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<th>Partially disordered photonic-crystal thin films for enhanced and robust photovoltaics</th>
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<tr>
<td>Citation</td>
<td>APPLIED PHYSICS LETTERS (2012), 100(18)</td>
</tr>
<tr>
<td>Issue Date</td>
<td>2012-03</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/2433/160629">http://hdl.handle.net/2433/160629</a></td>
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<tr>
<td>Type</td>
<td>Journal Article</td>
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Recently interest in enhancing the light-trapping functionality of thin-film photovoltaics has lead to a large number of proposals for different nanostructured designs that exploit the wave nature of incident light.1–7 The performance of these designs is typically optimized for only a limited set of operating conditions involving a reduced bandwidth, narrow-angular cone, and single polarization. In this letter, we show that by introducing a slight amount of disorder into a multi-lattice photonic-crystal (PC) slab, we can increase the light trapping over a wideband spectrum while also reducing its angular and polarization sensitivity. The presence of disorder itself may potentially make the design more feasible for large-scale production. We demonstrate that too much disorder, while improving the robustness of the design to properties of the incident light, actually lowers the light absorption and thus depend mostly on film thickness, not lattice design.

The delicate interference effects that underlie waveoptics designs for photovoltaics often give rise to performance that is sensitive to the wave properties and thus makes it difficult to obtain enhanced light-trapping over a wideband spectrum spanning multiple angles and polarizations. A variety of different PC designs have already been proposed for improved light-trapping in thin-film photovoltaics.2–5 The core principle of such designs is a collection of narrow-band resonances that together contribute to broadband absorption enhancement relative to an unpatterned slab of a given absorbing media (usually silicon or gallium arsenide). Figure 1 shows the absorption profile for two thin-film photovoltaic designs consisting of a 500 nm-thick silicon (Si) absorbing layer, with and without a PC, having a metal back-reflector. The PC is formed by patterning a square lattice (periodicity 350 nm) of oxide (refractive index 1.8) rods (radius 140 nm, height 200 nm) within the Si film (a cross section of the unit cell is shown in the schematic of Fig. 1). These specific design parameters for the PC, while not optimized for photon absorption over the given spectrum (quantified in the next section), represent a valid starting point for exploring the extent to which variations to the unperturbed lattice can improve light absorption. No front- or rear-surface texturing is employed to boost scattering into the guided modes of the slab as we are only interested in the effect of the nanostructured lattice on the light trapping. A normally incident (later, we will consider a range of oblique angles) plane-wave spanning the wideband spectrum from 500 nm (Si is strongly absorbing below 500 nm which renders less important the effect of the lattice to boost light trapping) to 1100 nm (the indirect bandgap of Si corresponds to a wavelength of 1107 nm) impinges on the structure from above through a glass (n = 1.5) substrate. We use an open-source finite-difference time-domain (FDTD) simulation tool to

![Graph showing absorption vs. wavelength with and without a PC.](https://via.placeholder.com/150)

**FIG. 1.** Absorption versus wavelength profile at normal incidence for two thin-film photovoltaic designs: with a PC (blue) and without (bare slab, red). The PC consists of a square lattice (periodicity, 𝑎 = 350 nm) of circular rods (𝑟 = 140 nm, ℎ = 200 nm) of oxide patterned in silicon (Si). The photon-absorption efficiency (from Eq. 1) is a measure of light trapping relative to a perfect absorber. The peaks circled in green are in the limit of strong Si absorption and thus depend mostly on film thickness, not lattice design.
compute the fractional absorptivity of the Si film. The absorption spectra for the PC show narrow, high-amplitude peaks—signatures of the coherent–resonant–Bloch modes—whereas the unpatterned slab has broad Fabry–Pérot resonances with low amplitude.

We can quantify the light-trapping efficiency of each design relative to an ideal perfect absorber (unity absorptivity over the wavelength interval of interest) by assuming that each absorbed photon with energy larger than the bandgap of crystalline Si generates an exciton which contributes directly to the short-circuit current.\textsuperscript{12} This corresponds to the following definition of photon-absorption efficiency:

\[ \frac{\int_{500 \text{ nm}}^{1100 \text{ nm}} \lambda A(\lambda) d\lambda}{\int_{500 \text{ nm}}^{1100 \text{ nm}} \lambda \, d\lambda}, \tag{1} \]

where \( \lambda \) is the terrestrial power density per unit wavelength from a blackbody at a temperature of 5778 K (Ref. 15) and \( A(\lambda) \) is the absorptivity computed from the simulations. Figure 1 shows that the introduction of a PC lattice into the absorbing Si layer results in a near doubling of the overall efficiency compared to an unpatterned slab (48.6\% vs. 27.4\%). Somewhat non-intuitively, the effect of removing the absorbing material (Si) to form the PC lattice has been to enhance the absorption via an increase in light localization. The sharp peaks of the PC (corresponding to a large Q factor\textsuperscript{11}) indicate that coupling into (and out of) the modes is challenging and will depend strongly on the incident-wave conditions which we will verify later on. While a patterned design seems to be better for light trapping than an unpatterned one, what is less clear is whether the individual, narrow-band, large-amplitude peaks can be somehow broadened to further boost the overall absorption and the extent to which a given lattice design can be made robust with respect to different angles and polarizations of incident light.

The complex nature of the wave scattering that gives rise to the Bloch-mode resonances of the PC lattice depends delicately on perfect-structural order. It is natural to wonder then how the absorption spectra change as a gradual amount of disorder is introduced into the lattice. Figure 2 shows the evolution of the absorption profile for a steadily increasing amount of positional disorder. Each rod is perturbed from its position in the unperturbed lattice, a supercell consisting of 10 \( \times \) 10 unit cells, by an amount \( \Delta p \) chosen randomly from a uniform distribution of values between 0 and \( \Delta p \). The efficiency values, in green, are the absolute change relative to the unperturbed lattice. Insets a, b, and c (in red, with maximal light trapping) show traces of the Bloch-mode resonances, while inset d is Anderson localized with sub-optimal absorption.

In addition to the large efficiency improvement of a partially disordered lattice compared to an unperturbed one, the slight broadening of the peaks offers another significant advantage: it reduces the dependence of the localized modes on the incident-wave properties. Up to this point, the absorption spectra have only been shown for the case of a normally incident planewave source. At off-normal incidence, the
polarization degeneracy is lifted enabling us to better investigate the dependence of a given design’s efficiency on the wave-source conditions. Figure 3 shows the absorption profile for two structures—an unperturbed PC and one with optimal disorder—at four off-normal angles of incidence with the TE polarization. The absorption profile for the individual angles is colored, while the averaged profile is shown in black. Note large increase in robustness with disorder (i.e., standard deviation of the averaged efficiency decreases sharply). The TM polarization data (not shown) have similar characteristics.

outside conditions, while too much disorder lowers the efficiency relative to an optimal amount (albeit any disordered lattice is superior to the unpatterned slab). Such an insight into the light-localization phenomenon of disordered structures points the way towards an interesting design strategy: find the maximum amount of disorder that still preserves some fundamental Bloch character of the modes and retains features of the large peak amplitudes to improve light trapping and robustness without broadening too much so as to be completely incoherent and leaky.

An important design consideration then, stemming from the observations made above, is to find a structure where the disorder (of different types and length scales) has both a small footprint and can be precisely controlled (similar to engineering disorder in surface-texturing approaches) in order to better combine aspects of the high-absorption peaks of the unperturbed PC with the broadened, polarization- and angle-independent peaks of the strongly disordered lattice. To investigate this point in more detail, we now examine a multi-lattice design that consists of two sublattices, where the positional disorder of each sublattice can be independently tuned (the radius of all rods are equal). This multi-lattice structure, shown in Fig. 4, is an example of a lattice design that should offer a finer degree of control for introducing an optimal amount of disorder into the unperturbed structure to obtain the desired characteristics especially when compared to the single-lattice structure where all rods are perturbed in the same way. Figure 4 shows the absorption spectra, at normal incidence, of five different multi-lattice structures with steadily increasing disorder where only one of the two independent sublattices is perturbed. The broadening of the peaks happens gradually enough, acting to increase the absorptivity in regions where it was nearly negligible in the unperturbed lattice while simultaneously better preserving traces of the high-peak resonances, that the light-trapping efficiency can be made to surpass that of the optimal single-lattice structure of Fig. 2 (in this example, the multi-lattice structure shows an efficiency gain of 7.7% at a

FIG. 3. Absorption profile for two different structures (the original unperturbed PC and one with optimal disorder) at four off-normal angles of incidence with the TE polarization. The absorption profile for the individual angles is colored, while the averaged profile is shown in black. Note large increase in robustness with disorder (i.e., standard deviation of the averaged efficiency decreases sharply). The TM polarization data (not shown) have similar characteristics.

FIG. 4. Absorption profile, at normal incidence, for a multi-lattice structure composed of two independent sublattices (white and grey), where only one is perturbed ($\Delta p$). Data for five different structures are shown (in color) with the unperturbed PC (in black) added for reference. Efficiency values for the five perturbed multi-lattice structures are the absolute change relative to the unperturbed lattice.
ment was small by comparison (only 2.2% at a absorption gains, although the maximum efficiency improve-
discovered similar trends of increasing and then decreasing scattering with the broadening due to disorder.

While we demonstrated peak-broadening behavior using only positional disorder, the same phenomenon was observed for radial disorder although for a fixed supercell size the latter disorder type does not preserve the quantity of Si thus somewhat complicating the analysis. We also investigated the effect of disorder starting with an optimized unperturbed PC lattice (53.2% at $a = 500$ nm and $r = 150$ nm) and discovered similar trends of increasing and then decreasing absorption gains, although the maximum efficiency improvement was small by comparison (only 2.2% at $D_p$ of 0.05 $a$). This might suggest that ultimately the optimal amount of disorder, different for each unperturbed starting lattice, will result in nearly identical maximum efficiencies (in this case around 55%, likely limited by the material properties and film thickness of Si) and that the main advantage of using a non-optimal starting lattice is simply that more disorder can be incorporated therefore making the device more robust. Minor fluctuations in the absorption spectra, particularly in the long-wavelength regime for large disorder, are strictly numerical noise due to the finite-supercell size and periodic boundary conditions. In fact, as the supercell size is increased (and with it the effect of randomness), these small oscillations diminish and the absorption profile becomes smoother. Another approach, more relevant for reducing noise in smaller-wavelength features, would be to average the results over a larger number of random iterations (currently two). In addition to a uniform distribution for our random model, we also investigated a normal distribution where the mean positional disorder is fixed at 0 and the standard deviation is varied. The only significant difference, indeed a major one, in the absorption spectra between the two distribution models was that the uniform distribution leads to slightly less broadening due to their being an upper limit for the perturbation. It therefore appears that a uniform model of randomness is better at controlling the disorder than a normal one. A more comprehensive investigation of the role of different lattice designs and random distribution models will be undertaken in a future publication.

In summary, we have described a design principle for enhancing both light trapping and robustness using a par-tially disordered photonic-crystal multi-lattice structure where the amount of disorder, a parameter controlling the DOS as well as the coupling rate between external and internal modes, has both a small footprint and can be carefully chosen. As the performance of typical wave-optics based designs for photovoltaic applications depends sensitively on structural order and external conditions, this strategy may provide a route towards the realization of thin-film photovoltaics with high performance over a wide range of operating criteria.

This work was supported by Core Research for Evolutional Science and Technology (CREST) from the Japan Science and Technology Agency and the Japan Society for the Promotion of Science (JSPS).

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