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Research Article

Disorder Improves Light Absorption in Thin Film Silicon Solar Cells with Hybrid Light Trapping Structure

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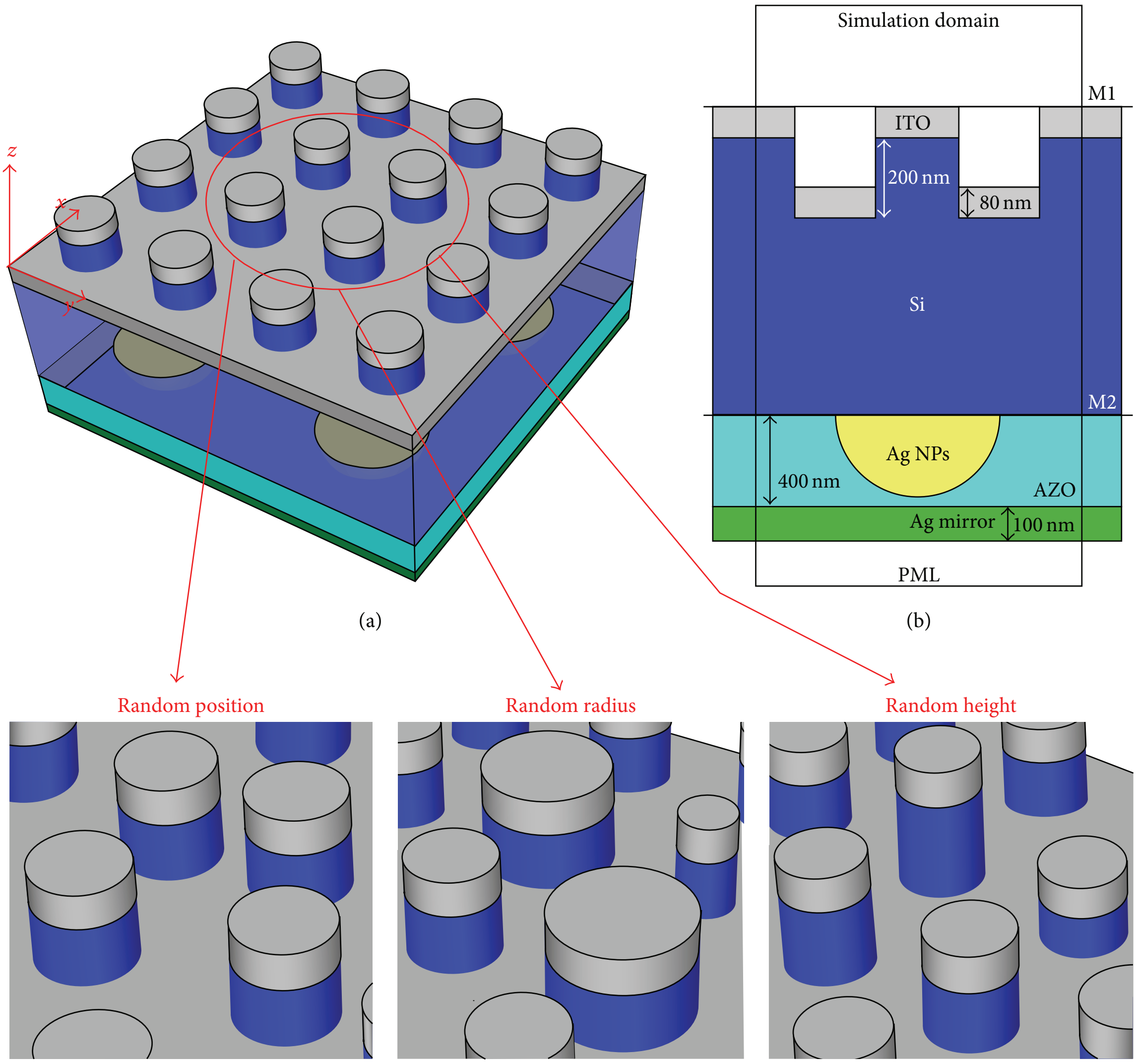
We present a systematic simulation study on the impact of disorder in thin film silicon solar cells with hybrid light trapping structure. For the periodical structures introducing certain randomness in some parameters, the nanophotonic light trapping effect is demonstrated to be superior to their periodic counterparts. The nanophotonic light trapping effect can be associated with the increased modes induced by the structural disorders. Our study is a systematic proof that certain disorder is conceptually an advantage for nanophotonic light trapping concepts in thin film solar cells. The result is relevant to the large field of research on nanophotonic light trapping which currently investigates and prototypes a number of new concepts including disordered periodic and quasiperiodic textures. The random effect on the shape of the pattern (position, height, and radius) investigated in this paper could be a good approach to estimate the influence of experimental inaccuracies for periodic or quasi-periodic structures.

1. Introduction

Thin film crystalline silicon (TF c-Si) solar cells show a great potential in the worldwide application of photovoltaic technologies. It has an active layer thickness of a few micrometers which decreases the material cost greatly and it could be fabricated in a low-cost, feasible way. However, the photocurrent conversion efficiency is largely constrained by the deteriorated light absorption due to the ultrathin active layer. For this reason, advanced light trapping strategies in solar cells are essential since they increase the absorption of incident sunlight. In the last decade, a variety of photonic nanostructure designs have opened unprecedented opportunities for boosting the light absorption, such as photonic crystal [1, 2], light gratings [3–8], plasmonic metal nanoparticles [9–12], and other nanostructures [13, 14].

The question whether random or periodic photonic nanostructures lead to better light trapping in solar cells is currently hotly debated and remains controversial. Lots of works have been done to find which structure behaves better in enhancing light absorption in solar cells, the random structure or the periodic structure. Battaglia et al. [15] reported that periodic structures rival random textures unambiguously based on their work. Han and Chen [16] found that randomness that destroyed the periodic arrangement could bring further light absorption enhancement, as the mirror symmetries are broken. Ferry et al. [17] demonstrated that certain randomness could give broadband and isotropic photocurrent enhancement in TF c-Si solar cells. Recently, Hong et al. [18] have conducted a symmetric study comparison between solar cells with periodic and random nanohole, and they found that random nanohole behaves better in the light absorption enhancement performance. However, little effort has been done trying to combine the advantages of both the periodic and the random structures. Theory predicts that periodic structures should outperform random textures, as they avoid scattering into lossy radiation modes; meanwhile random structures perform better in some realistic experiments and they can be obtained by low-cost, feasible ways [19]. Actually, controlling the optical modes of two-dimensional disordered structures constitutes a new approach for photon management. The disordered



(a) (b)

(c) (d) (e)

Figure 1: The solar cell with hybrid light trapping structure (a) and the solar cells with random grating pillar position (PRSC) (b), with random grating pillar radius (RRSC) (c), and with random grating pillar height (HRSC) (d) used in the simulations.

nanopatterning which provides quasi-guided modes formed by an engineered multiple-scattering process can improve the light coupling efficiency between free space and the films [20]. In our previous work [3, 21, 22], we promoted a hybrid light trapping structure combined of front grating and rear-located silver nanoparticles in TF c-Si solar cell and obtained a short circuit current density (J_{sc}) as high as 29.7 mA/cm^2 within 1 μm c-Si film. In this paper, we attempt to further improve the performance of TF c-Si cells with hybrid light trapping structures through introducing disorder. We study systematically the impact of disorder of initially periodic arrangements of nanostructures as part of an already advanced nanophotonic light trapping concept of prototype thin film solar cells in our study before [3, 22]. We mainly aim to demonstrate the mechanism of the randomness enhancing light absorption and supply a new way of improving thin film solar cell performance. In addition, the random effect on the shape of the pattern investigated in this paper may also find practical use for estimating the influence of experimental inaccuracies of periodic and quasi-periodic structures.

2. Numerical Method

Figures 1(a) and 1(b) show the schematic of the hybrid light trapping structure we have investigated in our previous work [22], which is combined of front grating and rear-located silver (Ag) nanoparticles. Figures 1(c), 1(d), and 1(e) display the solar cells with randomness in the position, radius, and height of the grating pillar labeled as PRSC, RRSC, and HRSC, respectively. We have simulated the effects of the structural parameters on the optical absorption of the solar cells and identified that the optimum structure with the radius is equal to 160 nm and the height is 200 nm, which gives rise to the highest short circuit current density of 29.7 mA/cm^2. In terms of the optimum silver nanoparticles, the light absorption enhancement is almost constant when the radius is in the range of 350–400 nm, so we fix the radius of Ag nanoparticles as 350 nm. The optimum periodic structure will serve as a starting point and a reference (the REF cell). In the simulation, we define a unit square cell with an area of 2.8 μm by 2.8 μm on the x-y plane. Each unit cell includes 49 grating pillars. The parameters in the cell including the position, radius, and height were randomly generated within certain range. For the PRSC (position random solar cell), the randomness is introduced through setting a certain deviation from the center, as illustrated in Figure 1(c). The center of the grating pillar is randomly displaced from the original center by a maximum of 40 nm, reaching the maximum possible value without overlapping with the neighboring grating pillar; meanwhile other parameters are fixed at their optimum values. For the RRSC, the radius varies from 120 nm to 200 nm, and, in the HRSC, the height varies from 50 nm to 200 nm, while other parameters are fixed at their optimum values.

A numerical analysis of the electromagnetic field features is performed utilizing finite-difference time-domain (FDTD) method (https://www.lumerical.com/). The dielectric functions are modeled using a Drude model for Ag and a Drude–Lorentz model for Si. Periodic boundary conditions are applied in the x- and y-directions while perfectly matched layer boundary conditions are used for the z-direction. The calculated absorption is obtained through the difference of power flux through the monitors located on the front and back surfaces of silicon. In the simulations, plane wave is incident normally onto the nanostructure with a wavelength ranging from 300 nm to 1100 nm. We firstly used MATLAB to randomly generate 49 uniformly distributed pillar positions, which are then fed into the FDTD software to simulate the optical absorption. Note that since the unit simulation area includes 49 grating pillar periods, it can be described as quasi-periodicity more exactly. The randomness is introduced on the basis of the periodic structure.

In addition, a quantitative measure is needed for evaluating the light absorption over the entire solar spectrum. A suitable measure of the performance of the structure is the short circuit current density, that is, J_{sc}, excited by the AM1.5 solar spectrum, which is calculated according to the following equation assuming unit internal quantum efficiency:

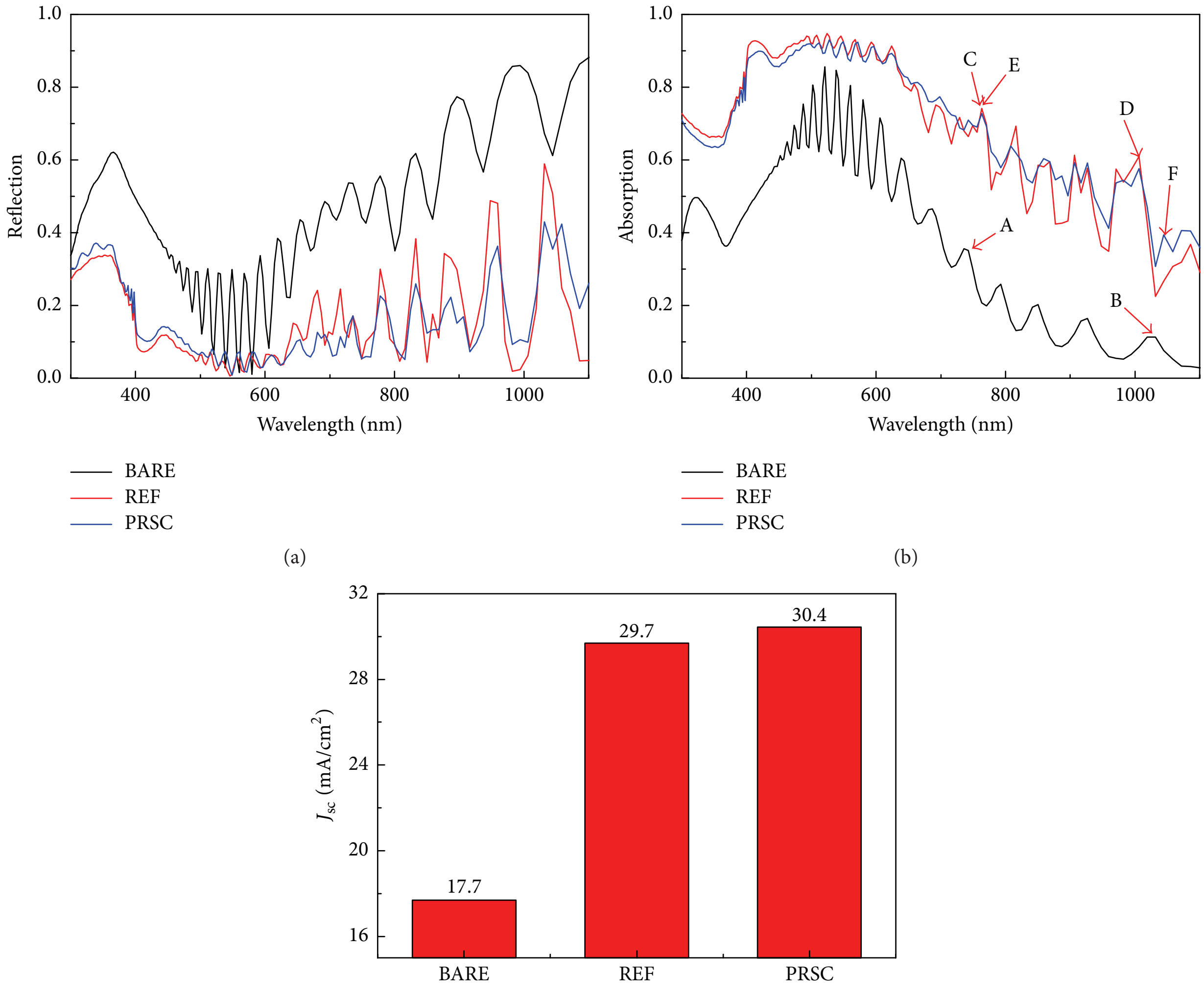
$$J_{sc} = e \int \frac{\lambda}{hc} \frac{P_{abs}(\lambda)}{P_{in}(\lambda)} I_{AM1.5}(\lambda)\, d\lambda, \tag{1}$$

where $I_{AM1.5}$ is reference solar spectral irradiance, P_{abs} is the power absorbed by silicon, P_{in} is the incident power, h is Planck's constant, e is the charge of the electron, and c is the speed of light.

3. Simulation Results

3.1. The Simulation Result of the PRSC with Random Position of the Grating Pillar. Figure 2 shows the optical characteristics of the PRSC with random position of the grating pillar and compared with those of the BARE cell (without any light trapping structure) and the REF cell. It can be seen in Figure 2(a) that both the PRSC and REF cell have lower reflectance compared to the BARE cell over almost the entire wavelength range investigated. This indicates the great antireflection capability of the diffraction grating. Between the REF cell and the PRSC, the reflectance is further decreased in the PRSC, especially in the long wavelengths, which illustrates that the presence of randomness improves the antireflection capability of the diffraction grating. In Figure 2(b), it is seen that the absorption spectrum of the BARE cell consists of multiple peaks, which indicated the presence of the guided mode in thin film silicon [23]. Each absorption peak corresponds to a guided resonance. The absorption is strongly enhanced in the vicinity of each resonance. Hence, one can enhance light absorption over the broad spectrum by a collection of these peaks. These guided modes can be guided into the nanostructures, and this is accomplished by light trapping. This can be seen from the absorption spectrum of the REF cell. Much more peaks and higher peak value appear in the spectrum compared to that of the BARE cell, which indicates the strong light trapping effect of the hybrid light trapping structure [22]. However, there are resonances that cannot be coupled to incident light due to symmetric constraints within a symmetric structure. Generally, symmetries result in degeneracy of the modes, and mirror planes in the symmetric structure result in certain mode not coupling to the incident light [16]. By introducing randomness in the grating position, the structural symmetry in the REF cell is broken. The light absorption spectrum of the PRSC does not show many isolated diffraction peaks, but a broad continuum, flatter and stronger than that of the REF cell. The fact is that there are so many peaks that form a continuum, which cannot be identified. Therefore, the structural randomness results in additional resonances and broadening of the existing resonance. Consequently more light coupled to the guided modes of the PRSC and enhanced the light absorption [24]. J_{sc} of these cells is shown in Figure 2(c), which gives 17.7, 29.7, and 30.4 mA/cm^2, respectively. With the assistance of hybrid light trapping structure, J_{sc} is greatly increased up to 29.7 mA/cm^2, while Yablonovitch [25] gives a theoretical limit of 33.0 mA/cm^2 within 1 μm c-Si. J_{sc} of the REF cell is so high that it is very difficult to be further increased. However, J_{sc} of the PRSC is still boosted up to 30.4 mA/cm^2 resulting from the disordered structures. It is noticed that no structural optimization has been made on the disordered structures, indicating that the disorder structure is a powerful approach for photon management in energy efficiency technologies and may form a new generation of high-efficiency thin film photovoltaic devices.

3.2. The Simulation Result of the RRSC with Random Radius of the Grating Pillar. Figure 3 shows the optical characteristics of the RRSC. It is found that their light reflection and absorption spectra reveal a similar trend as in the case of the PRSC. This radius distribution has impacts on the incident light of both the long wavelengths and the short wavelengths.



(a)

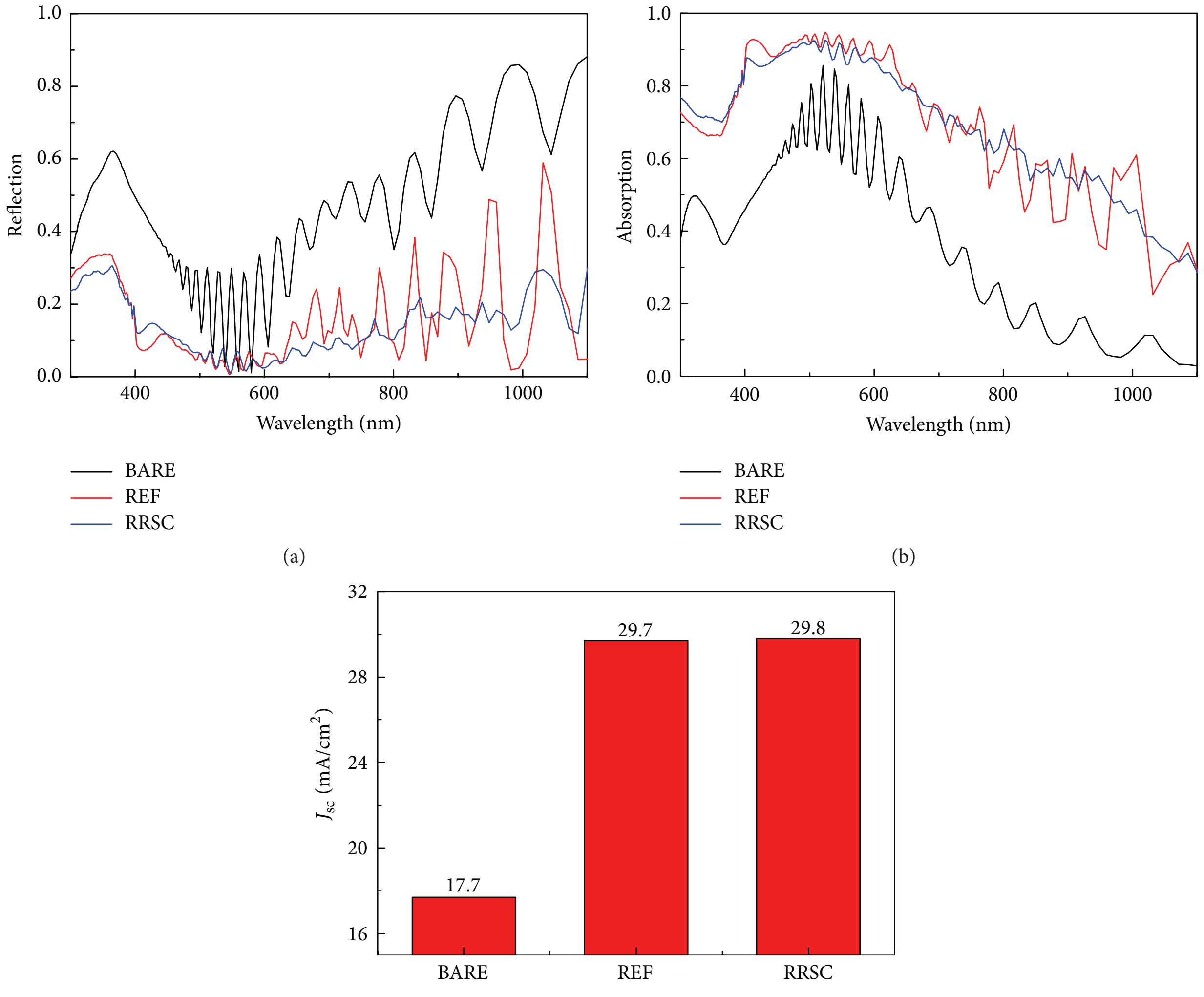
(b)

(c)

Figure 2: The reflection (a), the absorption (b), and the short circuit current density (c) of the BARE cell, the REF cell, and the PRSC with random position of the grating pillar.

Generally, for the asymmetric case, the number of resonances that can contribute to the absorption doubles compared to the symmetric case [5]. It is seen that the reflection of the long wavelength light is reduced dramatically as more guided modes are excited by the randomness introduced into the light trapping structure. These broadening modes are ascribed to the variations in the structural parameters of the RRSC. In the absorption spectrum of Figure 3(b), the higher frequency region has denser peaks, since the density of resonances in the film in general increases with frequency. As for the long wavelengths, a new mechanism for photon absorption is introduced by Oskooi et al. [26] based on quasi resonances, which combine the large absorption of impedance-matched resonances with the broadband and robust characteristics of disordered systems. This makes the absorption spectrum of less sharp peaks but broadening, higher absorption values. J_{sc} of these cells with all these configures are 17.7 mA/cm^2, 29.7 mA/cm^2, and 29.8 mA/cm^2.

3.3. The Simulation Result of the HRSC with Random Height of the Grating Pillar. For the case of the HRSC, due to the height randomness, the incident light experiences a more gradual change in the effective refractive index, which is also known as the "impedance matching." Consequently, with better index matching between air and the HRSC, light reflection is substantially reduced as seen in Figure 4(a). For the absorption spectrum shown in Figure 4(b), the absorption enhancement can be explained by the richer Fourier spectrum of the disordered structures [7], which increases the number of accessible diffraction orders. However, there is also certain decrease in the absorption of some wavelengths, especially in the short wavelength range. The optimal HRSC is thus determined by a trade-off between the increased coupling efficiency to the guided modes, which improves light trapping, and the coupling to the radiative components, which leads to diffraction in air and degrades light trapping when the disorder becomes too large. Meanwhile, similar



(a)

(b)

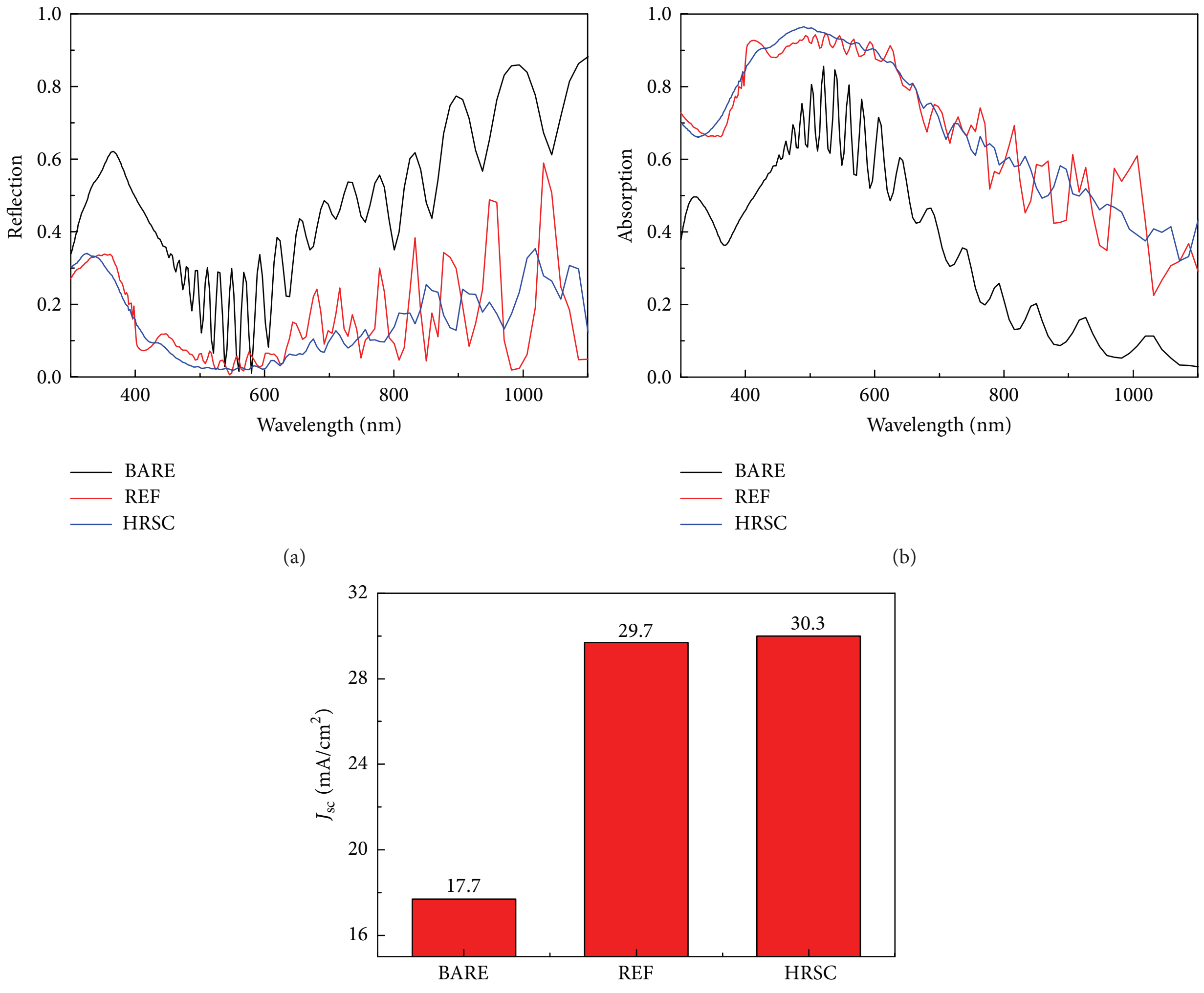
(c)

Figure 3: The reflection (a), the absorption (b), and the short circuit current density (c) of the BARE cell, the REF cell, and the RRSC with random radius of the grating pillar.

peak-broadening behavior also happens due to height disorder. This phenomenon also exists in the PRSC and RRSC. The final J_{sc} of the HRSC is 30.3 mA/cm^2.

4. Discussion

To gain insight into the mechanism behind this strong absorption enhancement, it is instructive to observe how the electromagnetic energy density is distributed in the cells. The repartition of the energy density between a dielectric material and free space allows the determination of the maximal enhancement of absorption in the material [23, 27]. Figure 5 illustrates the electromagnetic field maps at six representative wavelengths (i.e., 736 and 1019 nm for the BARE cell, 763 and 1006 nm for the REF cell, 763 and 1045 nm for the PRSC). These several wavelengths correspond to the absorption peaks labeled in Figure 2(b). For the BARE cell, the electromagnetic field maps are typical Fabry-Perot resonances. In planar system, the Fabry-Perot resonance can only induce few absorption peaks at typical wavelength where the normal incident light strongly interferes with the reflected light by the rear flat surface. On the contrary, the REF cell is composed of much richer interfaces and cavity modes rather than the planar system. Therefore, much more guided modes could be excited in the REF cell. Its electromagnetic field maps exhibit a Bloch mode-like diffraction pattern, with a periodicity in the horizontal x-direction. However, strict periodicity brings degeneracy of the modes, which prevents the light absorption from further increasing. In the PRSC, strict symmetry is broken by the randomness of the grating pillar position which could also be clearly distinguished through comparing the electromagnetic field maps between C and E. Once the strict symmetry disappears, more modes could be guided in the cell. The complex field pattern is due to the superposition of the different optical modes in the active layer and reflects the underlying energy transport process.



(a) (b)

(c)

Figure 4: The reflection (a), the absorption (b), and the short circuit current density (c) of the BARE cell, the REF cell, and the PRSC with random height of the grating pillar.

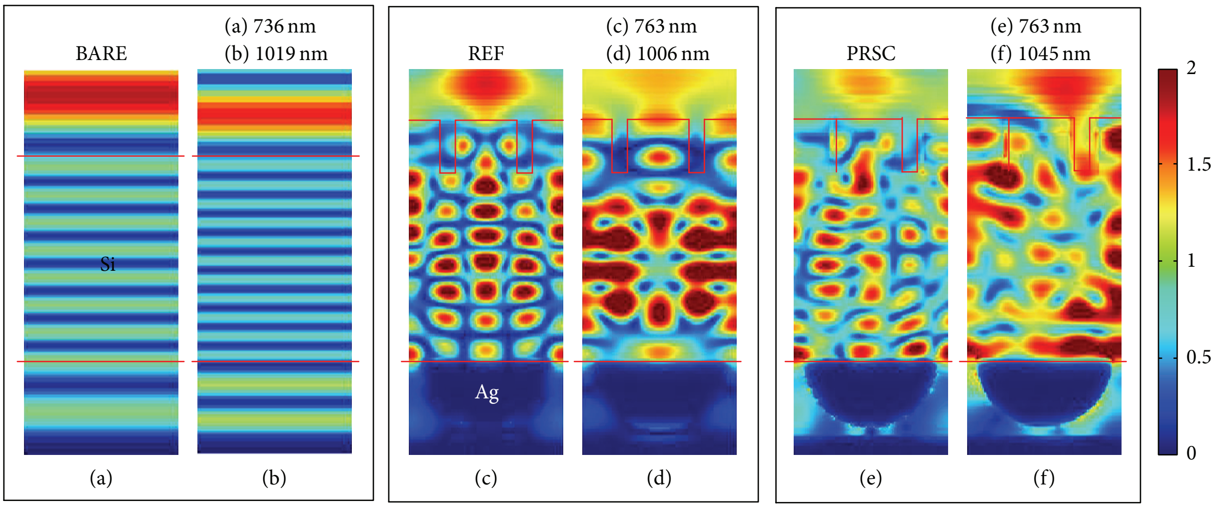


Figure 5: The electromagnetic field maps of the BARE cell (a, b), the REF cell (c, d), and the PRSC (e, f), respectively. The wavelength selected for the BARE cell is of (a) 736 nm and (b) 1019 nm and for the REF cell is of (c) 763 nm and (d) 1006 nm, while for the PRSC it is of (e) 763 nm and (f) 1045 nm.

5. Conclusion

In summary, we calculated the optical characteristics of a hybrid light trapping structure with randomness introduced into the structural parameters which include the radius, depth, and position. The light absorption of solar cells with these quasi-periodic nanostructures is improved compared to the reference structure due to reduced reflection, additional resonances induced, and broadening of the existing resonance. Therefore, the structural randomness is beneficial for light absorption enhancement in thin film silicon solar cells. Due to the loss of the strict symmetry resulting from the disorder, many dark modes are introduced into the solar cell, resulting in the increase of the short circuit current density. We conclude that periodic structures contributed a lot in the light absorption enhancement, and on the basis of periodic structures, random structure could further improve the light absorption by breaking the mirror symmetry. The most prominent strategy of employing a periodic nanostructure is to diffract light into several light beams with different directions, resulting in increased light path length in solar cells. Through introducing disorder into the periodic structures, both the periodic and random structures can be utilized in improving the performance of thin film silicon solar cells. The optimal configuration from the point of view of light trapping is neither perfectly ordered nor totally random, but rather an engineered combination of both order and disorder. In conclusion, utilizing certain disorder on the basis of the periodic structures, the performance of TF solar cells can be further improved, and the random effect on the shape of the pattern (position, height and radius) investigated in this literature could be a good approach to estimating the influence of experimental inaccuracies for periodic and quasi-periodic structures.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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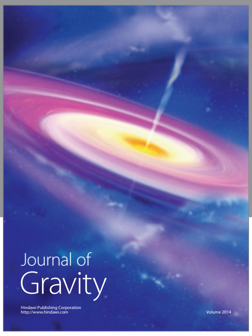
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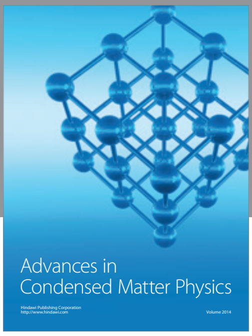
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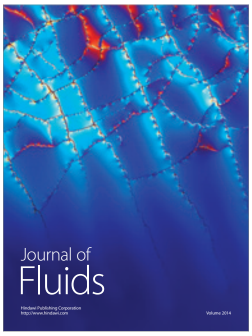
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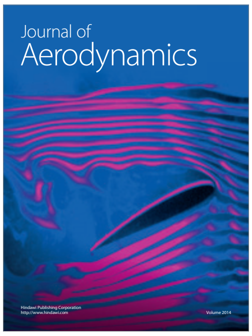
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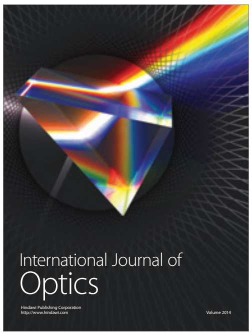
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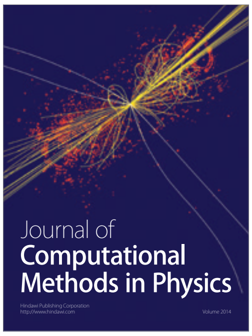
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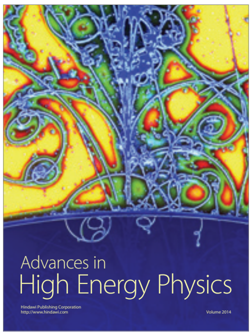
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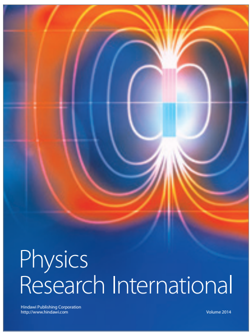
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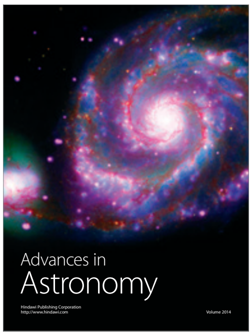
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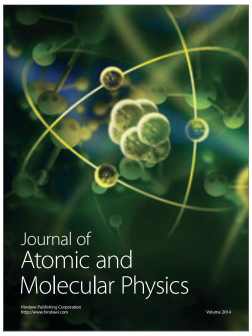
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