Efficiency enhancement in GaAs solar cells using self-assembled microspheres

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Abstract: In this study we develop an efficient light harvesting scheme that can enhance the efficiency of GaAs solar cells using self-assembled microspheres. Based on the scattering of the microspheres and the theory of photonic crystals, the path length can be increased. In addition, the self-assembly of microspheres is one of the simplest and the fastest methods with which to build a 2D periodic structure. The experimental results are confirmed by the use of a simulation in which a finite-difference time-domain (FDTD) method is used to analyze the absorption and electric field of the 2D periodic structure. Both the results of the numerical simulations and the experimental results show an increase in the conversion power efficiency of GaAs solar cell of about 25% when 1 μm microspheres were assembled on the surface of GaAs solar cells.

OCIS codes: (160.4670) Optical materials; (040.5350) Photovoltaic.

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1. Introduction

Improvements in the efficiency of Si solar cells have been achieved in recent years with structures designed to reduce frontal reflection and provide better absorption of the incoming solar radiation [1-2]. The designed structures achieve the function of increased light-trapping by extending the length of the optical path of incident rays in the solar cells which can increase the absorption. Random pyramidal textures (based on the <111> crystallographic plane), produced using wet-chemical etching, are now commonly used for crystalline silicon wafer solar cells. However, pyramidal textures are not good enough for highly efficient structures, because of the large fraction of resurfaced light that escapes from the frontal surface of the solar cell. M. A. Green [3] has proposed that the efficiency of pyramidal-textured solar cells can be improved by replacing this structure with a V-grooved one. Instead of the spontaneous etching method, lithographic techniques can be used with anisotropic etching to obtain V-grooved surfaces.

However, neither pyramidal textures nor V-grooved structures can be applied to improve the efficiency of GaAs solar cells. Since its crystallographic plane is on the <001> surface, there is no convenient etching method, like for silicon, which can be used to spontaneously produce pyramidal structures. In addition, the surface recombination velocity is too high to achieve a good passivated surface and the absorption coefficient is also high enough to decrease the diffusion length of GaAs. Whenever the carriers are generated in an etched GaAs surface itself, the recombination will happen either at the etched surface, or on the way to the field-bearing region. The solution is to fabricate the texture using a different material [4] on the surface of the GaAs. The frontal surface texture has the effect of scattering the incident rays away from the original direction. Some of the rays will be absorbed completely due to the condition of total internal reflection; others may be deflected at a large deflective angle to extend the path length [5]. Increasing the path length means increasing the probability of photogeneration per incident photon. A maximum path length enhancement of $4n^2$ has been proposed in the film with refractive index n if there are textured structures on it [6].

In this study, we investigate a light harvesting scheme wherein a periodic structure of microspheres can be deposited using a self-assembly method [7] on the surface of a GaAs solar cell. Based on the scattering of the microspheres and the theory of photonic crystals, the path length can be increased. It should be noted that, the self-assembly of microspheres is one of the simplest and fastest methods with which to build a 2D periodic structure. The experimental results were confirmed by a finite-difference time-domain method (FDTD) simulation which was used to analyze the absorption and electric field of the 2D periodic structure.

2. Experiment

2.1 Cell structure

All of the GaAs solar cells described in this paper were grown using a commercially available horizontal reactor system (AIX200) under low pressure metalorganic vapor phase epitaxy (MOVPE) on GaAs substrates oriented 2 degree toward <111> from <100> with thicknesses of 300 μm. An n^+ GaAs buffer layer and a 0.1 μm p-doped GaAs capping layer were grown on the GaAs substrate, both of which were selectively removed from the photoactive area during processing. After the removal process, the solar cell was produced after growing 5

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more layers one at a time. The final product consisted of a 0.1 μm n-InGaP back-surface-field layer, 3 μm n-GaAs base, 0.5 μm p-GaAs emitter, and 0.03 μm p-InGaP window layer, from bottom to top, as shown in Fig. 1. The details of the epitaxial conditions are reported in greater detail in Ref. 8. The photocurrent was analyzed at room temperature using a dual source solar simulator (Wacom WXS-130S). The solar simulator included both a xenon lamp and a halogen lamp to more closely simulate the real AM 1.5G solar spectrum.

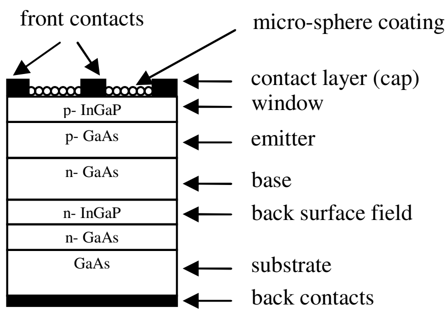

Fig. 1. Schematic diagram of a GaAs solar cell with a microsphere coating on the surface.

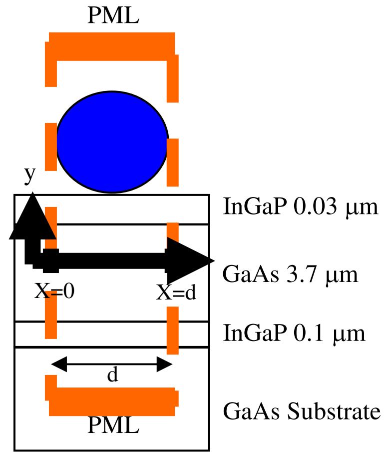

Fig. 2. Schematic diagram of the simulation.

2.2 Simulation

Generally, the most commonly used tools for the simulation of optical and photonic devices are the ray-tracing method and the FDTD method. The former is based on Snell's law, and the latter on Maxwell's equations which are used to calculate the propagation of the electromagnetic wave. The ray-tracing method is not suitable for the simulation of subwavelength scale structures. Thus, we carry out computational analysis (i.e., FDTD numerical simulations) to study the surface texture of GaAs solar cells with dip-coated microspheres. Although the FDTD method has successfully been applied for the simulation of multichannel filters based on photonic crystals, plasmonic waveguides and light extraction in GaN-Based LEDs [9-11] its use for, the numerical simulation of the surface texture on a solar cell device is still a challenge.

The simplified structure of the simulated solar cell structure is indicated by the dashed-line area in Fig. 2. The electrode in the GaAs-solar cell structure is neglected and the p and n active absorption layers are combined as a single layer. The incident light irradiates from the top surface down to the whole structure. The simulated wavelength is in the range of 400~900 nm. The wavelength-dependant refractive indices of GaAs and InGaP are 4.1 and 3.47 at 550 nm, respectively. The simulated grid is Δx□ $(\lambda/n)/15$ in the space domain and Δt□$\Delta x/(2c)$ in the time domain, where n, λ, and c are the refractive index of the material, the wavelength of the incident light, and the light speed, respectively. The width d of the structure is periodic, so the boundary treatment is applied when the periodic condition in the surface of x=0 and x=d. The top and bottom boundaries are surrounded by perfectly matched layers (PML) [12] with 64 layers to absorb outgoing electromagnetic waves in the y-direction. The details of the FDTD algorithm have been reported in Ref. 13-17. The transmittance and reflectance spectra of the cell were achieved after the FDTD numerical simulation.

2.3 Texturing process

In order to improve the absorption efficiency of the GaAs solar cell, the highly order two-dimensional (2-D) structures were fabricated on the top surface of GaAs solar cell of monodisperse polystyrene (PS) spheres, which is suitable for high-throughput and large-area

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processing. Figure 1 shows a schematic diagram of the microspheres coated on the top of the GaAs solar cell. PS spheres were synthesized with sizes of 0.3, 0.5, 1, 3 and 5 μm via emulsion polymerization at 70°C. After heating at 70°C for 24 hours, the latex was centrifuged. The PS spheres were collected and washed with fresh water six more times to remove any remaining impurities. They were then dispersed into a solvent. The solid content was controlled to about 10 wt%. The glass transition temperature (T_g) of the PS microspheres was 104°C, as measured by a differential scanning calorimeter (DSC). After fabricating the PS spheres, they were deposited in a highly ordered self-assembled structure on the substrate by a dip coating method. In other words, after synthesizing the PS spheres, a PS sphere array was fabricated on the surface of the GaAs solar cells using the dip coating method. The rising speed of the substrate was controlled at 5 mm/sec and the sample was heated to 70°C in air for 10 minutes to remove the solution.

3. Results and discussion

In this study, the simplified solar cell structure shown in Fig. 2 was constructed using an FDTD numerical simulation. A monolayer of PS microspheres (with sizes of 0.3 μm, 0.5 μm, 1 μm, 3 μm, and 5 μm) was simulated on top of a GaAs solar cell. The refractive index of the microspheres was about 1.59 at a reference wavelength of 550 nm. The transmittance $T(\lambda)$ and reflectance $R(\lambda)$ spectra of the cell were achieved during the FDTD numerical simulation. The absorption $A(\lambda)$ spectrum of the solar cell can be formulated as $A(\lambda)=1-T(\lambda)-R(\lambda)$, where $T(\lambda)$ and $R(\lambda)$ also included the interference effect due to the surface texture. The optical absorption spectrum $\Phi_{opt}(\lambda)$ can be integrated as follows:

$$\Phi_{opt}(\lambda)=\Phi(sun) * A(\lambda), \quad (1)$$

where $\Phi(sun)$ is the solar intensity at AM 1.5G. Figure 3 shows the optical absorption spectra $\Phi_{opt}(\lambda)$ for the different sizes of microsphere. We can see that the optical absorption became higher as the size of the microspheres became smaller (from 5 μm to 1 μm). However, when the size of the microspheres was 0.5 μm or 0.3 μm, the optical absorption decreased again.

To improve the optical absorption, highly ordered 2D structures were fabricated on the top surface of the GaAs solar cell. Figure 4 shows a scanning electron microscopic (SEM) image of the 1 μm PS microsphere coating. The SEM image reveals that there is a good periodic distribution of the spheres for diffracting and scattering the incident sunlight. The microsphere coating had to be a monolayer to avoid the effects of the photonic crystalline band gap [18] which would interfere with the absorption of the solar cell. The insert on the upper right of Fig. 4 shows the cross-section of the microsphere coating which forms only a monolayer.

The process discussed above was used to fabricate different sizes of microspheres on the surface of GaAs solar cells and the cell efficiency enhancement verified. The power conversion efficiency of the solar cell was measured under the standard AM1.5G spectrum with an illumination level of 100 mW/cm^2 at 298 K. The I-V characteristics of the solar cell samples with the 1, 3, 5 μm microsphere coatings were shown in Fig. 5. The results show an increase in open-circuit voltage Voc and short-circuit current density Jsc when the size of the microspheres decreased. We find that all cells had a similar Voc of ~ 0.7 V and a fill factor of around 77%. However, the Jsc increased from 22 mA/cm^2 without microspheres to 29 mA/cm^2 with 1 μm PS microspheres on the surface of the cells. The overall power conversion efficiency η increased from 11.67% to 14.56%. The absolute efficiency increase ($\Delta\eta$) is about 3% and the relative increase ($\Delta\eta/\eta$) is 25%. The samples and characterization are summarized in Table 1.

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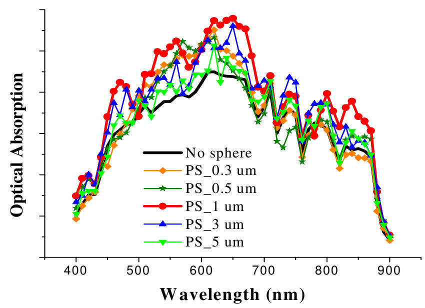

Fig. 3. Absorption spectrum for the GaAs solar cells with varying size of microspheres.

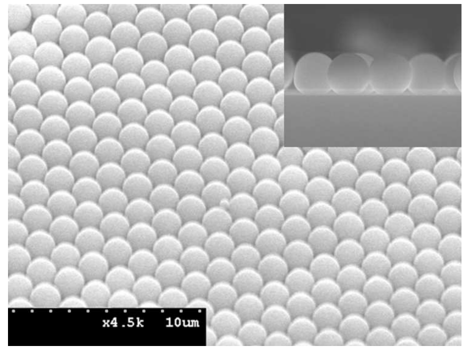

Fig. 4. SEM image of the 1 μm PS microsphere coating and the insert to the upper right shows its cross-section.

Table 1. Samples and characterization data.

	(a) Measurement			(b) Simulation
Sphere size (μm)	Efficiency without microspheres (%)	Efficiency with microspheres (%)	Relative Enhancement(%)	Relative Enhancement (%)
	A	B	$\frac{B-A}{A}\times 100\%$	
0.3	12.10	13.12	8.43	7.3
0.5	11.79	12.57	6.62	7
1	11.67	14.56	25	23.3
3	11.88	13.72	15	14.9
5	11.71	12.56	7	5.7

The external quantum efficiency (*EQE*) of GaAs solar cell samples without a microsphere coating (shown as the squared-dots in Fig. 6) was measured under AM 1.5G illumination. The *EQE* for the solar cells with different sizes of microspheres are also shown in Fig. 6. The results demonstrate that the 1 μm microsphere coating has the most efficient light harvesting enhancement in the whole GaAs absorption range.

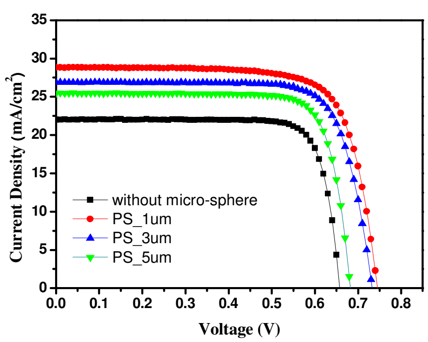

Fig. 5. Current-voltage characteristics of a GaAs solar cell coated with varying sizes of microspheres.

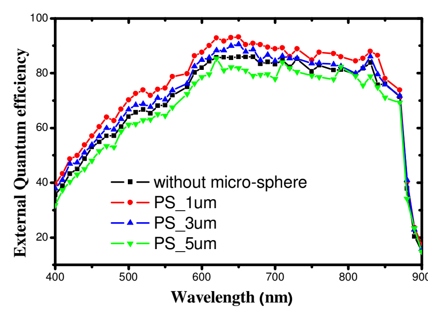

Fig. 6. Quantum efficiency measured under AM 1.5G illumination of GaAs solar cells with microspheres of varying sizes.

We now compare the above results with the simulation results, where the total electrical generation Φ_{total} can be calculated using Eq. (1) below

$$\Phi_{total}=\int \Phi_{opt}(\lambda)*EQE(\lambda)\,d\lambda, \tag{2}$$

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based on the optical absorption spectrum shown in Fig. 3 and the *EQE* shown in Fig. 6. Because the open-circuit voltage is similar, the relative efficiency enhancement can be achieved as follows:

$$\frac{\phi_{Sphere} - \phi_{No-sphere}}{\phi_{No-sphere}} \times 100\% . \quad (3)$$

The simulation results are indicated by the dashed-line and the measured results (from the I-V characteristics of the cells) are indicated by the solid-line; see Fig. 7. The amount of enhancement depends on the size of the spheres as listed in Table 1. The best measured enhancement was 25%, achieved when the size of the microspheres was 1 μm, which is closed to the scale of the incident wavelength. It can be seen that the simulation results are in very good agreement with the measured results.

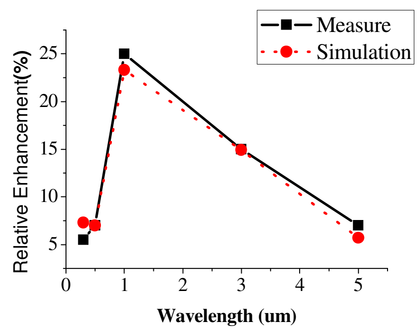

Fig. 7. Relative enhancement-- measurement and simulation results.

4. Conclusion

There is no convenient etching method for the spontaneous production of pyramidal structure when the crystallographic plane of the GaAs solar cell is on the <001> surface. In this study, we develop an efficient light harvesting scheme to enhance the efficiency of GaAs solar cells fabricated using self-assembled microspheres. These highly ordered two-dimensional (2-D) structures are fabricated on the top surface of a GaAs solar cell from monodisperse polystyrene (PS) spheres. This technique is suitable for high-throughput and large-area processing. Based on the scattering of the microspheres and the theory of photonic crystals, the path length can be increased. The self-assembly of microspheres is one of the simplest and the fastest methods with which to build a 2D periodic structure. An FDTD method is also applied to analyze the absorption and electric field of the 2D periodic structure produced during the simulation, confirming the experimental results. The results of the numerical simulation and the experimental results both show that the conversion power efficiency of GaAs solar cell could be increased by about 25% when 1 μm microspheres were placed on the surface of GaAs solar cells.

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