Solar energy trapping and harvesting in thin-film photonic crystals

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Light trapping in thin-film photonic crystals provides new avenues for higher-efficiency solar energy harvesting.

A significant source of inefficiency in conventional silicon solar cells is their inability to trap incoming light from the sun over a broad range of incident angles and a broad range of incident frequencies. In conventional silicon thin films, the majority of incident sunlight is transmitted or reflected rather than absorbed. While specific structuring of thin films can provide resonant absorption at specific frequencies and specific incident angles, a simple, broadband, wide-acceptance-angle, thin-film architecture has yet to be implemented for light trapping and solar-energy harvesting.

Photonic crystal (PC) materials are periodic nano-structured dielectric materials with engineered periodicity in the range of one-third to one-half the wavelength of light. While well-known for their ability to localize light\(^1,2\) in a suppressed electromagnetic density of states (DOS), photonic crystals can also provide significant enhancements of the photonic DOS in spectral ranges of importance to optical absorption. Such enhancements are often associated with slow moving light due to multiple bounces within the structure, leading to absorption even when the intrinsic absorption time-length scale of the bulk material is very long. Moreover, it is possible to engineer the refractive coupling between external plane waves and modes in enhanced photonic DOS. The Bloch nature of electromagnetic modes in the PC, whereby light at a fixed frequency, polarization, and incident angle in the PC exists as a superposition of propagating and evanescent modes resulting from the PC's eigenstates, enables strong focusing of light intensity in specific regions. Here, absorption of a pair of photons can occur when neither individually can be absorbed. In this way, PC materials offer new and unexplored avenues to address the fundamental issues of photon and electron management in solar cells.

Silicon nanowire arrays have recently been considered as an alternative to standard solid thin-film solar cells.\(^3-10\) These architectures concentrate generated charges inside the absorber due to the radial construction of the PN junction around the nanowire. However, neither optimization of 2D photonic crystal properties of existing nanowire arrays, nor patterning in 3D has been considered. Our work has shown that the sinusoidally-modulated silicon nanowires that form 3D simple cubic photonic crystals (see Figure 1) can be used to provide better solar absorption than their straight counterparts. Such crystals exhibit enhanced electromagnetic DOS and slow group velocity.

Figure 1. (left) A 3D simple-cubic photonic crystal of modulated silicon nanowires consist of antireflection cones, a parallel-to-interface refraction light-trapping section, and a chirped Bragg reflector. The lattice spacing between wires is 350nm and the overall length of each wire is ~5μm. The total amount of silicon is equivalent to a solid slab thickness of 1.03μm. The nanowires are encased in silicon dioxide, and they sit on a quartz substrate with no metallic mirrors. For a slab of silicon of equivalent thickness the maximum achievable photocurrent density is 8.8mA/cm\(^2\), whereas for our photonic crystal, it is 25.9mA/cm\(^2\). (right) The fraction of incident sunlight absorbed as a function of wavelength and angle of incidence.

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providing a continuous spectral distribution of high quality optical resonances with strong light focusing in specific regions of the modulated nanowire PC. Coupling of sunlight from nearly any incident angle occurs through the phenomenon of parallel-to-interface (negative) refraction. This leads to a long dwell time for light within the thin film over a spectral range where the intrinsic absorption of silicon is weak. The top section of each nanowire is tapered in the form of a cone to provide an effective refractive index gradient for the incoming light, while the bottom section is modulated to provide a 1D photonic crystal back-reflector. This results in a continuously red-shifted reflection spectrum as light propagates deeper within the nanostructure.

Our design (see Figure 1) enables absorption of 75% of all available sunlight in the 400nm–1000nm spectral range from nearly any angle of incidence using only 1μm of equivalent bulk thickness of crystalline silicon. It builds upon our previous designs, including modulated pore arrays, simple cubic woodpiles, and slanted pore photonic crystals. Our modulated nanowire arrays are packaged in a silicon dioxide matrix that fills all the interstitial regions between the nanowires up to the tip of the nano-cones.

To estimate the overall power efficiency of our sinusoidally-modulated nanowire photonic crystal solar cell, we coupled the solution of Maxwell’s equations to the semiconductor drift-diffusion equations governing the charge carrier transport within the nanowire. Given our overall light absorption, typical non-radiative recombination losses, and open-circuit voltages in the silicon solar cells, we anticipate an overall power efficiency in the range of 15–20% in our photonic crystal, with only one micron of the equivalent bulk thickness of silicon. This estimate is based on the assumption that photogenerated carriers instantaneously thermalize and that optical response is linear.

In a silicon solar cell, roughly 19% of the incident solar power is lost due to photons having energy less than the indirect electronic band gap of silicon. We hope to up-convert these low-energy photons by doping the glass matrix with rare earth ions. These promote non-linear recombination of photons in the glass matrix surrounding the nanowires, producing a single photon of greater energy than the silicon electronic band gap. We expect this enhancement to increase by a factor of 150 in certain regions due to photonic crystal focusing effects. In summary, our modulated nanowire photonic crystals increase the absorption efficiency of thin-film silicon solar cells. Next steps will be to consider the recycling of energy lost by carrier recombination and thermalization, as well as the exploration of photonic crystal architecture with improved light-trapping capabilities.

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