Dielectric metasurfaces for light trapping in high-efficiency low-cost silicon solar cells

Investigators

Albert Polman	Center for Nanophotonics, FOM Institute AMOLF, Netherlands.
Mark Brongersma	Materials Science, Stanford University (Lead-PI).
Harry A. Atwater	Applied Physics, California Institute of Technology

Abstract

Our team is working on realizing efficient light trapping in thin Si solar cells using dielectric metasurfaces, i.e. 2-dimensional metamaterials constructed from a dense array of optically resonant nanostructures. For these materials the spacing between the nanostructures is substantially smaller than the wavelengths of the light incident from the sun and the light trapping is thus very different from conventional grating coupling. The resonant nanostructures are high-index dielectric nanoparticles, made of Si, TiO_2, Si_3N_4, or Al_2O_3, with diameters dimensions in the 50-500 nm range 50-500 nm, that are placed on the surface of the solar cell. These particles support dielectric geometrical resonances, of which the resonance wavelength can be precisely controlled by the particle size, diameter and interparticle coupling. Resonant light scattering from arrays of coupled nanoparticles can lead to strongly enhanced light coupling and path length enhancement inside a solar cell.

Light scattering from nanoparticles for enhanced light trapping has been extensively investigated for metallic nanoparticles. While significant advances have been achieved, these structures suffer a major fundamental limitation i.e. the metal absorbs part of the incident light, creating heat. Dielectric nanoparticles have very large scattering cross sections, similar to those of metallic nanoparticles, but their resonant modes do not experience spurious loss. In a preliminary study we have shown (Spinelli et al., Nature Comm. 2012) that Si nanoparticles on a Si wafer can render it completely black (reflectivity 1.3%), demonstrating the strong potential of the dielectric light scattering concept.

In this project, the Brongersma group has demonstrated that flat optical elements can be realized that redirect and trap light as well as concentrate light for concentrated solar photovoltaics. To this end, we optimized the size, shape and arrangement of the dielectric scatterers. Together with our collaborators, we aim to apply these metasurfaces to thin (5-50 μm) single-crystalline silicon solar cells that are made using commercially available lift-off and layer transfer techniques. Numerical simulations show that it is feasible to realize dielectric-metasurface-enhanced single-crystalline Si solar cell thinner than 20 μm with an AM1.5 conversion efficiency over 20%. If successful, this will demonstrate a highly efficient silicon solar cell that can be made at low silicon materials cost. As the cost of silicon is a major cost factor in conventional wafer scale Si solar cells (~0.25 \$/Wp) this project would present a major step forward in Si solar cell technology. Dielectric metasurfaces can be made onto any solar cell surface using large-area inexpensive soft-imprint lithography. The subcontracts to FOM and CalTech are currently being put in place and this report contains the contributions from the Brongersma group.

Introduction

Crystalline Si (c-Si) has dominated the solar cell market for decades. This should not come as a surprise as this material exhibits many desirable traits. It is earth abundant, environmentally-friendly, easy to process, and features a close-to-ideal bandgap to realize high efficiency cells. By also leveraging advances in the Si electronics industry, very high efficiency (~27%) c-Si solar cells can be realized[1] and are sold commercially at efficiencies as high as 22.4%.[2] As the cost of the solar cell itself is becoming a decreasing fraction of the total cost of an installed solar array, achieving such high efficiencies has become one of the key factors behind the continued success of Si photovoltaics. While achieving high-efficiency is paramount, it remains essential to reduce the materials and processing costs of high-efficiency Si cells. Thin-film amorphous or multicrystalline Si solar cells, deposited on inexpensive substrates can be made at lower costs, but suffer from efficiency limits due to carrier recombination in the defective silicon layers. The persistent dichotomy between *high-efficiency-at-high-cost* versus *low-efficiency-at-low-cost* in silicon photovoltaics could be overcome if <u>high-efficiency thin-film crystalline Si</u> solar cells could be made.

Background

Recently, major developments have been made in the inexpensive production of ultra-thin (5–20 μm) c-Si wafers. These include a variety of epitaxial lift-off processes and wafer splicing techniques that employ etching, ion implantation, and/or local stress generation techniques, such as SMART-cut and SLIM-cut[3,4]. With the new potential of these ultra-thin Si wafers appearing, it is essential to investigate dedicated solar cell architectures that can turn these wafers into high-efficiency solar cells.

The rapid advances in the fields of nanophotonics are spurring a wave of new research aimed at improving light trapping in thin-film solar cells. Whereas the theory of light trapping is well-established for conventional cells[5,6], it was recently pointed out that the standard theories start to break down for ultra-thin cells with nanostructured light trapping layers. Here, the absorption enhancements can potentially exceed the well-known Yablonovitch limit[7,8]. This limit states that absorption enhancement in a medium with a refractive index n cannot exceed a factor of $4n^2/\sin(2\theta)$, where θ is the angle of the emission cone in the medium surrounding the cell. There is growing recognition that nanoscale light trapping structures may well outperform conventional macroscopic surface textures for very thin cells[9,10]. Moreover, when combining very thin semiconductor layers with complex nanostructures for light trapping, more sophisticated wave- and near-field optics-based approaches need to be applied to optimize light trapping. Because of the added complexity, it is unclear at this time what the optimum light trapping nanostructures for ultra-thin Si wafers might be. For fundamental and practical reasons, it is thus worth exploring new pathways that provide new insights and may help resolve this important question. In this proposal we propose to develop coatings that are inspired by recently discovered metamaterials physics and can be realized by novel, inexpensive, large-area nanofabrication techniques.

Metamaterials are artificial materials that are engineered to display optical properties that go beyond those of conventional materials found in nature.[11,12,13] They are capable of manipulating the flow of light in radically new ways[14] and in this project we aim to exploit their properties to realize high performance light trapping layers. Metamaterials consist of large numbers of subwavelength building blocks termed ‘meta-atoms’, whose optical properties can be engineered at the nanoscale to realize desired properties of the metamaterial. The opportunity to use metamaterials in solar cells has emerged for two clear reasons. First, nanotechnology has spawned a wide range of synthesis techniques for the nanoscale meta-atoms, which now can be chosen to have metallic, semiconducting, magnetic, insulating etc. properties. Secondly, it has recently been shown that there is no need to fabricate complex 3-dimensional metamaterials to realize valuable optical functions. Simple planar metamaterials can exhibit extremely valuable optical functions.[15,16,17] Such structures can nowadays be realized inexpensively by means of new nanopatterning techniques capable of generating nanostructures over large areas.[18,19]

Metamaterials are most commonly constructed from resonant metallic (i.e. plasmonic) nanostructures and such structures have also been explored quite extensively for light trapping layers.[,20,21,22,23,24] Interestingly, recent research has begun to also exploit the optical resonances of high-permittivity semiconductor and dielectric nanostructures to realize similar optical functionalities. As purely dielectric or semiconductor nanostructures do not suffer from the undesired parasitic loss seen in metallic nanostructures, they have potential for even greater light trapping efficiencies.

Much of the light trapping physics for such structures is currently unknown and there is a high potential for breakthrough science. In the proposed effort we are paying significant attention to understanding the basic optical resonances of high-index dielectric and semiconductor nanostructures by themselves and when placed on top of a high index semiconductor layer of a solar cell. We will also aim to elucidate the possible ways in which such high index nanostructures can coherently couple when they are spaced by distances that are much smaller than the wavelength of light. Through a detailed understanding of these phenomena, the flow of light into a high index solar cell can be maximized. *This metamaterials approach to light trapping constitutes a substantial deviation from conventional light trapping strategies that tend to rely on grating coupling with wavelength scale structures.*

In this proposal, we are working on demonstrating that the strong light scattering properties of densely-packed, high-index dielectric and semiconductor nanostructures can be used effectively for light trapping in 5-20 µm thick cells. To facilitate the large-scale implementation of such nanostructured light trapping coatings, we will take advantage of developments in soft-imprint nanolithography and nanosphere self-assembly[25,26]. We believe that we are in an excellent good position, in terms of knowledge and resources, to realize Si solar cells with 20% efficiency in cells with a thickness below 20 µm.

Results

Our team is using high-index semiconductor nanostructures as excellent light scatterers with scattering efficiencies that are as large as similar-sized metallic/plasmonic nanostructures. Their strong scattering properties rely on the excitation of optical (Mie) resonances supported by these small structures, which can be tuned in frequency via their size, shape, and environment. Thus far, the research on light trapping layers based on such Mie scatterers has focused on periodic arrangements with wavelength-scale separations. With the exciting recent developments in the metamaterials field, we believe that the realization of nanopatterns consisting of subwavelength semiconductor nanostructures spaced by subwavelength distances represents a very logical next step. In the previous period of our GCEP project, we demonstrated how a metasurface could be created that serves as a diffraction grating capable of trapping light in a solar cell. The followed design principles are extremely general and we have learned that it is easy to create any flat optical element. In this period, we demonstrated that we can realize a flat optical lens that may be used for compact solar concentrator technology that can easily be integrated with thin film solar cell technology. This work was published in Science last year.[27]

Fig. 1A shows a scanning electron microscope image of the central region of a flat lens created from 10^4 optically-resonant Si nanobeams. The light concentrating ability is shown in the inset to Fig.1A (focal spot created by the lens illuminated with a plane wave) and Fig.1B (cross section of the focus). Conventional lenses that rely on a propagation phase feature thicknesses that are typically at least a few millimeter. In contrast, this lens relies on a geometric phase that is attained by generating a spatially-variant orientation of the nanobeams.

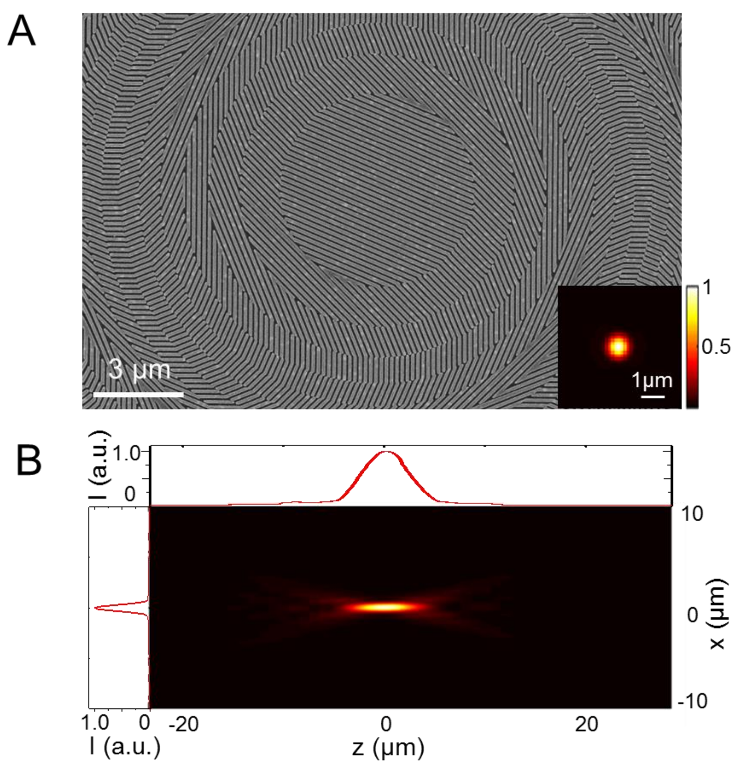

Fig. 1. Optical, light concentratigproperties of a flat lens based on Si nanobeam antennas. (A) SEM image of a fabricated DGMOE lens with a focal length of 100 μm and Numerical Aperture of 0.43 at λ = 550 nm, near the peak of the solar spectrum. The diameter of DGMOE lens is 96 μm. The inset shows the 2D intensity profile in the focal plane (B) Measured intensity profile measured behind the DGMOE lens in the x-z plane. The intensity distribution along the optical axis and through the focus are shown along the vertical and horizontal axes. The size of the measured focused spot is about 1.54μm, with full-width at half-maximum of 670 nm, close to the expected diffraction limited spot size.

The geometric phase stems from a geometric gradient associated with a closed loop traverse upon the Poincare sphere. It can be achieved by space-variant polarization manipulations as opposed to the propagation phase that requires the traversal of a certain thickness of material. As such, it can open new avenues to realize ultrathin (sub-λ) optical elements. In practice, the flat optical elements are constructed from a multitude of waveplate elements for which the orientation of the fast-axes depends on the spatial position. There are well-defined algorithms for realizing specific optical functions. For example, by tiling a surface with half-waveplates with their fast-axes orientations according to a function $\theta(x,y)$, an incident circular polarized light beam will be fully transformed to a beam of opposite helicity and imprinted with a geometric phase equal to $\varphi_g(x,y) = \pm 2\theta(x,y)$. By controlling the local orientation of the fast-axes of the waveplate elements between 0 and π, phase pickups can be achieved that covers the full 0-2π range while maintaining equal transmission amplitude for the entire optical component. This provides full control over the wavefront, allowing for the realization of a myriad of complex phase optical elements. A continuous desired phase function can also be approximated using discrete waveplate orientations. In this work we use 8 orientations with which a high theoretical diffraction efficiency of 95% can be achieved. From the above discussion, it is clear that the design of the waveplate elements represents a crucial step in making practical PBOEs. In this work we made these waveplates from judiciously arranged, resonant Si nanobeams. Based on their anisotropic nature, light polarized along and orthogonal to the nanobeams experience a different refractive index and a waveplate can be realized. As the beams are made from the same semiconductor material a Solar cell is made from, potential current can also be extracted from a lens or grating structure. For this reason, some light absorption in the lens may not be a large detriment to the overall performance.

Future Plans

This work demonstrated that high-diffraction efficiency optical elements can be realized by patterning of a thin semiconductor film into smartly-arranged arrays of Si-nanobeam-antennas. The elements are ultrathin and thus address an increased need for low-cost, light-weight, compact, optical elements that easily be integrated into complex systems requiring assembly of optical, electronic, and mechanical components. In the next phase of the project, we hope to work with our collaborators to integrate these elements with high efficiency solar cells. We are also working on making these optical elements, polarization insensitive and effective over a broad angular range of incidence. By studying different light trapping designs, we hope to further elucidate the potential and limitations of dielectric metasurfaces for use in high performance light trapping layers.

Publications and Patents

1 D. Lin, P. Fan, E. Hasman and M. L. Brongersma, *Science*, 2014, **345**, 298–302.
2 A provisional a patent application has been filed.

Contacts

Mark Brongersma : brongersma@stanford.edu
Albert Polman : Polman@amolf.nl
Harry Atwater : haa@caltech.edu

References

1. http://www.nrel.gov/pv/
2. http://us.sunpowercorp.com/
3. R. Brendel, Japan. Journ. Appl. Phys. **1**, 4431 (2001).
4. I. Gordon, F. Dross, V. Depauw, A. Masolin, Y. Qiu, J. Vaes, D. VanGestel, and J. Poortmans, Sol. En. Mater. Sol Cells **95**, S2 (2011).
5. E.J. Yablonovitch, J. Opt. Soc. Am. **72**, 899 (1982).
6. P. Campbell and M.A. Green, J. Appl. Phys. **62**, 243 (1987).
7. Z.F. Yu, A. Raman, and S.H. Fan, Proc. Nat. Acad. Sci. **107**, 17491.
8. M. A. Green, Prog. Photovolt: Res. Appl. **19**, 473 (2011).
9. A. Chutinan and S. John, Phys. Rev. A **78**, 023825 (2008).
10. I. Tobias, A. Luque, and A. Marti, J. Appl. Phys. **104**, 034502 (2008).
11. V.G. Veselago, Sov. Phys. Uspekhi **10**, 509 (1968).
12. J. B. Pendry, D. Schurig, and D. R. Smith, Science **312**, 1780 (2006).
13. C. M. Soukoulis and M. Wegener, Science **330**, 1633 (2010).
14. N.I. Zheludev and Y. S. Kivshar, Nature Mater **11**, 917 (2012).
15. N. Yu, P. Genevet, M.A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, Science **334**, 333 (2011).
16. X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, V. M. Shalaev, Science **335**, 427 (2012).
17 L. Zou, W. Withayachumnankul, C.M. Shah, A. Mitchell, M. Bhaskaran, S. Sriram, and Ch. Fumeaux, Optics Express **21**, 1344 (2013)
18. *Substrate conformal imprint lithography for nanophotonics*, M. Verschuuren, Ph.D. Thesis, Utrecht Univ (2010).
19. B. Kobrin, E.S. Barnard, M.L. Brongersma, M.K. Kwak, and L. Guo, Proc. SPIE **8249**, 82490O (2012).
20. H.A. Atwater, and A. Polman, Nature Mater. **9**, 205 (2010).
21. R.A. Pala, J. White, E.S. Barnard, J. Liu, and M.L. Brongersma, Adv. Mater, **2**1, 3504 (2009).
22. C. Rockstuhl, and F. Lederer, Appl. Phys. Lett. **94** (2009)..
23. S. Mokkapati, F.J. Beck, A. Polman, and K.R. Catchpole, Appl. Phys. Lett. **95** (2009).
24. J.N. Munday, and H.A. Atwater, Nano Lett. **11**, 2195 (2011).
25. 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).
26. V. Kitaev, and G. A. Ozin, Adv. Mater. **15**, 75 (2003).
27. D. Lin, P. Fan, E. Hasman and M. L. Brongersma, *Science*, 2014, **345**, 298–302.