Improving dielectric nano-resonator-based antireflection coatings for photovoltaics

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ABSTRACT

We demonstrate optical and electrical property enhancement of solar cells using a variety of dielectric nano-resonator array coatings. First, we study close-packed silicon dioxide (SiO_2) nano-resonator arrays on top of silicon (Si) and gallium arsenide (GaAs) solar cells. From macroscale measurements and calculations, we find that absorptivity of solar cells can be improved by 20 % due to the resonant couplings of excited whispering gallery modes and the thin-film antireflection effect. Next, we image photocurrent enhancement at the nanoscale via near-field scanning photocurrent microscopy (NSPM). Strong local photocurrent enhancement is observed over each nano-resonator at wavelengths corresponding to the whispering gallery mode excitation. Finally, for better optical coupling to solar cells, we explore hybrid nano-resonator arrays combining multiple materials such as silicon dioxide, silicon nitride, and titanium dioxide. Due to higher number of photonic modes within such hybrid coatings, absorptivity is enhanced by more than 30 % in a Si solar cell.

Keywords: Antireflection coatings, nanospheres, nanoresonators, whispering gallery modes, absorptivity enhancements, photocurrent enhancements, near-field scanning optical microscopy (NSOM), near-field scanning photocurrent microscopy (NSPM)

1. INTRODUCTION

Innovative nanoscale light management schemes have been introduced in order to make cost-effective photovoltaics (PVs) [1]-[10]. Among various approaches, light management using arrays of dielectric nano-resonators has been considered a promising route to significantly increase light absorption and power conversion efficiency of solar cells due to several positive aspects. This method does not require direct surface patterning of active materials, and therefore the open circuit voltage remains intact. Furthermore, this method is relatively cheap. However, there are some other factors that still need to be addressed to apply such light management technique to commercial PVs. First, as only macro-/microscale characterizations have been made so far, clear demonstration of nanoscale optical coupling and photocarrier collection is still lacking. Second, the best performance of such antireflection coating lags that of the conventional thin-film antireflection technology. Third, research has been conducted in application to a few specific materials, and the versatility of this approach remains unclear.

To address the aforementioned issues, we demonstrate the nanoscale optical coupling and photocurrent enhancement with dielectric nano-resonators atop various solar cell materials (e.g., Si and GaAs). To examine nanoscale optoelectronic responses, we employ a near-field scanning photocurrent microscopy technique. By utilizing an atomic force microscopy (AFM) probe with an attached optical fiber, we measure local photo-response of solar cells [11]-[13]. While the probe makes a raster scanning, topography and photocurrent of samples are obtained at the same time. Correlating with other characterization techniques, we find that the combination of a thin-film interference effect and resonant coupling of whispering gallery modes improves solar cells by more than 20 %. We also suggest novel hybrid nano-resonator arrays composed of various materials (e.g., SiO_2, silicon nitride (Si_3N_4), and titanium dioxide (TiO_2)) that can surpass the conventional thin-film-based antireflection technologies.

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2. RESULTS AND DISCUSSION

We deposit close-packed 700 nm SiO_2 nano-resonators as antireflection coatings atop Si and GaAs solar cells to improve their optical and electrical properties. Nano-resonators are deposited by a Meyer-rod rolling technique [11], [12], [14]. By adjusting either a concentration of suspension containing SiO_2 nano-resonantors or the size of a Meyer-rod, a monolayer coating can be made. Deposited nano-resonators have a finite variation of diameters: 697 nm ± 80 nm. We measure light absorptivity enhancement with such nano-resonators (see Fig. 1a and d). Absorptivity enhancement is determined by comparing light absorption with nano-resonators with light absorption of bare samples. We also determine absorptivity enhancement from finite-difference time-domain (FDTD) calculations (see Fig. 1b and e).

Enhanced light absorption is observed with 700 nm SiO_2 nano-resonators in macroscopic measurements and FDTD calculations. While mostly broadband features are visible in the measurements, both broadband and narrowband features are clearly shown in the calculations. The broadband features can be explained by the thin-film interference effect. We model a thin-film layer atop Si and GaAs substrate and determine how this layer affects optical responses (see Fig. 1c and f). The thin-film layer has an effective refractive index varying in vertical position to mimic the properties of the close-packed SiO_2 nano-resonators: the effective refractive index of the film is calculated by averaging refractive indices of air and SiO_2 according to the geometric fraction of two materials in close-packed configurations [11], [12]. The thin-film model effectively describes broadband absorptivity enhancement observed in the experiments and calculations.

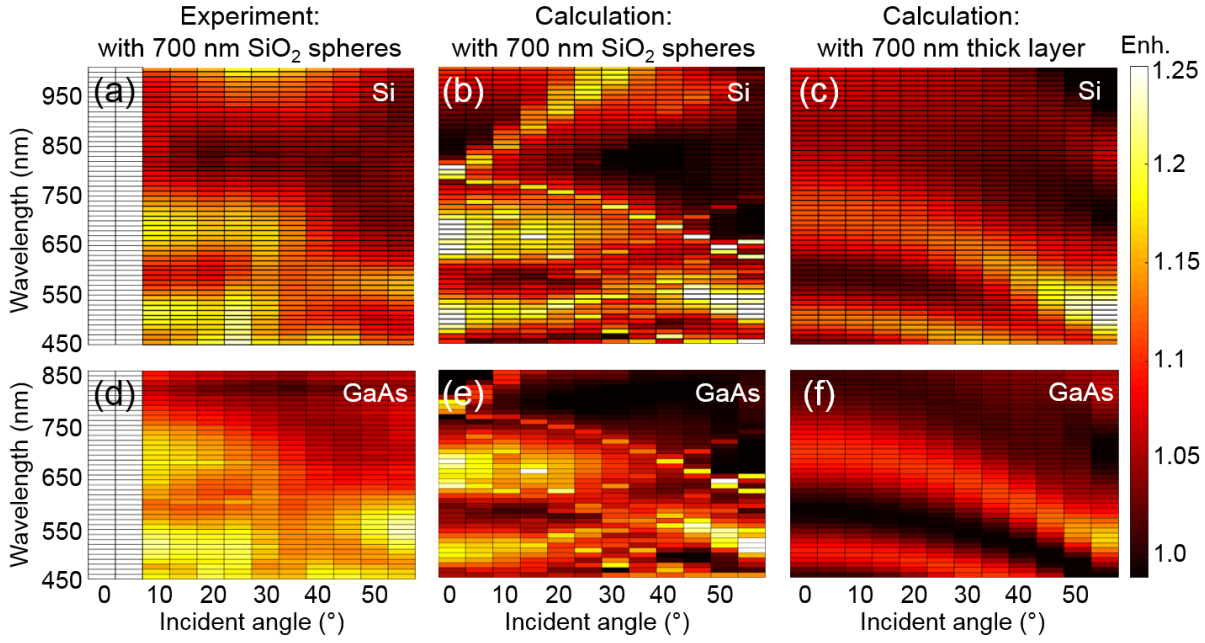

Figure 1. Absorptivity enhancements determined by macroscopic optical measurements for (a) a Si solar cell and (d) a GaAs solar cell with deposited SiO_2 nano-resonators with a mean diameter of 697 nm and a standard deviation of 80 nm. Absorptivity enhancements determined by FDTD calculations for (b) a Si solar cell with close-packed 700 nm SiO_2 nano-resonators, (c) a Si solar cell with a 700 nm thick thin-film layer, (e) a GaAs solar cell with close-packed 700 nm SiO_2 nano-resonators, and (d) a GaAs solar cell with a 700 nm thick thin-film layer.

Narrowband features can be explained by the excited whispering gallery modes within nano-resonators. We calculate the electric field intensity profiles at wavelengths where significant absorptivity enhancement is observed (see Fig. 2). Electric field profiles at wavelengths of 635 nm and 798 nm (marked with number 3 and 4) under transverse magnetic (TM) incident polarization show strong confined optical modes within nano-resonators. They are the excited whispering gallery modes responsible for the narrowband absorptivity enhancement at the corresponding wavelengths. However, such enhancement is barely seen in the macroscopic measurement due to the size variation of the nano-resonators [11], [12]. Repeated readings under identical conditions yields maximum measurement variation less than 1 % [11], [12].

Excited whispering gallery modes can be tuned by the size of nano-resonators (see Fig. 2). They are either blue- or red-shifted as the size of nano-resonators become smaller or larger: the excited whispering gallery modes at the wavelengths

of 635 nm with 700 nm nano-resonators (marked with number 3) appear at the wavelength of 455 nm for 500 nm nano-resonators (marked with number 1) and at the wavelength of 906 nm for 1000 nm nano-resonators (marked with number 5), and the modes at the wavelength of 798 nm with 700 nm nano-resonators (marked with number 4) is reproduced at the wavelength of 573 nm for 500 nm nano-resonators (marked with number 2).

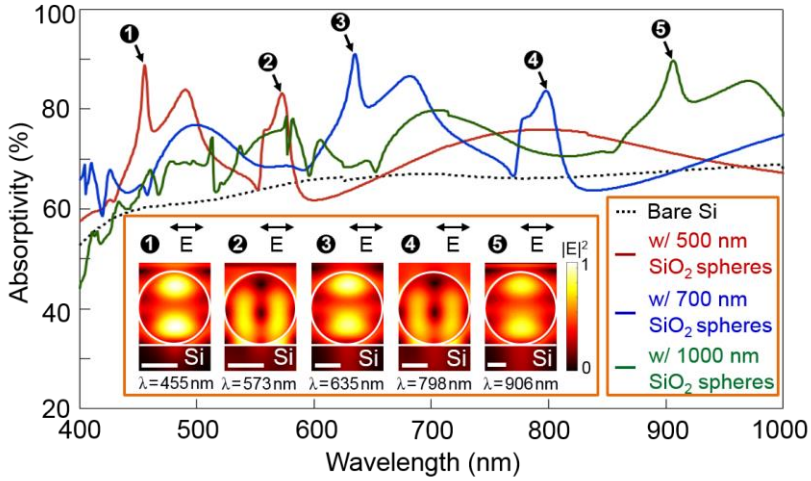

Figure 2. Absorptivity profile of a Si solar cell with close-packed 500 nm (red), 700 nm (blue), and 1000 nm (green) nano-resonators. Inset: electric field profile intensity profiles show excited whispering gallery modes at corresponding wavelengths under TM incident polarization (see matched number in absorptivity profiles). Scale bars are 250 nm.

Despite the marked enhancement with such nano-resonators, however, there is no clear experimental evidence confirming the narrowband features that originate from the whispering gallery modes. Only broadband features are seen in macroscale measurements. Therefore, we perform nanoscale photocurrent measurements using near-field photocurrent microscopy (NSPM) to experimentally demonstrate the photo-response enhancement induced by the excitation of whispering gallery modes.

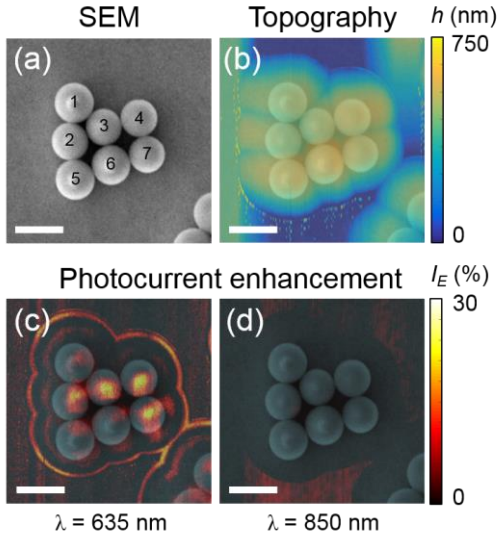

Figure 3. (a) An SEM image showing an area selected for NSPM measurements. Nano-resonators with numbers 2, 3, 4, and 7 have their size of ≈ 700 nm, and nano-resonators with numbers 1, 5, and 6 have their size of ≈ 750 nm. Both (b) topography and (c, d) photocurrent images are simultaneously obtained during the NSPM measurements. Photocurrent enhancement (c) at a wavelength for the excitation of whispering gallery modes and (d) at an off-resonance wavelength. Scale bars are 1 μm.

During the NSPM measurements, both topography and photocurrent of the sample are simultaneously obtained from the selected area of a GaAs solar cell with seven nano-resonators (see Fig. 3). Photocurrent enhancement is determined by normalizing the measured photocurrent to the photocurrent obtained in a bare area. NSPM measurements are performed at a resonant wavelength (λ = 635 nm) and an off-resonance wavelength (λ = 850 nm) that are found from the FDTD calculations (see Fig. 1b, e, and Fig. 2). A value of photocurrent enhanced by more than 30 % is measured over nano-resonators with the diameter ≈ 700 nm at the wavelength of the excitation of whispering gallery modes (λ = 635 nm), and the enhancement is smaller as the size deviates from 700 nm. At an off-resonance wavelength (λ = 850 nm), no specific photocurrent enhancement is detected with such nano-resonators.

As the optical resonances depend on the size of nano-resonators (Fig. 2), it is necessary to find an optimal size that can offer the maximum light absorption averaged across the solar spectrum. We first determine how different diameters affect the absorptivity peaks on a Si solar cell (see Fig. 4a). As previously discussed, in larger nano-resonators the resonance peaks shift to the longer wavelengths. For nano-resonators with diameters larger than ≈ 700 nm, second order resonance peaks are observed at shorter wavelengths. Next, we determine the current densities weighted with air mass 1.5 global (AM1.5G) solar spectrum. The second order peaks contribution results in the higher photocurrent densities as the diameter increases (see Fig. 4c). Based on Fig. 4c, we conclude that the optimal diameter of SiO_2 nano-resonators for a Si solar cell is ≈ 940 nm, where we calculate the highest AM1.5G solar spectrum-weighted photocurrent density, ≈ 31 mA/cm^2.

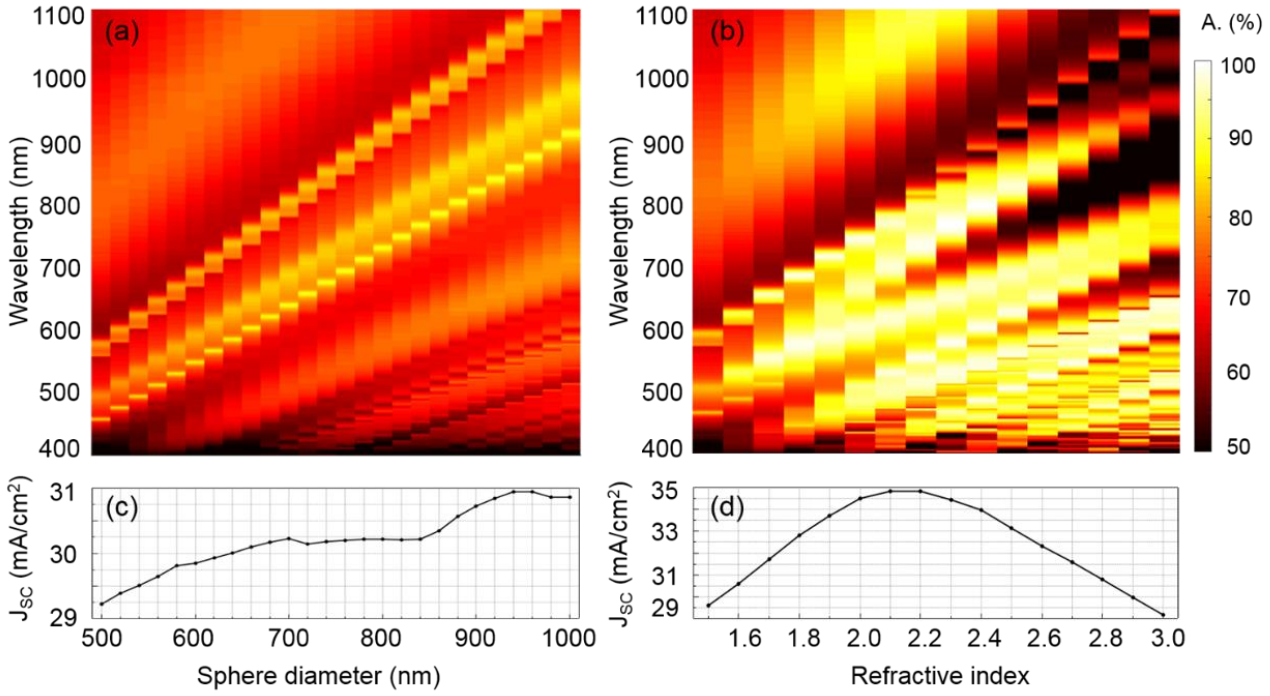

Figure 4. Absorptivity with nano-resonators can vary depending on (a) the size or (b) the refractive index of materials. Corresponding solar spectrum-weighted current densities also vary depending on (c) the size or (d) the refractive index of materials.

Alternatively, the optical resonances can be tuned by the refractive index of materials for nano-resonators [12]. To find the optimal refractive index, we fix the size of nano-resonators to 500 nm. Then, the optimal refractive index corresponding to the highest AM1.5G solar spectrum-weighted photocurrent densities is ≈ 2.1. This value is about the same as the refractive index of Si_3N_4, the optimal material for a single layer thin-film antireflection coating at the air-Si interface.

Despite the marked photo-response enhancement with nano-resonators, the maximum achievable enhancement still lags behind thin-film-based antireflection technologies. To further improve optical responses, we suggest novel hybrid arrays of nano-resonators that are composed of three different materials. We combine nano-resonators made of SiO_2, Si_3N_4, and TiO_2 to excite more photonic resonance modes within the arrays [12]. This results in the photo-response enhanced by

more than 30 % compared to a bare cell, surpassing the maximum achievable enhancement with a single layer thin-film antireflection coating (e.g., ≈ 80 nm thick Si_3N_4 thin-film atop a Si solar cell). Table 1 summarizes the enhancement values expected from each type of nano-resonators-based antireflection coating atop a Si solar cell.

Table 1. Solar spectrum-weighted current density and its enhancement from a bare Si solar cell for each type of nano-resonators-based antireflection coating

Antireflection coating type on a Si solar cell	**Solar spectrum-weighted current density (mA/cm^2)**	**Enhancement from a bare Si solar cell (%)**
Bare Si (without an antireflection coating)	27.7	-
500 nm SiO_2 nano-resonators	29.2	5.4
700 nm SiO_2 nano-resonators	30.2	9.0
1000 nm SiO_2 nano-resonators	30.9	11.6
500 nm Si_3N_4 nano-resonators	34.9	26.0
500 nm TiO_2 nano-resonators	29.5	6.5
Mixed combination of 500 nm SiO_2, TiO_2, and Si_3N_4 nano-resonators (equally distributed)	36.2	30.7

3. CONCLUSIONS

Various dielectric nano-resonators-based antireflection coatings have been introduced. With SiO_2 nano-resonator arrays placed atop a Si substrate, significant absorptivity enhancement is observed due to the combined effect of the excited whispering gallery modes and the thin-film interference. The spectrum of the whispering gallery modes is tunable by the diameter of SiO_2 nano-resonators. The effect of refractive index of nano-resonators on optoelectronic properties is also investigated. Finally, novel configurations of hybrid arrays made of SiO_2, Si_3N_4, and TiO_2 nano-resonators are introduced. The arrays show substantial absorptivity and photocurrent enhancements due to larger number of resonant and photonic modes. The use of dielectric nano-resonator arrays as antireflection coatings can reduce the cost and/or improve efficiency of solar cells, as these coatings do not require either surface patterning or complicated fabrication processes.

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