Carefully mixing disorder and periodicity to optimize solar light trapping

Christian Seassal, Lalouat Loic, He Ding, and Emmanuel Drouard

Optimum sunlight absorption in thin absorbers such as silicon can be achieved via the introduction of novel pseudo-disordered photonic nanopatterns.

The efficiency of today’s photovoltaic (PV) solar cells is constrained by a number of energy-loss mechanisms (e.g., limited incoupling of sunlight, weak absorption of long-wavelength photons, and charge-carrier energy losses by thermalization). To enable the development of novel PV devices with record efficiencies, all of these optical processes must be carefully controlled.

Several groups have proposed theoretical limits on the absorption efficiency of PV devices. The models upon which these limits—which primarily depend on the thickness of the absorbing layer (e.g., silicon)—are based make predictions regarding the amount by which an efficient light-trapping strategy can increase the mean-free path of sunlight in the absorbing medium of a solar cell, compared to flat (unpatterned) devices. Increasing the mean-free path causes trapped photons to explore the absorbing medium more extensively, thereby increasing overall absorption. Although the limits that are frequently used to make these predictions (i.e., $4n^2$ and Lambertian limits) rely on strong assumptions (e.g., the need to consider thick layers or weakly absorbing media), they nonetheless provide useful references for benchmarking novel absorbers for use in PV devices (e.g., those using nanopatterns). The introduction of micro- and nanopatterns in such devices could, however, mitigate these limits or—in very specific cases, with limited wavelength ranges—overcome them entirely.

Last year, a decade after increasingly intense research began in this area, the production of fully functional solar cells integrated with nanophotonic structures showed a net conversion-efficiency increase for the first time. A number of key challenges and open questions remain, however. For example, it is not yet clear how appropriate patterns can be integrated in a real solar cell made of standard PV materials, what is the most appropriate active-layer thickness, or what the most appropriate geometry for micro- and nanopatterns might be. In our attempt to provide answers to these questions, we have demonstrated that by integrating a periodic array of nanoholes or nanopyramids (see Figure 1) in a crystalline-silicon-based solar cell, a photocurrent exceeding 23mA/cm$^2$ can be generated with an active layer of only 1/$\mu$m. This photocurrent, which we predicted using rigorous coupled-wave analysis and a finite-difference time-domain method, is twice the value expected from an unpatterned device of the same thickness.

Recent experiments, including those performed in the European PhotoNVoltaics project, have shown that nanopattern-integrated PV devices with efficiently passivated surfaces can increase the conversion efficiency by 20% or more. Additionally, the optimization of technological processes and photonic pattern

Continued on next page
Figure 2. (a) Scanning electron micrograph of a pseudo-disordered structure (PDS) with a $3 \times 3$ supercell. (b) Reflection spectra measured for simple periodic and PDS patterns. (c) Schematic view of an optimized PDS pattern.

designs is likely to further enhance the conversion efficiency of such PV devices. Indeed, several authors have claimed that the generated photocurrent could be increased by introducing some disorder within a periodic light-trapping structure (such as a photonic crystal). However, the impact of such a perturbation has rarely been evaluated with respect to a perfectly optimized periodic structure. Additionally, clear design rules that enable selection of the relevant type of disorder for specific applications are still missing. Moreover, the full picture regarding physical mechanisms behind light trapping in such complex structures is not yet clear.

To determine the influence of disorder in such devices, we have proposed the implementation of complex patterns based on a periodic square array of air holes. Using this simple array as a base, we define a large supercell in which the position of each nanohole is randomly shifted. The resultant structure is referred to as a pseudo-disordered structure (PDS): see Figure 2(a). We have demonstrated both theoretically and experimentally that the absorption in such a PDS can exceed that of a fully optimized solar-cell stack with a simple periodic nanopattern: see Figure 2(b). In particular, the long-wavelength reflection peaks are substantially decreased, leading to a predicted photocurrent increase of 2–3%. We have also demonstrated the need for appropriate metrics to determine the type of disorder that can lead to optimized conversion efficiency. Indeed, we have found that different types of PDS may lead to a broad dispersion of absorption efficiencies for the same nanohole mean shift. From such considerations, we have defined more specific parameters, referred to as clustering (relating to the minimal distance between nanoholes) and compactness (which quantifies how many nanoholes are closely packed within a supercell). We used these parameters to sort the randomly obtained PDS and their corresponding expected photocurrent.

Among our results, the most important show that disorder does lead to a net absorption increase, provided that holes are not clustered together. The pattern should also simultaneously exhibit spatial frequencies with low amplitudes in the short-frequency range (to inhibit the outcoupling of trapped light) and high amplitudes in the long-frequency range (to promote light trapping). Using design rules based on these results, we have developed an optimized PDS pattern with an evenly distributed ensemble of air nanoholes: see Figure 2(c).

In summary, we have demonstrated that the introduction of PDS in the active layer of a PV device is likely to increase its absorption and, therefore, the conversion efficiency. Combining relevant designs inspired by photonic crystals with careful perturbation and optimized nanopatterning and passivation processes could enable the high potential of these approaches for next-generation solar cells to be realized. Moreover, manufacturing methods such as these are well suited for the generation of efficient devices using a limited amount of materials. In addition to the introduced sustainability, this novel approach may also enable the fabrication of flexible solar cells. Beyond thin-film solar cells based on silicon, this methodology could be used to optimize hybrid devices (e.g., those combining perovskites and silicon), and to control sunlight absorption in appropriate locations within a device (e.g., the top or bottom of a layer stack or, in the case of a tandem device, between two junctions). In our future work, we plan to fabricate and test fully functional single-junction solar cells that incorporate PDS. We also intend to develop these complex patterns for use in advanced devices, such as tandem solar cells, and to assist in up- or down-conversion processes in PV devices.

We acknowledge support from the European Commission Seventh Framework Programme project PhotoNVoltaics (grant agreement 309127) and the French Research Agency (ANR) project NATHISOL (grant agreement ANR-12-PRGE-0004-01). He Ding acknowledges support from the China Scholarship Council (CSC). Results were obtained thanks to close collaboration with Jia Liu, Regis Orobtchouk,

Continued on next page
Author Information

Christian Seassal, Lalouat Loic, He Ding, and Emmanuel Drouard

INL, University of Lyon
National Center for Scientific Research (CNRS), École Centrale de Lyon
Écully, France

Christian Seassal is senior researcher at the French CNRS. His research activities concern photonic nanostructures and their applications in integrated photonics and solar photovoltaics. He has authored and co-authored around 110 research papers in international journals, and over 50 invited conferences.

Emmanuel Drouard has been associate professor at the École Centrale de Lyon since 2005. His research interests concern photonic crystals for integrated photonics and light harvesting for solar energy, and he coordinates the ANR NATHISOL project. He has co-authored around 100 communications, including 50 publications in peer-reviewed journals.

References