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Thin films with disordered nanohole patterns for solar radiation absorbers

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The radiation absorption in thin films with three disordered nanohole patterns, i.e., random position, non-uniform radius, and amorphous pattern, are numerically investigated by finite-difference time-domain (FDTD) simulations. Disorder can alter the absorption spectra and has an impact on the broadband absorption performance. Compared to random position and non-uniform radius nanoholes, amorphous pattern can induce a much better integrated absorption. The power density spectra indicate that amorphous pattern nanoholes reduce the symmetry and provide more resonance modes that are desired for the broadband absorption. The application condition for amorphous pattern nanoholes shows that they are much more appropriate in absorption enhancement for weak absorption materials. Amorphous silicon thin films with disordered nanohole patterns are applied in solar radiation absorbers. Four configurations of thin films with different nanohole patterns show that interference between layers in absorbers will change the absorption performance. Therefore, it is necessary to optimize the whole radiation absorbers although single thin film with amorphous pattern nanohole has reached optimal absorption.

1. Introduction

Thin film solar cell can reduce the cost of raw material and be assembled on flexible substrate, thus has attracted significant research interest recently [1–5]. However, due to the extremely small thickness (hundreds of nanometers in general) of these films, the radiation absorption is quite small, which strongly limits the energy conversion efficiency [1]. To achieve high absorption in thin film, many photon management schemes have been proposed to enhance light trapping in the thin film, such as photonic crystal [2], plasmonics [3,4], grating [5–7], random textured surface [8], nanowires or nanoholes [9–11], etc. Theoretical investigations showed that for structures with features size comparable to the wavelength, the radiation absorption enhancement can exceed the conventional Yablonovitch $4n^2$ limit [12]. This provides large space for design of radiation absorbers to achieve further light trapping in these thin films.

Most of the theoretical investigations in the thin film structure have been focused on ordered structures, for example, nanowire or nanohole arrays with square or triangular lattice [9–11]. However, by considering a thin film with shallow gratings, Yu et al. presented a theoretical analysis based on statistical temporal coupled mode

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theory and showed that aperiodicity could be helpful to enhance broadband absorption, because symmetry can sometimes prevent the guided resonance in the film structure from coupling outside [13]. Based on numerical electromagnetic simulations, Bao et al. demonstrated that in vertically aligned nanowire arrays with random position, diameter, and length, there is further enhanced light absorption compared to their ordered counterparts [14]. Many numerical simulations have also been carried out to optimize the aperiodic structure to further enhance the ultimate absorption efficiency and the results are quite encouraging [15–18]. For example, Sturmberg et al. numerically demonstrated that for an array of nanowires with optimized diameter distributions, the ultimate absorption efficiency can be 28% larger than an array with uniform diameter [18]. Although numerical results have been demonstrated, the mechanism of absorption enhancement in disordered nanowires or nanoholes has not been fully understood. The different explanations include enhanced multiple scattering [14] or better matching of solar spectra using leaky mode resonance [18,19]. Recently, Vynck et al. studied the two-dimensional slab with short range positioned hole pattern and pointed out that amorphous pattern with short range correlation could achieve better broadband absorption enhancement in relatively broad frequency range [20]. Oskooi et al. proposed a scheme to form nanohole pattern with short range correlation, which gradually make appropriate displacements in ordered nanohole arrays [21]. Pratesi et al. demonstrated that semiconductor solar cells with correlated disordered nanoholes have larger absorption efficiency than ordered counterparts [22].

On the other hand, most of the disordered structures have been compared to their ordered counterparts, which are generally not optimized. The solar spectrum and real semiconductor materials have been considered when evaluating the performance of solar radiation absorption. Though it is necessary to do so from an application point of view, it is hard to decouple the contribution of intrinsic material absorption and the enhancement due to the nanopattern. Also, radiation absorption features of different disordered nanohole patterns are difficult to be analyzed to compare with each other. In addition, when disordered nanohole patterns are applied in solar cells, it lacks an explicit application criterion to determine the optimal occasions where they are feasible and pivotal for absorption enhancement. Most importantly, absorption enhancement of thin films with disordered nanohole patterns in integrated devices is rarely concretely discussed. Therefore, it is necessary to study basic principles of radiation absorption in thin films with various disordered nanohole patterns, and to explore their absorption enhancement mechanisms. Application conditions of disordered nanohole patterns, as well as light trapping in the whole integrated devices are also important issues for further engineering application.

In this paper, we systematically investigate the radiation absorption in thin film with three types of disordered nanoholes, i.e., random position, non-uniform radius, and amorphous pattern using finite-difference time-domain (FDTD) simulations. We also discuss intrinsic material absorption of thin film with nanohole patterns to obtain the application condition for amorphous pattern nanoholes. Amorphous silicon is used in thin films with disordered nanoholes. In addition, by adding a transparent conductive layer and a metallic layer, we pile up the thin films with different nanopatterns to assemble solar radiation absorbers. Considering interference between layers in thin film stacks, radiation absorption in absorbers with different nanopatterns is numerically studied.

2. Three types of disordered nanohole patterns

2.1. Models and method

In this paper, a square slab containing circular holes is used to mimic the thin film with disordered nanohole pattern, as shown in Fig. 1. Circular holes may be randomly positioned or have non-uniform radiuses according to different nanohole patterns. The thickness of slab is chosen to be 100 nm, which is comparable to that of a typical amorphous silicon solar cell. Finite-difference time-domain (FDTD) method is employed in numerical simulations. The algorithm is implemented with Lummerical FDTD solutions that is a commercial photonic design software. And the incident wavelength range is from 500 nm to 1100 nm. In simulations, we take the slab consisting of a certain number of complete nanoholes as an unit, and periodic boundary condition is applied in the x and y direction while the perfect-matched layers (PML) are used to truncate the z direction of the simulation domain. To lead common conclusions and avoid the strong dependence of radiation absorption on material type, a fictitious material is used in simulation models. The real part ε_1 of the dielectric function is 12 and the absorption length l_a is 3.3 μm over the entire incident spectrum. Automatic adaptive mesh is introduced to discretize the simulation domain. To extract the transmissivity and reflectivity, a plane wave source is placed above the upper surface of the slab and two power monitors are placed above and below the slab to measure the reflected and transmitted power. The reflectivity R and transmissivity T are obtained by normalizing the recorded power at two monitors by the source power. The absorptivity spectra can be calculated with energy conservation $A = 1 - R - T$. Unless specified, all the results presented below are based on normal light incidence.

To quantify the broadband absorption within the whole spectrum we are interested in, the integrated absorption (IA) η is defined as

$$\eta = \frac{1}{\lambda_{\max} - \lambda_{\min}} \int_{\lambda_{\min}}^{\lambda_{\max}} A(\lambda) \mathrm{d}\lambda \tag{1}$$

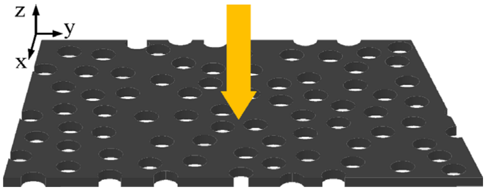

Fig. 1. Schematic of the thin film with disordered nanohole pattern.