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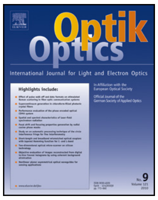

Efficient light trapping in tapered silicon nanohole arrays

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ABSTRACT

We have proposed a novel Silicon solar cells with the tapered nanoholes arrays (TNHs) for the efficient light trapping. After the optimization of the structural parameters, we obtain an exciting value of ultimate conversion efficiency (UCE) about 28.6% for the TNHs structured solar cells with the thickness of active layer of only 1 μm. And the performance of the TNHs solar cells is better than those of the existing cone-shaped nanoholes arrays (CNNHs) and the pure nanoholes arrays (NHs). The Ag nanoparticles (Ag NPs) can be formed automatically during the process of manufacturing the Ag backreflector (AgBR) for the TNHs solar cells. We have also systematically investigated the influence of the structural parameters of Ag NPs to the performance of the solar cell, and the corresponding optimal UCE can reach to 30.1% nearly, which can serve as a practical guideline for designing plasmonic silicon solar cell.

1. Introduction

In the past several tens years, solar cells have been investigated fully to take advantage of solar energy. Due to its non-toxicity, abundance and stability, the photovoltaic industry has been dominated by c-Si for the last 50 years. However, the indirect band gap leads to the poor optical absorption of Si, so the active layers of Si cells should be more than 100 μm for absorbing the incident light fully, which accounts for 40% cost of solar cells and is the barrier of the application of Si solar cells. In order to resolve the problem of the cost, thin film solar cells have been proposed, which can reduce the cost of solar cells and benefit the collection of photon-generated carriers effectively. In order to increase the absorption of thin film solar cells, various structures, including randomly structured surface [1,2], periodic gratings [3–5], photonic crystals [6] and plasmonic structures [7–10], have been widely used in the recently reported works. As a potential approach to increase optical absorption, texturing the active layer itself has been received considerable researching attentions, which leads to the appearances of nanowires arrays (NWs) [11–13] and nanoholes arrays (NHs) [14]. Han and Chen applied NHs in solar energy harvesting for the first time, and they proposed that NHs was superior than NWs for light harvesting when the thicknesses were fixed. Later, cone-shaped nanoholes arrays (CNNHs) were proposed [15], and then the CNNHs had been systematically investigated and optimized for solar cell applications [16], which made a remarkable contribution in improving the ultimate conversion efficiency (UCE) of CNNHs solar cell.

In this paper, we have proposed a novel nanostructure of the tapered nanoholes arrays (TNHs) with a controllable hole array in the silicon thin slab (with a depth of only 1 μm) for thin film solar cell application. The TNHs solar cells shows more prominent UCEs than the existing CNNHs solar cells and NHs solar cells. By optimizing the structural parameters, the UCE of the TNHs solar cells reaches to 28.6% nearly, which is an exciting result for the only 1 μm thickness of the active material. We have investigated electric field intensity distribution in TNHs, which demonstrates that there are Bloch modes coupling in the TNHs structure. We have also incorporated the TNHs with Ag nanoparticles (NPs) and Ag backreflector (AgBR) by a practical and convenient way, which can further improve the performance of the TNHs solar cells by optimizing the structural parameters of the Ag NPs. The structural parameters have been systematically discussed in detail, and the UCE of the combined solar cell can reach to 30.1% nearly.

2. Structure and simulation

Fig. 1(a) shows the 3D schematics of the designed TNHs periodic structure. We set the parameters of a, L, D1, D2 to be lattice constant, hole length (depth of the film), diameter at the top and diameter at the bottom, respectively. Fig. 1(b) shows the schematic of the calculated unit cell (a quarter of the periodic unit). As we utilized the graded refractive index theory to reduce the reflection, the refractive index mismatch between the air and the top of the Si TNHs should be reduced to a minimum value. In real condition, if we set $D1 = a$, the side walls of the Si TNHs may be too thin to

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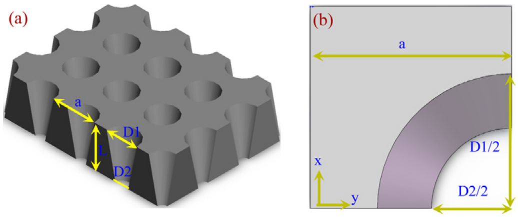

Fig. 1. (a) The schematics the TNHs arrays. (b) The top view of the calculated cell of the TNHs arrays.

support the whole structure. In order to find a proper value for D1, we defined the filling ratio (FR) as $FR = \pi(D1)^2/4a^2$. When D1 equals the lattice constant, FR = 0.78. Hence, we choose FR to be 0.75, and if the parameter of a is determined, D1 can be obtained easily. Here, the lattice constant of a is set to be 300 nm, so D1 is 293 nm, and the hole length of L is set to be 1000 nm (the depth of the TNHs). We can change D2 and a gradually, and calculate the corresponding UCE. By this way, we can find the optimized parameters for the designed structure.

In the simulations, the incident light is set to be an x-polarized plane wave propagating along the z-direction. The wavelength of the incident light changes from 310 nm to 1127 nm. Perfect electric and magnetic conductors (PECs and PMCs) are used on the side walls so that the volume of the calculated unit cell can be reduced to its quarter [17]. Perfect matched layers (PMLs) are used at the top and the bottom of the unit cell to simulate the infinite air. The wavelength-dependent optical-constants of Si and Ag can be obtained from the handbook of optics [18]. The absorption in Si and the parasitic absorption in Ag nanoparticle and AgBR is calculated by the following equation [19]:

$$A_{\mathrm{Si,Ag}} = \frac{\iiint Q_{\mathrm{Si,Ag}}(x, y, z, \lambda)dV}{E_{\mathrm{t}}} \tag{1}$$

Here, refers to the total energy of incident light in the unit cell and $Q_{\mathrm{Si,Ag}}(x, y, z, \lambda)$ refers to the power loss density in Si or Ag, which can be expressed by the following equation [20]:

$$Q_{\mathrm{Si,Ag}}(x, y, z, \lambda) = \frac{1}{2}\omega\, Im(\varepsilon(\lambda))\left|E(x, y, z, \lambda)\right|^2 \tag{2}$$

By calculating Eq. (2), we can obtain the absorption in Si and Ag. The absorption in the Ag is the so-called parasitic loss, which is one of the main mechanisms of loss. The ultimate conversion efficiency, η at AM1.5G condition can be calculated for evaluating the overall absorption and conversion efficiency of the solar cell in the whole solar spectrum, which can be expressed by the following equation:

$$\eta = \frac{\int_{310\mathrm{nm}}^{\lambda_g} I(\lambda)A_{\mathrm{Si}}\lambda/\lambda_g d\lambda}{\int_{310\mathrm{nm}}^{4000\mathrm{nm}} I(\lambda)d\lambda} \tag{3}$$

where $I(\lambda)$ is the spectral irradiance at AM 1.5 direct normal conditions in W/m^2/nm, $\lambda_g = 1127$ nm corresponds to the bandgap energy of silicon (1.1 eV). Eq. (3) assume that each photon with energy greater than the bandgap energy can generate only one electron–hole pair and the excessive energy will convert into heat. The short circuit current density can also be defined to evaluate the photoelectric conversion efficiency and it can be expressed by the following equation:

$$J_{SC} = \frac{e}{hc}\int_{310\mathrm{nm}}^{\lambda_g} \lambda I(\lambda)A(\lambda)d\lambda \tag{4}$$

where e is the electron charge, h is the Planck constant and c is the speed of the light, $I(\lambda)A(\lambda)$ refers to the absorbed energy at specific wavelength of λ, and hc/λ refers to the energy of a photon.

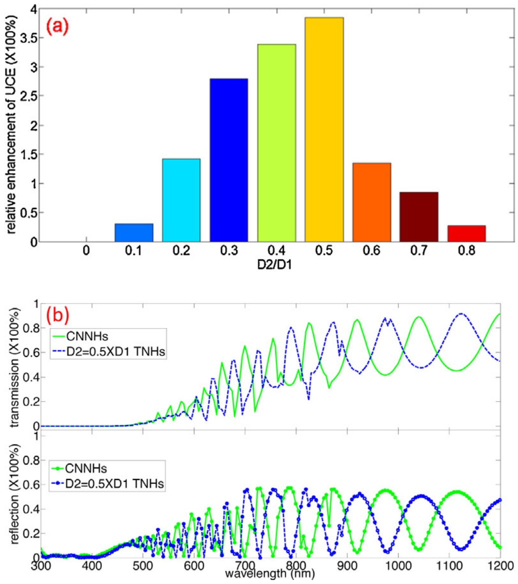

Fig. 2. (a) The relationship between the relative enhancement factor of ultimate efficiency and D2/D1. (b) The transmittance and reflectance spectra of CNNHs and TNHs with D2 = 0.5*D1.

The average reflectance can be calculated to evaluate the overall reflectance, which is defined as [21]:

$$R = \frac{\int_{1200\mathrm{nm}}^{310\mathrm{nm}} I(\lambda)R(\lambda)d\lambda}{\int_{1200\mathrm{nm}}^{310\mathrm{nm}} I(\lambda)d\lambda} \tag{5}$$

where $R(\lambda)$ is the reflectance as a function of the wavelength. Eq. (5) is the weighted average for the reflectance $R(\lambda)$. Likewise, we can calculate the averaged parasitical loss, which can be expressed as:

$$L = \frac{\int_{1200\mathrm{nm}}^{310\mathrm{nm}} I(\lambda)A_{\mathrm{Ag}}(\lambda)d\lambda}{\int_{1200\mathrm{nm}}^{310\mathrm{nm}} I(\lambda)d\lambda} \tag{6}$$

Similarly, we can also express the averaged transmittance as:

$$T = \frac{\int_{1200\mathrm{nm}}^{310\mathrm{nm}} I(\lambda)T(\lambda)d\lambda}{\int_{1200\mathrm{nm}}^{310\mathrm{nm}} I(\lambda)d\lambda} \tag{7}$$

3. Results and discussions

For comparisons, three kinds of structures, bare TNHs arrays, TNHs with AgBR (Ag backreflector), and TNHs with AgBR and AgNPs (Ag nanoparticles) have been investigated in detail.

3.1. The bare TNH arrays

We investigate the optimized structural parameters for bare TNHs arrays. Firstly, we fixed the lattice constants to be 300 nm, and searched for the best D2 by changing D2 from 0 nm to 0.8*D1. According to the result of the simulation, our TNHs can outperform CNNHs (TNHs with D2 = 0). In order to illustrate the enhancement of the ultimate efficiency, we define the relative enhancement factor of ultimate efficiency as:

$$\eta = \frac{(E_{\mathrm{TNHs}} - E_{\mathrm{CNNHs}})}{E_{\mathrm{CNNHs}}} \tag{8}$$

where E_{TNHs} and E_{CNNHs} are the UCEs of TNHs and CNNHs solar cells, respectively. Fig. 2(a) illustrates the relationship between D2 and the relative enhancement factor of UCE. According to this graph, the best value for D2 is 0.5*D1 and the corresponding UCE is 19.1%.