u>Insight into role of randomness vs order in light trapping nanostructures</u>: Many papers have now been written about light trapping in thin solar cells and enhanced photocurrents. However what has been lacking to date is fundamental understanding of the relation between the observed photocurrent enhancements and the spatial correlations and surface topography of periodic and random nanostructured scatterers. In this project, we present for the first time a systematic study of this relation, involving more than 1000 solar cells, establishing a direct relation between the spatial coherence spectral density and measured and simulated photocurrent spectra.

Simultaneous rear reflector-enhanced red response and front surface-enhanced blue response. The backside reflector in our work is a randomly nanopatterned reflector with power spectral density such that light preferentially couples to waveguide modes of the solar cell over a broad spectral range in the red/near-infrared. At the same time, the front surface topography is composed of arrays of weakly coupled Mie resonators that strongly enhance the light coupling into the cell and redirect light into localized modes of the cell over a broad band in the UV/blue spectral range.

A highly efficient extremely thin a-Si:H cell. In our new design, both these geometries are combined in the same cell, leading to the realization of an extremely thin solar cell (90 nm intrinsic Si layer thickness) with enhanced spectral response in both the UV/blue and red/infrared solar spectral bands. We demonstrate a power conversion efficiency of over 9.5% which is approaching the single-junction cell record efficiency for a-Si:H of 10.2%, but with a cell approximately one-third as thick as the record cell.



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Pattern	Efficiency (%)	J_{sc} (mA/cm2)	V_{oc} (V)	FF
400/Medium	9.6	16.9	864	0.66
500/Medium	8.8	15.4	889	0.64
Random/L	9.4	16.8	872	0.64
Random/M	9.4	16.2	888	0.65
Random/S	7.3	14.2	835	0.61
Penrose	9.3	16.7	864	0.64
Flat	6.3	11.5	845	0.65
Asahi Replica	6.9	12.5	890	0.62

Figure 3 | Current-voltage characteristics of nanopatterned cells. The cells are conformally deposited over the patterned substrate, as shown schematically in (a) and in SEM cross section (5° angle) in (b). The maximum particle diameter in the back pattern was chosen so that nanostructures in the ITO top layer would touch without overlap. (c) Current-voltage measurements for the best-efficiency cells on the substrate with 90 nm intrinsic layers. The optimized periodic pattern and the pseudo-random pattern have efficiencies of 9.6% and 9.4%, respectively. (d) Electrical characteristics of highest-efficiency cells. From Ferry *et al.* Nano Lett. **11**, 4239 (2011).

In our work we introduce for the first time the concept of weakly coupled Mie resonators that are integrated with the surface topography of the cell. These resonantly absorb light and redirect it into the cell, thereby effectively enhancing the incoupling of light into the device. These scatterers avoid the need of macroscopic surface texture which is very difficult to apply to ultra-thin solar cells.

Our work is enabled by the recent availability of soft imprint lithography, which makes it possible, for the first time, to fabricate engineered random arrays of nanopatterns over large areas. Indeed, our new design is easily scalable to the very large areas required for solar cell manufacturing.

Ultra-thin film solar cells offer many advantages over their thick film counterparts, including reduced fabrication costs, higher open circuit voltages, less dependence on inabundant elements, and improved stability under light illumination (for a-Si:H). We demonstrate in this project that our new design can effectively reduce the cell thickness nearly 3-fold (from 250 to 90 nm intrinsic layer thickness) while maintaining an efficiency close to the world record for a-Si:H. While the spatial correlation design concepts are presented and implemented here for a-Si:H, the physical concepts are potentially applicable to many other solar cell technologies.

Project 2: Light trapping in Si solar cells using coupled plasmonic antenna arrays

We have demonstrate how the incoupling and trapping of light in thin Si solar cells can be improved by using an array of metallic nanoscatterers placed at the surface of the solar cell. The silver antennas act as efficient receivers for a broad spectral band within the solar spectrum and reradiate the incident light over a wide angular range and (for very thin cells) into waveguide modes of the solar cell. In this way the effective optical path length is increased and the photocurrent of the solar cells enhanced. This work enables the design of (ultra-)thin solar cells while maintaining efficient spectral conversion of the sunlight.

Our work is comprised of finite-difference time domain (FDTD) modeling, fabrication of antenna arrays on single-crystal solar cells, optical measurements and photocurrent spectroscopy. First, FDTD simulations were carried out to study the incoupling of light into a Si substrate using a single Ag nanoparticle (diameter 100-300 nm). We find that the scattering and incoupling spectra depend strongly on particle shape and dielectric environment, in particular in the near-field region close to the substrate. Due to the coupling to the high-index substrate, the resonant scattering spectra from these Ag antennas are quite complex. By carrying out a systematic study in which we gradually increase the refractive index of the substrate we identify all scattering peaks and relate them to the (strongly anisotropic) field distribution in the contact area between antenna and substrate. In some geometries we find strong Fano resonance effects that reduce the light incoupling for short wavelengths. Placing the antennas on a thin transparent spacer layer provides further control over the scattering and coupling spectra. We carried out a systematic analysis of all antenna coupling parameters, finding an optimized geometry for 130 nm tall, 200 nm diameter Ag antennas at a 450 nm pitch, placed on a 50 nm Si_3N_4 layer on Si. Most interestingly, we find that this geometry is more efficient for light incoupling than the standard Si_3N_4 anti-reflection coating.

These simulation results are confirmed by optical reflection spectroscopy carried out on 200 µm thick Si solar cells covered with different Si_3N_4 spacer layers (thickness 20-90 nm). By using electron-beam lithography, we fabricate 80x80 micron arrays of Ag antennas, each array with different antenna diameter and pitch. The optical measurements are in full agreement with the trends found with FDTD simulations regarding particle size, array pitch and Si_3N_4 layer thickness. Most importantly, the optimal antenna array has a reflection coefficient (averaged over the solar spectrum) of only 2%, much better than the standard AR coating. Ag nanoparticle antenna arrays thus provide full impedance matching between sunlight and the semiconductor. The physical insights derived from this work are applicable to any type of solar cell, including polycrystalline Si, amorphous Si and CdTe thin film solar cells.

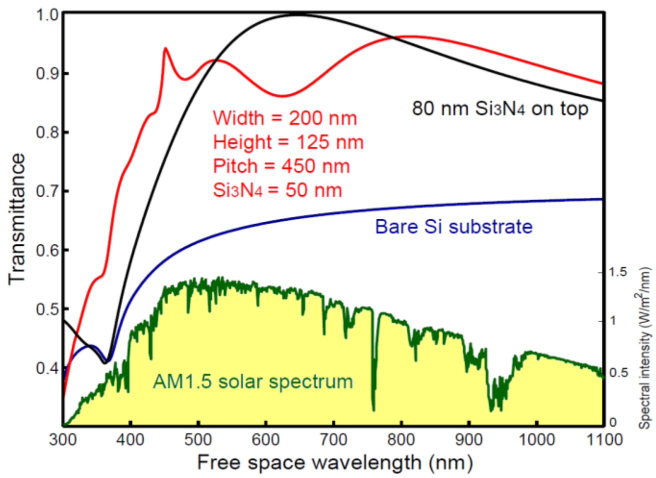

Figure 4 | Optical impedance matching using metal particle arrays. Spectra of transmission into Si for a bare Si substrate (blue), a Si substrate coated with 80 nm Si_3N_4 (black, standard AR coating), and the optimal configuration of Ag nanoparticles on a Si_3N_4 spacer layer (red). The presence of the particle array increases the light coupling in the near-infrared region, above 800 nm. The enhanced transmission in the blue is due to the reduced Si_3N_4 layer thickness compared to the 80 nm layer geometry. The AM1.5 solar spectrum is shown for reference. From Spinelli *et al.*, Nano Lett. **11**, 1760 (2011).

Project 3: Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators

Reflection is a natural phenomenon that occurs when light passes the interface between materials with different refractive index. In many applications, such as solar cells or photodetectors, reflection is an unwanted loss process. Many ways to reduce reflection from a substrate have been investigated so far, including dielectric interference coatings, surface texturing, adiabatic index matching and scattering from plasmonic nanoparticles. Here we present an entirely new concept that suppresses the reflection of light from a silicon surface over a broad spectral range. A two-dimensional periodic array of subwavelength silicon nanocylinders designed to possess strongly substrate-coupled Mie resonances yields almost zero total reflectance over the entire spectral range from the ultraviolet to the near-infrared. This new antireflection concept relies on the strong forward scattering that occurs when a scattering structure is placed in close proximity to a high-index substrate with a high optical density of states.

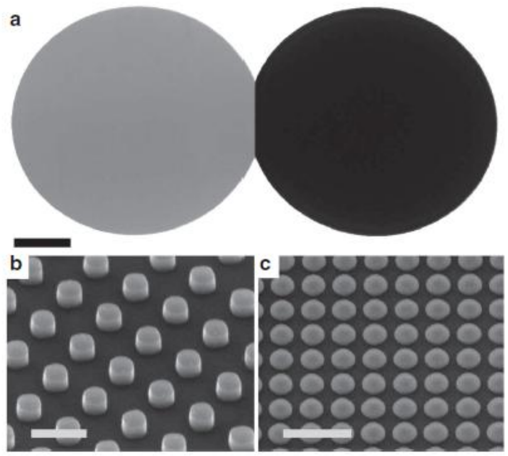

Figure 5 | Black silicon wafer with Si nanocylinders. (a) Photograph of a bare flat 4-inch Si wafer (left) and a 4-inch Si wafer fully imprinted with an optimized (250 nm diameter, 150 nm height, 450 nm pitch) Si nanoparticle array and overcoated with a 60-nm-thick Si_3N_4 layer (right). Scale bar represents 1 inch. (b) Scanning electron microscopy image taken under an angle of 40° of a bare Si nanoparticle array (scale bar represents 500 nm) and (c) a Si nanoparticle array coated with a 60-nm-thick Si_3N_4 layer (scale bar represents 1 μm). From Spinelli *et al.*, Nature Comm. **3**, 692 (2012).

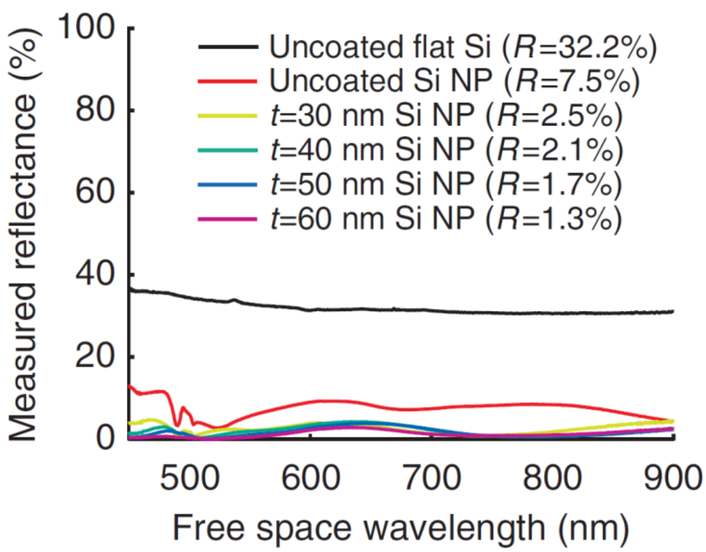

Figure 6 | Total reflectance of black silicon wafer. Measured total reflectivity of a bare Si wafer (black), an uncoated Si nanoparticle array (red) and four Si nanoparticle arrays coated with Si_3N_4 layers of different thicknesses, t (colours). The Si nanoparticles have a diameter of 125 nm, height of 150 nm and are spaced by 450 nm. For each configuration the average reflectivity, R, weighted with the AM1.5 solar spectrum in the 450–900 nm spectral range, is indicated. Reflectance is reduced over the entire spectral range, due to coupling of the Mie resonant scattering to the Si substrate. From Spinelli *et al.*, Nature Comm. **3**, 692 (2012).

Project 4: Prospects of near-field plasmonic absorption enhancement in semiconductor materials using embedded Ag nanoparticles

Metal nanoparticles are efficient antennas for light. If embedded in a semiconductor material, they can enhance light absorption in the semiconductor, due to the strong plasmonic near-field coupling. We used numerical simulations to calculate the absorption enhancement in the semiconductor using Ag nanoparticles with diameters in the range 5-60 nm for crystalline Si, amorphous Si, a PF10TBT-PCBM polymer blend, and Fe_2O_3. We studied single Ag particles in a 100×100×100 nm semiconductor volume, as well as periodic arrays with 100 nm pitch. We find that in all cases Ohmic dissipation in the metal is a major absorption factor. In crystalline Si, while Ag nanoparticles cause a 5-fold enhancement of the absorbance in the weakly absorbing near-bandgap spectral range, Ohmic losses in the metal dominate the absorption. We conclude crystalline Si cannot be sensitized with Ag nanoparticles in a practical way. The absorbance in the polymer blend and Fe_2O_3 can be enhanced by up to 50% using Ag nanoparticles, at the expense of strong additional absorption by Ohmic losses. Amorphous Si cannot be sensitized with Ag nanoparticles due to the mismatch between the plasmon resonance and the bandgap of a-Si. By using sensitization with Ag nanoparticles the thickness of some semiconductor materials can be reduced while keeping the same absorbance.

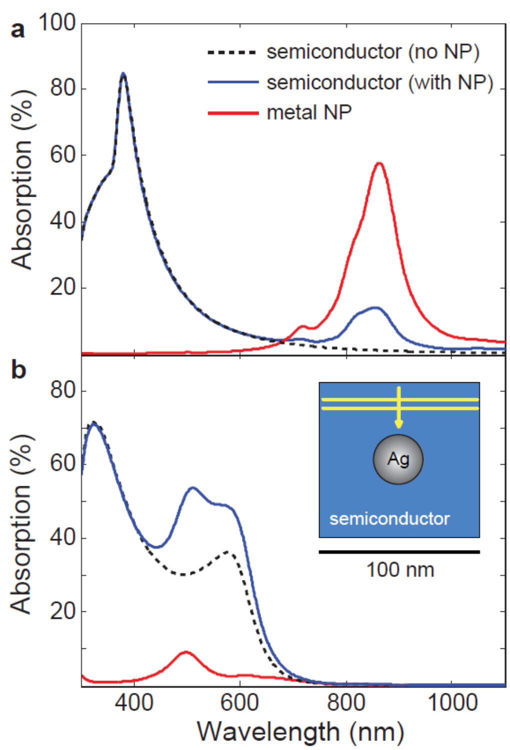

Figure 7 | Ag nanoparticle enhanced absorption in silicon. Simulated absorption spectra of a bare substrate (black dashed line), absorption in the substrate with a 30-nm-diameter Ag nanoparticle (blue) and absorption in the Ag nanoparticle (red), for a c-Si (a) and a PF10TBT-PCBM polymer blend (b) hosting semiconductor. A clear increase in absorption is observed for wavelengths around the nanoparticle plasmon resonance. In the case of a c-Si substrate, the near-field absorption in the nanoparticle is much stronger than in the semiconductor. The inset shows a sketch of the simulation geometry. From Spinelli *et al.*, submitted.

Project 5: Transparent conducting silver nanowire networks

We investigated a transparent conducting electrode composed of a periodic two-dimensional network of silver nanowires. Networks of Ag nanowires are made with wire diameters of 45−110 nm and a pitch of 500, 700, and 1000 nm. Anomalous optical transmission is observed, with an averaged transmission up to 91% for the best transmitting network and sheet resistances as low as 6.5 Ω/sq for the best conducting network. Our most dilute networks show lower sheet resistance and higher optical transmittance than an 80 nm thick layer of ITO sputtered on glass. By comparing measurements and simulations, we identify four distinct physical phenomena that govern the transmission of light through the networks: (1) excitation of localized surface plasmon resonances by light polarized transverse to the nanowire, (2) interference of this mode with the spectrally sharp Rayleigh anomaly giving rise to a Fano-lineshape in the transmission, (3) excitation of surface plasmon polaritons propagating along the metal nanowires through grating coupling from the periodic metallic mesh, and (4) excitation of metal-insulator-metal plasmons confined between wire pairs, that show cutoff at a wavelength determined by the wire spacing. The physical insights given in this work provide the key guidelines for designing high-transmittance and low-resistance nanowire electrodes for optoelectronic devices, including thin-film solar cells.

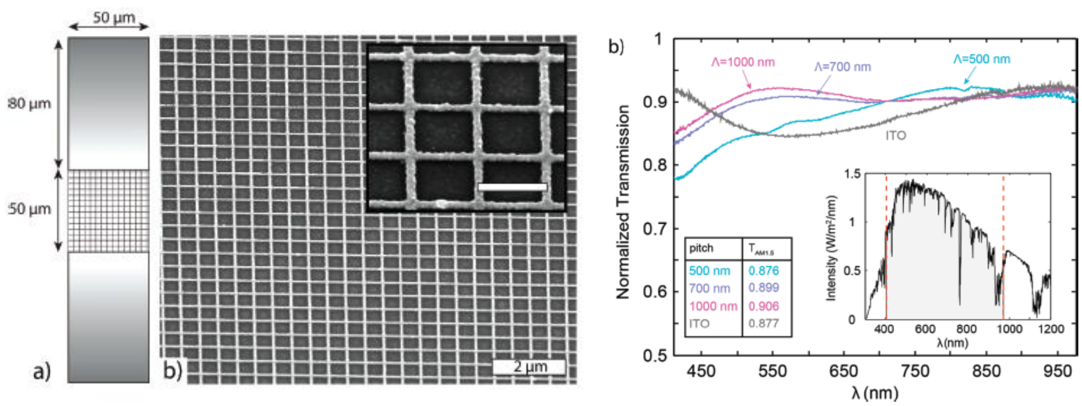

Figure 8 | Transparent conducting Ag nanowire network (a) Sketch of the sample geometry. Silver nanowire networks, 50 × 50 μm in size, with wire diameters between 45 and 110 nm and a pitch of 500, 700, or 1000 nm were fabricated using electron beam lithography. Silver electrical contact pads with a size of 80 × 50 μm were fabricated on two opposing sides. The lines in the network are not to scale. (b) Measured normalized transmission as a function of wavelength for networks with the smallest wire diameter (w = 45 nm) and pitch of 500 nm (blue), 700 nm (purple), and 1000 nm (pink). Also shown is the transmittance through an 80 nm thick layer of ITO sputtered on glass (gray). The inset shows the spectral intensity distribution of the AM1.5 solar spectrum, with the measured spectral region shaded in gray. The average transmission weighted for the AM1.5 spectrum is listed in the table as an inset.

Project 6: Photonic design principles for ultrahigh-efficiency photovoltaics

For decades, solar-cell efficiencies have remained below the thermodynamic limits. In a Commentary Article (A. Polman and H.A. Atwater, Nature Mater. **11**, 174 (2012)), we argue that new approaches to light management that systematically minimize thermodynamic losses will enable ultra-high efficiencies previously considered impossible. We developed several novel device designs in which light is efficiently trapped inside ultra-thin layers, spontaneous emission is controlled by controlling the local density of states inside the solar cell, and the directionality of emitted light is controlled thereby reducing entropy losses and enhancing the open circuit voltage of the cell. We also propose a parallel multi-junction solar cell architecture in which a spectrum splitting layer is used to direct different colors from the sun to different semiconductors with a bandgap matching the color. Photovoltaic conversion efficiencies up to 50-70% are in principle possible using these new designs.

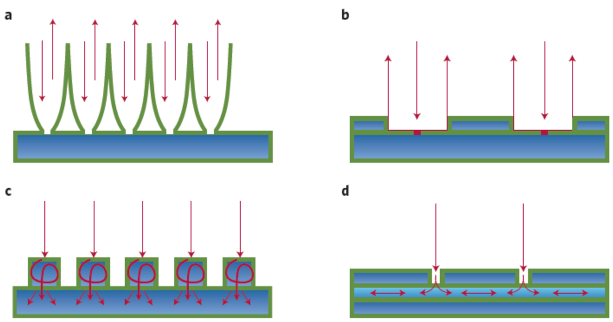

Figure 9 | Light-management architectures for reaching ultrahigh efficiency. (a) Three-dimensional parabolic light reflectors direct spontaneous emission back to the disk of the Sun. (b) Planar metamaterial light-director structures. (c) Mie-scattering surface nanostructure for light trapping. (d) Metal-dielectric-metal waveguide or semiconductor-dielectric-semiconductor slot waveguide with enhanced optical density of states to increase the spontaneous emission rate. From Polman and Atwater, Nature Mater. **11**, 174 (2012).

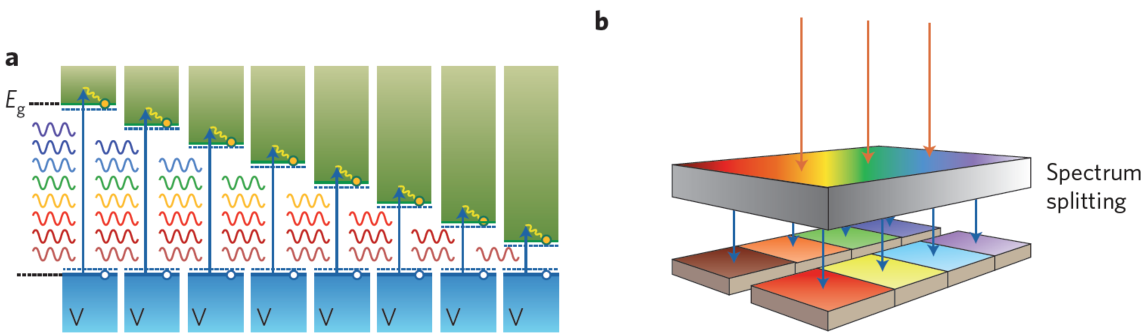

Figure 10 | Multi-junction solar cells. (a) Multi-junction energy diagram. Semiconductors with different bandgaps convert different portions of the solar spectrum to reduce thermalization losses. The quasi-Fermi levels defining the open-circuit voltage are indicated by the horizontal blue dashed lines. The yellow dots represent the electrons. (b) Parallel-connected architecture that can be realized using epitaxial liftoff and printing techniques of the semiconductor layers, followed by printing of a micro- or nanophotonic spectrum splitting layer. Each semiconductor layer can be combined with one of the structures in Fig. 9 to reduce entropy losses and these structures can be separately optimized for each semiconductor. From Polman and Atwater, Nature Mater. **11**, 174 (2012).

Publications resulting from this GCEP project

1. Photonic design principles for ultrahigh-efficiency photovoltaics
   A. Polman and H.A. Atwater, Nature Mater. **11**, 174 (2012)
2. Transparent conducting silver nanowire networks
   J. van de Groep, P. Spinelli, and A. Polman, Nano Lett. **12**, in press (2012)
3. Prospect of metal nanoparticle enhanced near-field enhancement in semiconductors
   P. Spinelli, and A. Polman, submitted to Optics Express
4. Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators
   P. Spinelli, M.A. Verschuuren, and A. Polman, Nature Comm. **3**, 692 (2012)
5. Plasmonic light trapping in thin-film solar cell nanostructures
   P. Spinelli, V.E. Ferry, J. van de Groep, M.C. van Lare, M.A. Verschuuren, R.E.I. Schropp, H.A. Atwater, A. Polman, J. Opt. **13**, 24002 (2012)
6. Modeling light trapping in nanostructured solar cells
   V.E. Ferry, A. Polman and H.A. Atwater, ACS Nano **5**, DOI: 10.1021/nn203906t (2011)
7. Microphotonic parabolic light directors fabricated by two-photon lithography
   J.H. Atwater, P. Spinelli, E. Kosten, J. Parsons, C. Van Lare, J. van de Groep, J. Garcia de Abajo, A. Polman, and H.A. Atwater, Appl. Phys. Lett. **99**, 151113 (2011)
8. Optimized spatial correlations for broadband light trapping in ultra-thin a-Si:H solar cells
   V.E. Ferry, M.A. Verschuuren, C. van Lare, R.J. Walters, R.E.I. Schropp, H.A. Atwater, and A. Polman, Nano Lett. **11**, 4239 (2011)
9. Controlling Fano lineshapes in plasmon-mediated light coupling into a substrate
   P. Spinelli, C. van Lare, E. Verhagen and A. Polman, Optics Express **19**, A303 (2011)
10. Optical impedance matching using coupled metal nanoparticle arrays
    P. Spinelli, M. Hebbink, R. de Waele, L. Black, F. Lenzmann and A. Polman, Nano Lett. **11**, 1760 (2011)
11. Light trapping in ultrathin plasmonic solar cells
    V.E. Ferry, M.A. Verschuuren, H.B.T. Li, E. Verhagen, R.J. Walters, R.E.I. Schropp, H.A. Atwater, and A. Polman, Optics Express **18**, A237 (2010)
12. Plasmonics for improved photovoltaic devices
    H.A. Atwater and A. Polman, Nature Mater. **9,** 205 (2010) and Editorial article
13. Improved red-response in thin film a-Si:H solar cells with soft-imprinted plasmonic back reflectors
    V.E. Ferry, M.A. Verschuuren, H.B.T. Li, R.E.I. Schropp, H.A. Atwater, and A. Polman, Appl. Phys. Lett. **95**, 183503 (2009)

Invited talks resulting from this GCEP project

1. *Plasmonic nanostructures for light trapping in ultrathin film solar cells (invited*), V. Ferry
   MRS Spring Meeting, San Francisco, April 9-12, 2012
2. *Efficient light trapping in thin-film Si solar cells using Mie resonators (invited),* A. Polman
   SPIE Photonics Europe, Brussels, April 16-20, 2012
3. *Light trapping in thin-film solar cells (invited),* A. Polman, Quantsol Winterschool Workshop, Salzburg, March 20-26, 2011
4. *Light trapping in plasmonic solar cells (invited),* A. Polman, International workshops on nanoplasmonics for energy and the environment, Vigo, June 8-10, May 2011
5. *Light trapping in plasmonic solar cells (invited),* A. Polman, Karlsruhe Days of Optics, June 29-30, 2011
6. *Light trapping in plasmonic solar cells (invited*), V.E. Ferry, OSA Frontiers in Optics Conference, San Jose, October 16-20, 2011
7. *Efficient light trapping in metallic and dielectric nanostructured thin-film solar cells (invited),* A. Polman
   MRS Fall Meeting, Boston, November 30 - December 4, 2011
8. *Plasmonic solar cells (invited),* A. Polman, International workshop on thin-film solar cells, Delft, January 23-23, 2010
9. *Plasmonic solar cells (invited),* A. Polman, MRS Spring Meeting, April 5-9, 2010
10. *Plasmonic photovoltaics (invited keynote presentation),* A. Polman, SPIE Europe, Brussels, April 12-16, 2010
11. *Plasmonic solar cells (invited),* A. Polman, MRS Fall Meeting, Boston, November 29 - December 3, 2010
12. *True nano-plasmonics: from nanoscale integrated circuits to nano-photovoltaics (invited keynote presentation),* A. Polman, SPIE Conference, San Diego, August 2-6, 2009

13. *Plasmonics: optics at the nanoscale (invited keynote presentation),* A. Polman, Euromat, Glasgow, September 7-10, 2009
14. *Plasmonics: optics at the nanoscale (invited),* A. Polman, Nanotech 2009, Berlin, September 2009
15. *Plasmonic photovoltaics (invited),* K. Catchpole, MRS Spring Meeting, March 2008, San Francisco, CA
16. *Plasmonics – optics at the nanoscale (invited plenary presentation),* A. Polman, CLEO/QELS Conference, May 6-9, 2008, San Jose, CA
17. *Plasmonic photovoltaics (invited),* A. Polman, Gordon Research Conference "Plasmonics", Keene, NH July 27 – August 1, 2008

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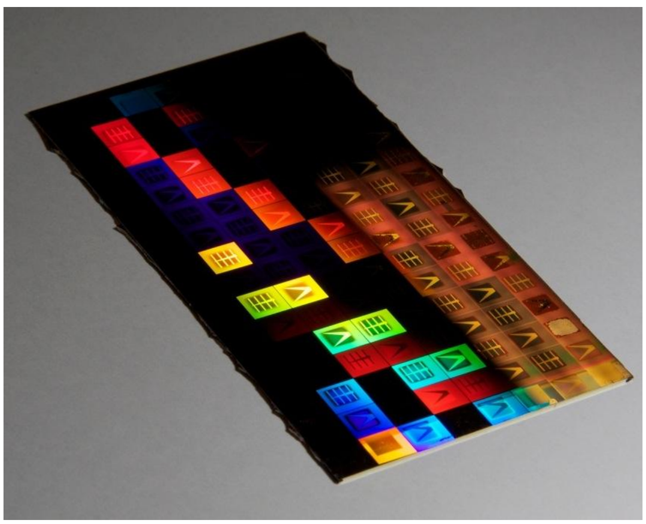

Photograph of plasmonic solar cells made in this GCEP project. An 8x16 array of ultra-thin amorphous silicon thin-film solar cells, 4x4 mm^2 each, is made in on a glass substrate patterned by soft imprint lithography. The different colors reflect the different light trapping geometries of the different cells.