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Quick design of high efficiency light trapping nanostructures for thin film silicon solar cells

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A B S T R A C T

Photonic nanostructures are now widely investigated as light trapping textures to achieve significant absorption in thin film solar cells. In this paper, we quickly designed a high efficiency photonic structure for thin film silicon solar cells. Based on the coupled mode theory, we compared classic lattice photonic structures and demonstrated triangular lattice structure exhibits better light trapping performance. Through analysis of short circuit current density, unit cells with heart-pentagon polygon arrangement were verified to offer superior absorption in entire silicon absorption spectrum. Finally, the comparisons with other reported textures validated our design.

1. Introduction

With the reduction of silicon layer in solar cell, light-trapping structures are required to scatter light and increase the optical path length of photons within the thin film solar cell. The conventional macroscopic surface textures commonly applied on thick crystalline cells might not be suited for thin devices particularly when the cell thickness is comparable to or smaller than the macroscopic textures [1]. The implementation of nanostructured light-trapping layers is proving to be more effective. The simplest light-trapping scheme was realized by building solar cells on top of randomly textured substrates capable of redirecting incident sunlight into the plane of the semiconductor [2,3]. For this scheme it is often hard to predict the performance of a solar cell. Light-trapping scheme employing plasmonic nanostructures has gained significant attentions over the past decade due to their strong light concentration and scattering properties [4,5]. However, there are only a limited number of cases where the beneficial impact has been experimentally demonstrated on realistic cell designs. More recently, high-index insulating and semiconducting photonic nanostructures were introduced into solar cells to achieve significant absorption enhancement [6]. When properly sized and shaped, they can also exhibit very strong optical resonances that can further boost light-matter interaction compared with bulk materials. It is important to note that the strength of these resonances is similar to and even surpass those found in metallic nanostructures [7]. The PV community has started engineering these resonances with the aim to improve solar-cell performance [8,9]. Periodic lattice structures such as triangle [10,11], square [12,13], hexagon [14], and even disordered periodic structures [15,16] were proposed as the light trapping textures.

To further improve our ability to trap light in this scheme, it is important to understand which lattice texture is optimal and how they are best arranged spatially on the cell surface. To our knowledge, an adequate demonstration and analysis of a photonic structure combining both characteristics has yet to be produced. On the other hand, current design of high efficient light trapping structures is mainly based on optimization algorithm [17,18], which is really time-consuming. In this paper, we presented quick design of high efficiency light trapping structures. In second section, we briefly introduced the design method. In third section, we identified triangular lattice photonic structures are more suitable for high efficiency light trapping. In forth section, we quickly presented optimal unit cells for triangular lattice structures, which were finally evinced by spectra and angular comparisons with two reported structures in fifth section.

2. Design method

To evaluate the performance of a light trapping structure, it is usually necessary to calculate the absorption enhancement of a solar cell in a light spectrum of interest [10]. Now we introduce a weakly absorbing film with a thickness d and a refractive index n. The solar cell model is formed by the absorbing film with a 2D lattice photonic structure(grating), covered by a transparent conductive oxide(TCO) layer on the upside, and a metallic reflector (contact) on the backside, as shown in Fig. 1. The active film supports guided optical modes which have a propagation distance along the film that is much longer than the

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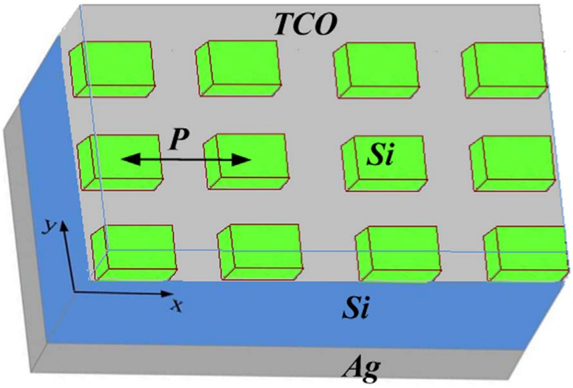

Fig. 1. Schematic illustration of the solar cell, consisting of TCO, 2D grating, absorbing film, and a metallic reflector.

thickness of the film. Once illumination, periodic lattice structures can couple the incident plane waves into these guided modes. Each incident plane wave is associated with at least one guided mode. Similarly, such guided mode can also couple to external plane wave, thus creating a guided resonance. The absorption of the active film is enhanced through the contribution of lots of such resonances. According to the coupled wave theory, for normal incident spectrum with bandwidth $\Delta\omega$, the upper limit of absorption enhancement is quantified as [10]:

$$F = \frac{A}{\alpha d} = \frac{2\pi\gamma_i}{\alpha d\Delta\omega}\frac{M}{N} \tag{1}$$

This upper limit is obtained by comparing the average absorption A with the single-pass absorption αd, where $\alpha = n\gamma_i/c$ is the absorption coefficient, γ_i is the intrinsic loss rate due to material absorption. If the absorption material is given, the limit is actually determined by accessible plane wave channels N and the number of resonances M.

If the grating on the active film has a mirror symmetric profile, the resonant modes either have an odd or even modal amplitude profile. The normally incident plane wave, which has even modal amplitude profile, cannot couple to modes with odd profiles. Therefore, for the symmetric case, the number of resonances that can contribute to the absorption is reduced by half when compared to the asymmetric case. As a result, the symmetric case has lower absorption enhancement than the asymmetric case. It is noted that the upper limit derived from Eq. (1) is only obtained by ideal light trapping structures. In the following, we designed a high efficiency light trapping structure based on the theory.

3. Determination of optimal lattice

We considered four 2D lattice gratings, triangular, square, hexagonal, and octagonal, with same periodicity of P. When a plane wave is normally incident upon the film, the gratings excite other plane waves in free space with specified parallel wave vectors that form the corresponding lattices in wave vector space(k-space). The total number of different wave vectors (blue points) that lie within a circle defined by the vacuum wave vector of the incident light $k_O=\omega/c=2\pi/\lambda$ is multiplied by two for both polarizations to determine the number of channels N.

Here square lattice is taken as an example for calculating the upper limit. In k-space, the area is occupied by each plane wave channel

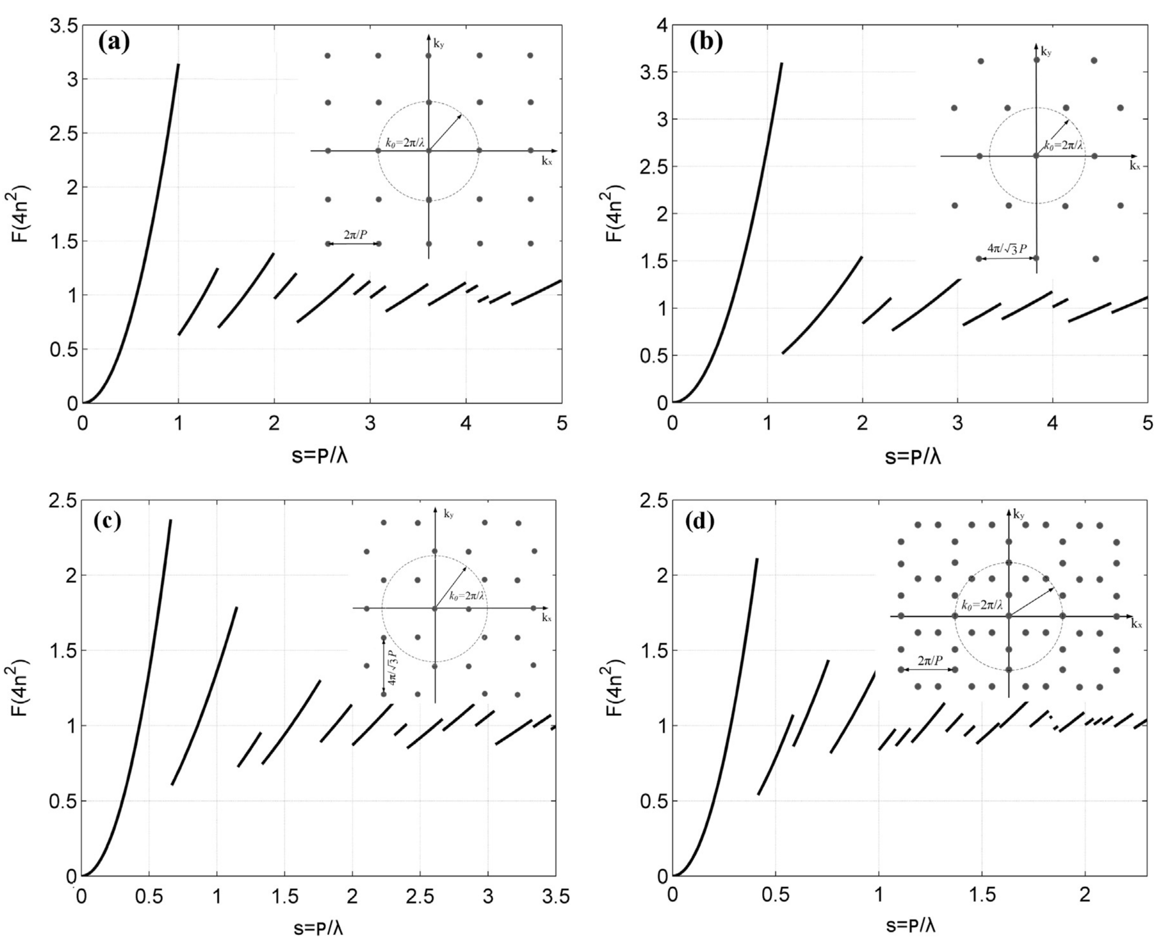

Fig. 2. The upper limits of absorption enhancement as a function of normalized frequency s=P/λ. The insets show the corresponding resonance channels (blue dots) in 2D k-space. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)