Investigations of the optical properties of Si surface with microwires for solar cell applications*

Li Li(郦莉)[1], Shi-Liang Wu(吴仕良)[1], Dong Yu(虞栋)[1], Wei Wang(王伟)[1], Wen-Chao Liu(刘文超)[2], Xiao-Shan Wu(吴小山)[1], and Feng-Ming Zhang(张凤鸣)[1,†]

[1] *Collaborative Innovation Center of Advanced Microstrucutres, Laboratory of Solid State Microstructures, School of Physics, Nanjing University, Nanjing* 210093, *China*

[2] *National Laboratory of Solid State Microstructures, Center of Photovoltaic Engineering and School of Modern Engineering and Applied Sciences, Nanjing University, Nanjing* 210093, *China*

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Combined with the rough textures which are usually used for fabricating the planar solar cells, textured-microwire (MW) structures (there are MW textures on the tops of MWs) are fabricated. Both simulative and experimental investigations of the optical properties of Si surface with microwires are carried out and the results show that surfaces of textured-MW structures exhibit lower reflectance in the short wavelength range, but higher reflectance in the long wavelength range than the conventional textured surface. It is also shown, consequently, that the textured-MW structures could absorb more photons in the short wavelength range, which could help improve the performance of the solar cells.

Keywords: microstructure, reflectivity, silicon, solar energy

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1. Introduction

In order to achieve higher efficiency, many approaches have been proposed. Using a low-reflection surface is one of the most effective ways.[1–8] Yablonovitch[9] used a statistical approach to study the optical properties of the media with complicated surfaces like random textured surfaces, while Campbell and Green[10] studied the light trapping properties of pyramidal textured surfaces. These two kinds of surface structures have been widely used in today's industry to reduce the reflection of silicon solar cells. Recently, solar cells with nano-structured surfaces have attracted a lot of attention, like black silicon[11–13] which exhibits an outstanding antireflection ability. Besides quite a low reflection, nanowire solar cells[14–18] with radial pn junctions can relax the requirement for the quality of materials by decoupling the direction of incident light absorption and the direction of photon-generated carriers' collection. So high-efficiency solar cells can be fabricated with low-quality materials by using this special radial junction structure.

However, little improvement of performance has been observed in experiments on these nano-structured solar cells,[19] and one of the main reasons is the poor quality of radial pn junctions.[16] So some groups studied solar cells with columnar arrays on the order of micrometers.[20–23] This kind of structure can also achieve the purpose of relaxing the requirement for material quality. As the conventional tube-furnace diffusion method is applicable to the microwires (MWs) and no dead layer problem occurs, it would be easy to fabricate MW solar cells with high-quality radial junctions in a low-cost way compared with fabricating the nanowire solar cells.

It is worthwhile to study the optical properties of these solar cells with radial junctions in order to improve their performances. Many groups have reported the results about low reflectivities of nanowires both experimentally and simulatively, which are mainly contributed by their special surface structures on a sub-wavelength scale.[24,25] Unlike nanowires, wires of micron-scale radius are expected to exhibit different optical properties on their different scales. Kosten *et al.*[26] developed a ray optics model to investigate the light trapping observed in silicon MWs. The calculated results showed that with the Lambertian back reflector, MWs could exceed the ergodic limit in the ray optics regime. Lee *et al.*[27] compared the experimental and simulative reflectance results of Si MW solar cells, showing that the reflectance of MWs all exceeded 30% in the range of visible light, which is much higher than that of nanowire solar cells. So it is important to reduce the reflectivities of MWs in order to improve the performance of cells. Based on the fact that wet-chemically textured surfaces are widely used in the photovoltaic industry, presented here is an investigation on the scenario of combining the structure of MWs and the textured surfaces for improving the optical properties of cells. As have been observed in nano-scale structures,[28,29] changing the radii of MWs would affect the optical properties of structures.

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†Corresponding author. E-mail: fmzhang@nju.edu.cn

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2. Experiment

Multi-crystalline silicon solar cells with conventional textured surfaces and textured-MW structured (with textures on the tops of MWs) surfaces with different radii have been fabricated. By comparing with the conventional textured surface prepared by acid etching, textured-MW structured surfaces were prepared with acid etching followed by inductive coupled plasma etching. A PECVD coating procedure was used to prepare the outmost SiN_x layer to reduce the reflectivity of the structure. Figure 1 shows the schematic of the textured-MWs structures. Textured-MW solar cells with three different radii (6 μm. 9 μm, and 12 μm) have been prepared. The edge-to-edge distance (d) of the wires of all these three MW samples were the same (4 μm). The heights of the wires were all about 10 μm. The wires had a hexagonal two-dimensional (2D) lattice. Scanning electron microscopy (SEM, Hitachi S-3400N2) was used to study the morphologies of silicon surfaces. The reflectivity of the surface was measured by using an integrating sphere. The finite-difference time-domain (FDTD) Solutions were used to calculate the reflectance and electric field magnitude distributions of the MW structures. In order to simplify the calculation process, surface textures of pyramid structures were used. Shown in Fig. 2(a) is the unit cell of simulation, while figure 2(b) displays the schematic of the calculated textured-MW structure. A periodic boundary condition is used in the x and y directions, while a perfectly matched layer (PML) boundary condition is used in the z direction. The radii and the heights of the wires are set to be the same values as those of the prepared samples, respectively. For textured-MWs, the total height is 10 μm which is the sum of the column height of 9 μm and the pyramid height of 1 μm. The thickness of the outmost SiN_x layer of columns and pyramids is 80 nm, which is an empirical value used in the industry. In order to understand the optical properties of silicon MW structures more clearly, Lumerical FDTD Solutions, an FDTD electromagnetic field simulation package, was used. The reflectance and electric field magnitude distributions of different solar cells have been calculated.

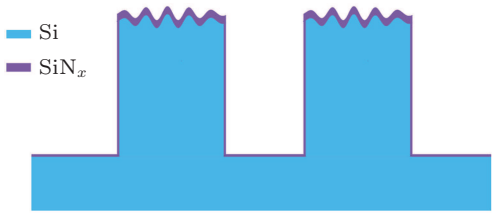


Fig. 1. (color online) Cross section image of textured-MWs.

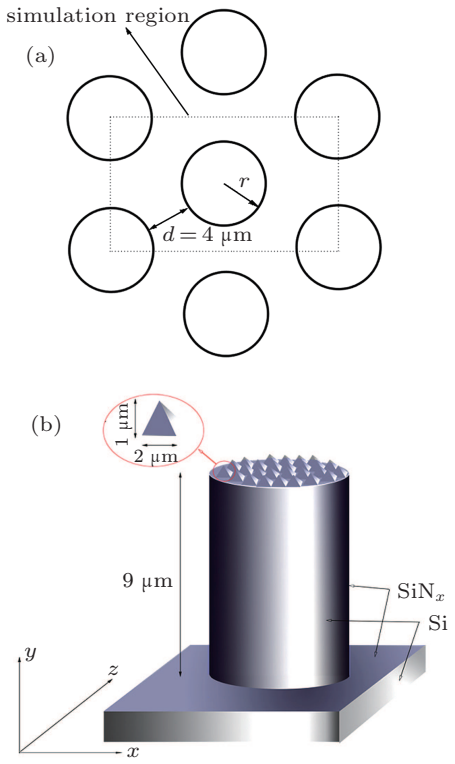


Fig. 2. (color online) Unit cell of simulation, and (b) schematic plot of the calculated textured-MW structure.

3. Results and discussion

The SEM image of a textured-MW structure sample (r = 12 μm) is shown in Fig. 3. It can be seen that the shapes and the sizes of the MWs are uniform. The textures prepared by acid etching can be seen clearly on the tops of wires.

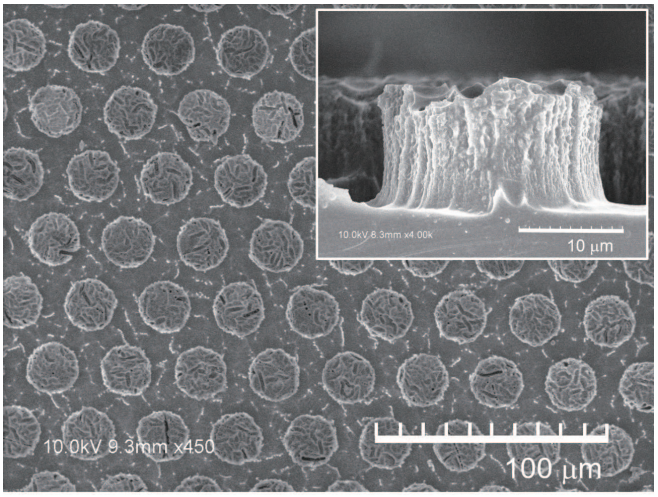


Fig. 3. The SEM image of a silicon surface with textured-MWs each with a radius of 12 μm.

Shown in Fig. 4 are the measured reflectivity results of the conventional textured surface and textured-MW structured surfaces. Compared with the conventional textured surface, the textured-MW structured surface exhibits lower reflectance in a short wavelength range and higher reflectance in a long wavelength range. It can also be found that the radii of MWs can affect the reflectivity obviously. From 400 nm to around 700 nm, MWs with smaller radii show lower reflectivities, while from around 700 nm to 1000 nm, MWs with larger

radii show lower reflectivities. The antireflection properties of the MW structures are quite different from those of nanowire structures.[26,27,30] As is well known, both the MWs themselves and the textures on the tops of the MWs could lead to multi-reflections. The same edge-to-edge distance between the MWs means that the samples with MWs of smaller radii have higher wire densities, which could cause more multi-reflections. This could explain the lower reflectivity of the samples with MWs of smaller radii in the short wavelength range. In the long wavelength range, on the other hand, it is not difficult to understand. As is well known, the photons with longer wavelength would have a longer penetration depth. The incident light which is perpendicular to the surfaces of wires would change the direction when it goes into the wires when considering the textured surfaces. As a result, wires of longer radii could absorb more photons of longer wavelength since these photons could go a longer distance before they could escape out of the sides of the wires. As a result, the MWs with smaller radii show higher reflectivity in the long wavelength range.

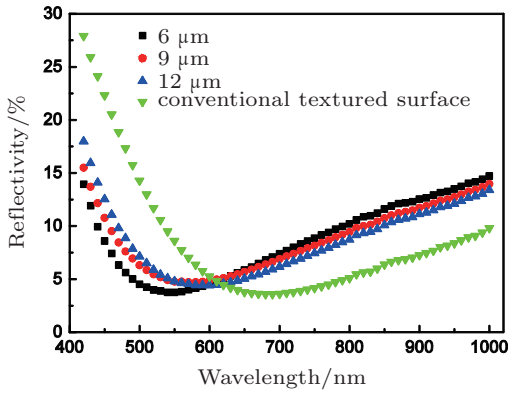


Fig. 4. (color online) Measured reflectivity results of conventional textured surface and textured-MW structured surfaces with different radii (6 μm, 9 μm, and 12 μm).

Based on the reflectivity (R), wafer thickness (t) and absorption coefficient (α), the absorbed photons $n(\lambda)$ at wavelength λ can be expressed as

$$n(\lambda) = n_0(\lambda) \cdot (1 - R) \cdot (1 - \mathrm{e}^{-\alpha t}), \tag{1}$$

where $n_0(\lambda)$ is the density of incident photons at wavelength λ and air mass 1.5.

From Eq. (1), the numbers of the absorbed photons in the wavelength from 420 nm to 1000 nm can be calculated for the structures with different radii of MWs and are shown in Fig. 5(a). In the calculation, the wavelength dependence of the absorption coefficient is considered, and 180 μm is assumed for an average thickness of the Si wafers. It can be seen that in the short wavelength range, textured-MW structures absorb more photons than the conventional textured surface. The smaller the radius is, the more photons are absorbed. In the long wavelength range, the results are just the opposite.

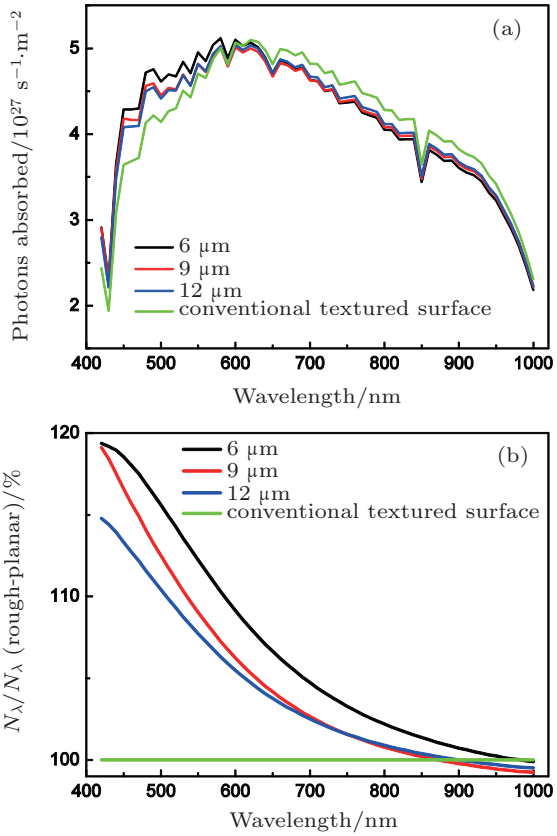


Fig. 5. (color online) (a) Dependences of the absorbed photons on wavelength, and (b) wavelength dependence of the total photons from 420 nm to 1000 nm, for different radii of textured-MW structured surfaces of 180-μm-thick Si wafers.

To better understand the effects of MW structures on the performance of solar cells, it is interesting to further analyze the photon absorption in the short wavelength range. The total photons absorbed in a wavelength range from λ_0 to λ can be expressed as

$$N(\lambda) = \int_{\lambda_0}^{\lambda} n(\lambda)\mathrm{d}\lambda. \tag{2}$$

By taking the $N(\lambda)$ of the conventional textured surface as the reference, the increase of $N(\lambda)$ for the textured-MW structured surfaces in percentage can be obtained from Fig. 5(a). Shown in Fig. 5(b) is the wavelength dependence of the total photons absorbed from 420 nm to λ for different radii of MW structured surfaces with a Si wafer thickness of 180 μm. It can be seen that the total numbers of photons absorbed from 420 nm to 1000 nm are quite close for different structures. However, in a wavelength ranging from 420 nm to about 850 nm, the total numbers of photons absorbed in textured-MWs are more than those in the conventional texture surface. The smaller the radius is, the more photons the textured-MWs can absorb in the short wavelength range. This is especially helpful for improving the blue response of the solar cells. So it can be assumed that the reflectance and absorption performance may help textured-MW solar cells exhibit better performance than solar cells of a conventional textured surface.

The simulated reflectance results of textured-MW structured surfaces with different wire radii (6 μm, 9 μm, and 12 μm) are obtained with FDTD Solutions and shown in Fig. 6. Compared with the experimental results shown in Fig. 4, the simulated reflectivity results exhibit a similar trend to those observed in the experiments, or in the short wavelength range, MWs with smaller radii show better antireflection effects, while in the long wavelength range, MWs with larger radii exhibit lower reflections.

In order to understand the difference in light distribution in Si wafers between conventional textured surface and textured-MW structured surface, their electric field magnitude distributions are calculated. Shown in Fig. 7 are the normalized cross-sectional electric field magnitude distributions (E denotes the electric field magnitude in the structure, E_0 represents the electric field magnitude of the incident plane wave) of different structures (conventional textured surface, flat-MWs: without textures at the tops of MWs, and textured-MWs) at wavelengths of 500 nm, 700 nm, and 900 nm. From the results, it is indicated that the electric field magnitude distributions of textured-MW surfaces are quite different from those of the conventional textured surface and the flat-MW surface.

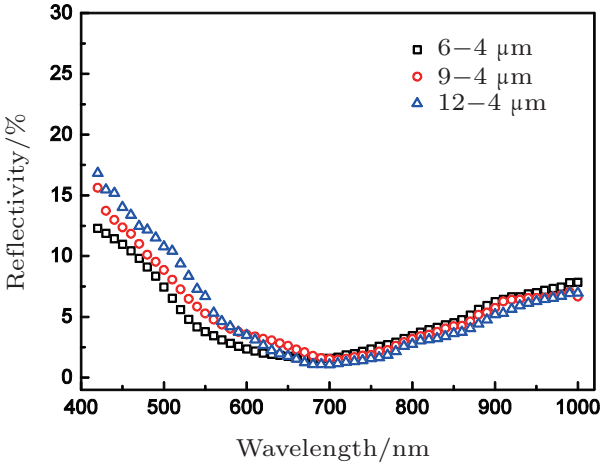


Fig. 6. (color online) Simulated reflectivity results of conventional texture surface and textured-MW structured surfaces with wires of different radii (6 μm, 9 μm, and 12 μm).

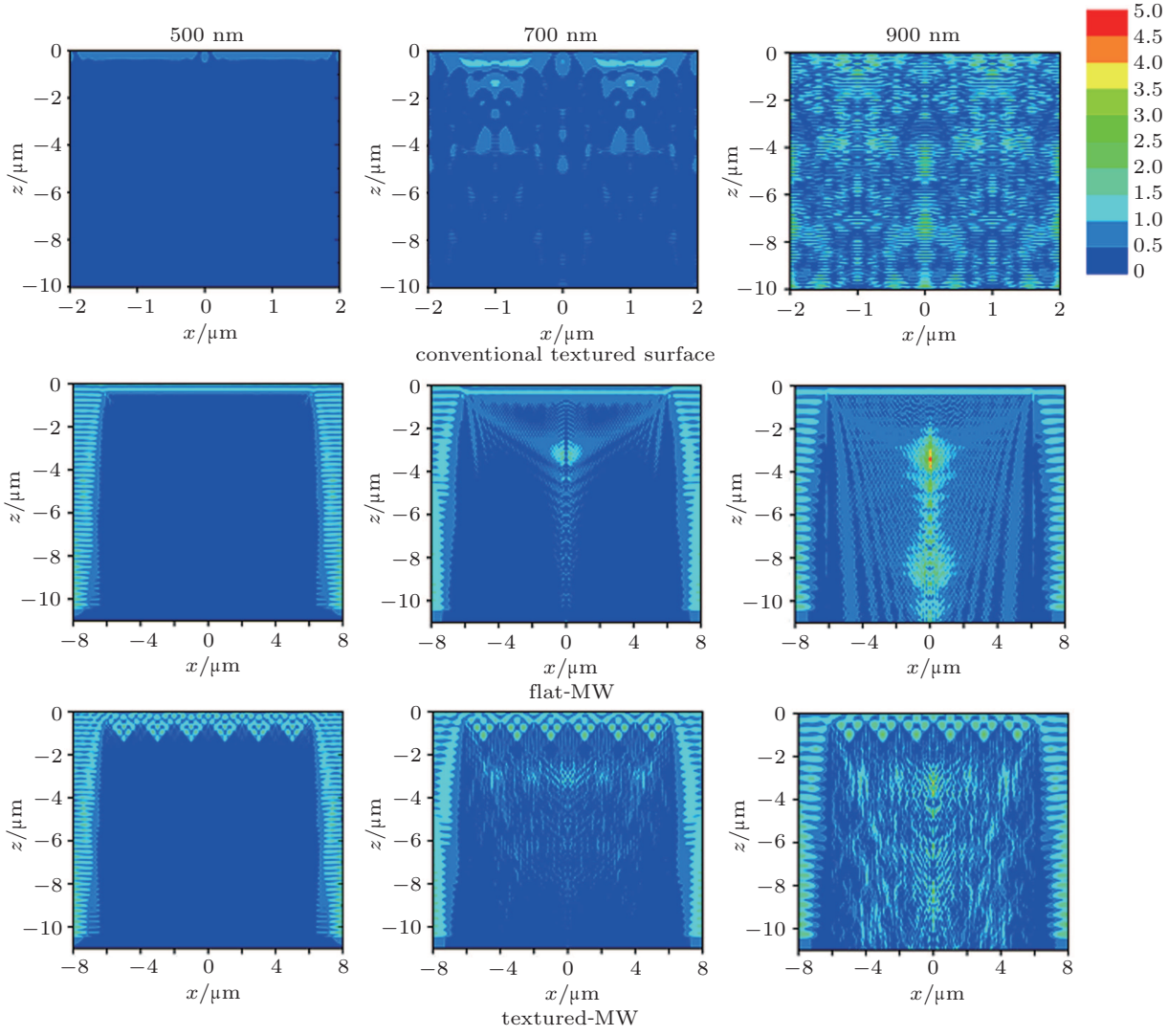


Fig. 7. (color online) Electric field magnitude distributions of three structures (conventional texture surface, flat-MW, and textured-MW) at wavelengths of 500 nm, 700 nm, and 900 nm.

The electric field magnitude distributions in the textured-MWs look like the combination of the electric field magnitude distribution in the conventional textured surface and that in a flat-MW surface. In the flat-MWs, there exists a tendency of higher light intensity distributed along the edges of the wires. For long wavelength light, two higher intensity areas appear: the edge and center in the wires, while almost all light is distributed along the edge area for short wavelength light. For the textured-MW surfaces, the light distribution in central areas in the wires becomes more uniform although the distribution in the edge areas seems to be unchanged. As is well known, the carriers generated in the MWs are collected in the radial direction. So the electric field magnitude distribution in the textured-MWs could help to improve the collection of carriers compared with those in both the flat-MWs structure and conventional textured surface due to the shorter distance to the edge junction of some photon-generated carriers.

4. Conclusions

The reflectivities of conventional textured surface and textured-MW structured surfaces are investigated. The experimental and simulated results are in good agreement with each other. Compared with the conventional textured surface, textured-MWs structures show a lower reflectivity in the short wavelength range and higher reflectivity in the long wavelength range. The surfaces of MWs with smaller radii exhibit lower reflectivities in the short wavelength range, but higher reflectivities in the long wavelength range. Further analysis indicates that textured-MWs can absorb more photons in the short wavelength range, which could help to improve the collection efficiency of carriers. Moreover, simulations on electric field magnitude distributions in the MWs show that textured-MWs structures demonstrate a better effect on the improvement of the carrier collections.

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