

Communication

High Broadband Light Transmission for Solar Fuels Production Using Dielectric Optical Waveguides in TiO Nanocone Arrays

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3 **High Broadband Light Transmission for Solar Fuels Production Using Dielectric Optical**
4 **Waveguides in TiO₂ Nanocone Arrays**
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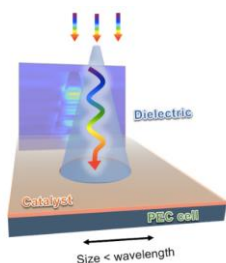
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Abstract

We describe the fabrication and use of arrays of TiO₂ nanocones to yield high optical transmission into semiconductor photoelectrodes covered with high surface loadings of light-absorbing electrocatalysts. Covering over 50% of the surface of a light absorber with an array of high-refractive-index TiO₂ nanocones imparted antireflective behavior (< 5% reflectance) to the surface and allowed > 85% transmission of broadband light to the underlying Si, even when thick metal contacts or opaque catalyst coatings were deposited on areas of the light-facing surface that were not directly beneath a nanocone. Three-dimensional full-field electromagnetic simulations for the 400 – 1100 nm spectral range showed that incident broadband illumination couples to multiple waveguide modes in the TiO₂ nanocones, reducing interactions of the light with the metal layer. A proof-of-concept experimental demonstration of light-driven water oxidation was performed using a p⁺n-Si photoanode decorated with an array of TiO₂ nanocones additionally having a Ni catalyst layer electrodeposited onto the areas of the p⁺n-Si surface left uncovered by the TiO₂ nanocones. This photoanode produced a light-limited photocurrent density of ~ 28 mA cm⁻² under 100 mW cm⁻² of simulated Air Mass 1.5 illumination, equivalent to the photocurrent density expected for a bare planar Si surface even though 54% of the front surface of the Si was covered by an ~ 70 nm thick Ni metal layer.

Keywords: dielectric nanocone, broadband transmission, nanophotonic, optoelectronic, photoelectrochemical, photovoltaic

Table of contents graphic:



Main Text

High efficiency conversion of solar energy to electricity or fuels using photovoltaic (PV)¹⁻⁵ or photoelectrochemical (PEC)⁶⁻⁸ cells requires optimization of the broadband absorption of sunlight. Anti-reflective coatings (ARCs)⁹, surface textures,¹⁰⁻¹³ and high-index light-trapping structures^{14,15} are among the many strategies that have been shown to increase broadband absorption relative to unmodified planar light absorbers. PECs and multijunction PVs generally require front contacts and/or electrocatalytic films that substantially reflect or absorb light, thereby reducing their photocurrent densities.¹⁶ In integrated PECs used to effect solar-driven water splitting or CO₂ reduction,¹⁷⁻¹⁹ the front contact is made to an electrolyte, and a catalyst located in the optical path increases the efficiency of the cell by reducing the kinetic barrier for the electrochemical half-reaction occurring at the top contact. Depending on the orientation of the design, as well as the chemical inputs and desired products, the catalyst may be optically opaque (such as CoP for water reduction or Cu for CO₂ reduction) or may be electrochromic (such as NiFeO_x for water oxidation).²⁰ Although an all-back-contact design^{21,22} can prevent contact shading losses in crystalline Si solar cells, such a design is not compatible with all of the solid/liquid interfaces either with integrated PECs for highly efficient fuel production or with multijunction PV device structures.²³

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3 Nanostructuring the semiconductor is one approach that has been developed to enhance
4 broadband absorption. Nanowires,²⁴⁻²⁶ inverted pyramids,²⁷ nanodomes,²⁸ nanoshells,²⁹
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Nanopillars,^{30,31} and nanocones³² have been explored for use in many optoelectronic devices. For example, for wavelengths ranging between 400 – 1100 nm and angles-of-incidence between 0° – 50°, Si microcone arrays exhibit nearly perfect angularly and spectrally averaged reflectivity (< 1 %) as well as high (89.1 %) absorption.³³ Sparse arrays of InP nanocones also exhibit angle-insensitive, near-unity (>90%), broadband (450–900 nm) optical absorption.³⁴ Cones inherently possess a continuous range of radii that provides a range of waveguide modes accessible for coupling with incident light.³⁵ Hence, cones are intrinsically favorable structures for enabling enhanced broadband absorption. Moreover, the radius at the base of the cone and the radius of any truncation can be chosen specifically to select a spectral range of interest.

Alternatively, broadband absorption can be enhanced by decorating the light-facing surface of the semiconductor with dielectric nanostructures, such as nanospheres,³⁶ that serve as waveguides. This approach requires a high-index dielectric that can be deposited on planar surfaces using scalable methods. For integrated PEC devices, the dielectric also must be stable in the chosen aqueous electrochemical environment. TiO₂ has been used in waveguides for near-visible and telecommunication wavelengths,³⁷⁻⁴² and has a higher index of refraction ($n \sim 2.5$) than many other dielectric materials commonly used in solar photovoltaic devices, including SiO₂ ($n = 1.5$) and Al₂O₃ ($n = 1.77$). TiO₂ is relatively inert electrochemically and has a wide band gap that allows transmission of incident solar illumination, and has been utilized extensively as a protective coating in efficient PEC devices.^{17-19,43-48} TiO₂ is therefore a promising candidate material for nanostructured waveguides in PEC devices.

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3 Devices that make use of nanostructured surfaces nevertheless require front contacts, either
4 to a conductor for PVs or to a catalyst for PECs, but the front contact can block light. In devices
5 that require connections between external circuits and nanostructured optical surfaces, front
6 contacts typically are formed by coating the surface with a transparent and conductive material,
7 such as indium tin oxide (ITO). However, efficient integrated PECs for fuel production
8 additionally require catalysts on at least one of the optical surfaces. Very high (> 90%) absorption
9 and high front-surface conductivity have been demonstrated using both simulation and experiment
10 in a device consisting of SiN_x-coated Si nanopillars protruding from a crystalline Si substrate
11 coated with an opaque Au front-side contact that covered 65% of the Si surface.³¹ Although the
12 selective etching process used in this approach limits its applicability to a few specific interfaces
13 such as Au/Si, this work shows that nanostructures can direct light around opaque metallic front
14 contacts deposited onto the optical surfaces of PV devices, and suggests a strategy for guiding light
15 around catalyst layers in PECs.
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34 Considered together, the prior work in the areas of antireflective nanostructures and
35 dielectric waveguides underscores the potential value and developmental feasibility of modular
36 antireflective coatings that promote broadband absorption over a spectral range above the
37 photoelectrode bandgap without requiring modification of the underlying semiconductor or contact
38 interfaces. Herein, we combine simulations and proof-of-concept experiments to evaluate and
39 demonstrate light management by an array of TiO₂ nanocones placed on the surface of a p⁺n-Si
40 photoanode with a metallic Ni contact covering the exposed Si surface.
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51 Figure 1 shows schematics for three device configurations that were compared using
52 simulations, to understand the optical properties of TiO₂ nanocones. In the first configuration
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(Figure 1a), TiO₂ nanocones with a height of 2300 nm and a base radius of 250 nm were placed on the Si substrate in a 2D hexagonal array with a 700 nm pitch. This arrangement left 54% of the Si surface uncovered by TiO₂ nanocones. In the second configuration (Figure 1b), 50 nm of Ni covered the area of Si that remained exposed in the first configuration. The third configuration (Figure 1c) was the same as the second, but the TiO₂ nanocones were removed, leaving a hexagonal array of circles of exposed Si in the Ni layer.

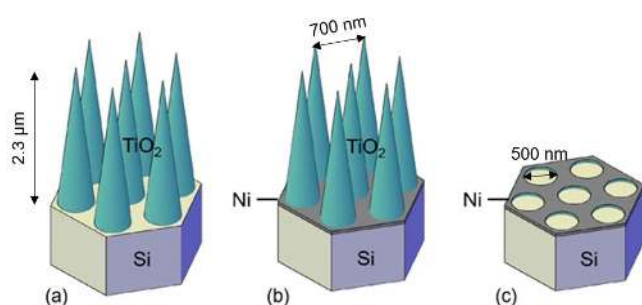


Figure 1: Schematics of the three configurations that were simulated. (a) TiO₂ nanocones on Si substrate; (b) Ni between the TiO₂ nanocones on Si substrate; (c) Ni hole arrays on Si substrate.

Figure 2 compares the simulated transmission, absorption, and reflection spectra for the TiO₂ and Ni components of the three structures, either in air ($n = 1.0$) or in water ($n = 1.33$). Figures 2a and 2d show that the TiO₂ nanocones neither absorb nor reflect substantially in the 400 – 1100 nm spectral range, with the nanocones allowing transmission of 97.5% of the total incident photons in air or 96.9% in water. The planar TiO₂ film simulations, with higher reflection losses, are shown in Figure S1, leading to transmission of 74.7% in air and 84% in water. When 50 nm of Ni was added into the spaces between the nanocones, the simulated transmitted photon flux was reduced to 86.2% in air or 84.7% in water (Figures 2b and 2e). The minima in transmission primarily result from absorption by Ni, and the wavelengths of the minima shift depending on the index of refraction of the surrounding environment.

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3 When the TiO₂ nanocones were removed from the simulation, leaving just the hexagonal
4 array of circular holes in a 50 nm layer of Ni that covered 54% of the optical plane, the transmitted
5 photon fluxes were reduced to 23.3% in air or 24.8% in water, with reflection and parasitic
6 absorption accounting for $\geq 75\%$ of the optical losses (Figures 2c and 2f). The size and pitch of the
7 holes in the Ni layer were particularly unfavorable for transmission of light through the Ni layer in
8 the absence of the TiO₂ cones, because over a large fraction of the incident solar spectrum, the
9 diameter of the holes was less than the wavelength of the incident light. In the specific
10 configuration shown in Figure 1b, the TiO₂ nanocones minimized the interaction between the light
11 and the Ni layer, enabling > 3 times the amount of light to be transmitted than for the Ni hole array
12 that did not also contain the TiO₂ cones. For the TiO₂ nanocone array with Ni, the simulated
13 transmission at the minima was $\geq 60\%$, Figures 2b and 2e, whereas for the Ni hole array without
14 TiO₂ nanocones, the simulated transmission of was 20-30%, Figures 2c and 2f. The simulations
15 thus indicated that incident light is expected to couple efficiently to the TiO₂ nanocones that guide
16 the light around the Ni layer.
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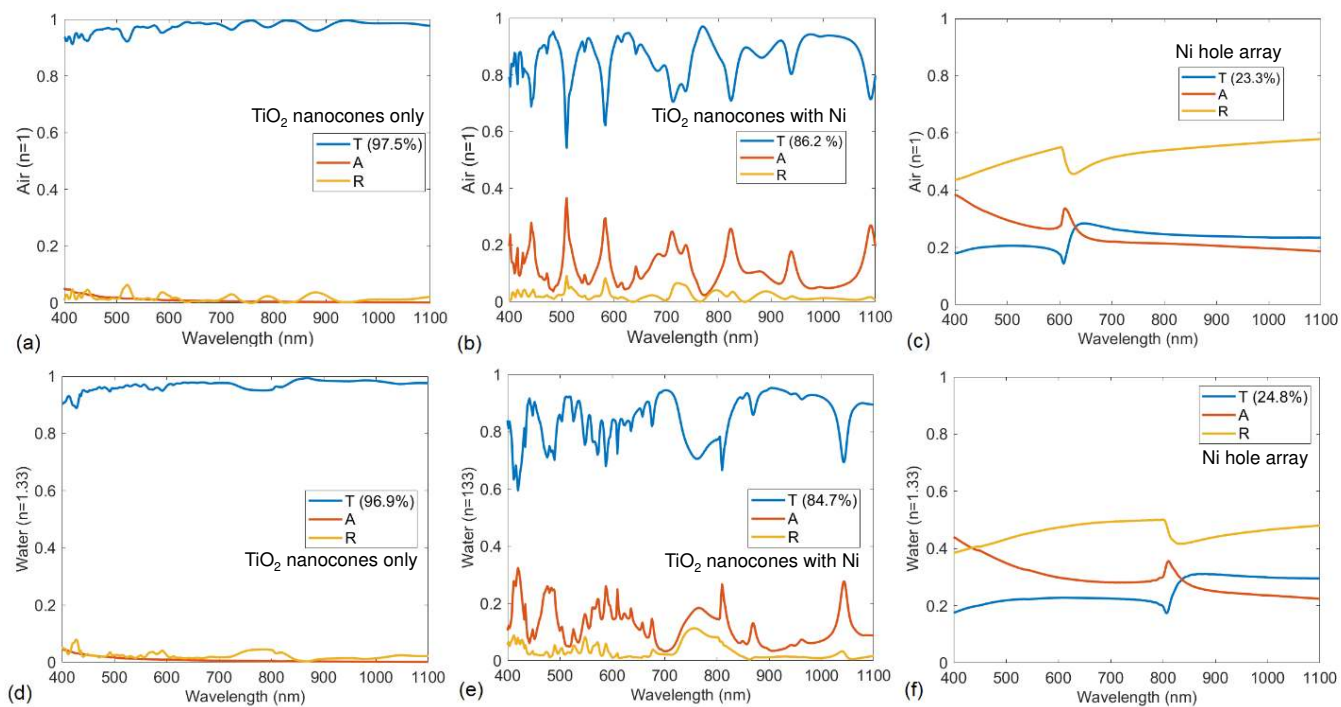


Figure 2: Simulated transmission (T), absorption (A), and reflection (R) spectra of the three configurations of the TiO₂ nanocone array and Ni layer in Figure 1. (a), (b), and (c) plot the spectra in air for an array of TiO₂ cones, a TiO₂ cone array with Ni, and a Ni hole array, respectively. (d), (e), and (f) plot the same structures but in water. The optical effects of the Si substrate are not shown.

Figure S2 plots the transmitted photon flux for each structure along with the Air Mass (AM) 1.5G solar spectrum. Using the transmitted spectral photon flux, the maximum photocurrent densities, $J_{\text{ph,max}}$, in air estimated from the simulations for a Si solar cell covered by either the TiO₂ nanocone array, the TiO₂ nanocone array with Ni, or the Ni hole array were $J_{\text{ph,max}} = 42.9 \text{ mA cm}^{-2}$, 37.9 mA cm^{-2} , and 10.9 mA cm^{-2} respectively. In water, the corresponding estimated simulated maximum photocurrent densities were $J_{\text{ph,max}} = 41.8 \text{ mA cm}^{-2}$, 36.5 mA cm^{-2} , and 10.7 mA cm^{-2} , respectively.

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Figure 3 shows the simulated profiles of the electric field along the central cross section of a nanocone. Figures 3c-3f show the field profiles for wavelengths of 484 nm, 552 nm, 628 nm, and 770 nm, respectively, which correspond to the maxima in the transmission spectra shown in Figure 2b. The electric field was predominantly confined to the waveguide modes in the nanocone, with strong coupling of incident light occurring at different radii for the different wavelengths, as expected for a conical nanostructure.³³⁻³⁵ In the simulation, the light propagated through the nanocone and was transmitted into the Si substrate, where the field intensity decreased due to absorption by the Si. Figures 3g-3j show the field profiles for wavelengths of 442 nm, 584 nm, 738 nm, and 940 nm, respectively, which correspond to the minima in the transmission spectra shown in Figure 2b. Compared to the field profiles shown in Figures 3c-3f, the profiles in Figures 3g-3j showed an increased intensity of the electric field in the space adjacent to the nanocone. The corresponding plots for transmitted light intensities $|E|^2$ versus $Y(\mu\text{m})$ at the interfaces of Si/Ni (indicated as on Si) and Ni/air (indicated as on Ni) are shown in Figure S3.

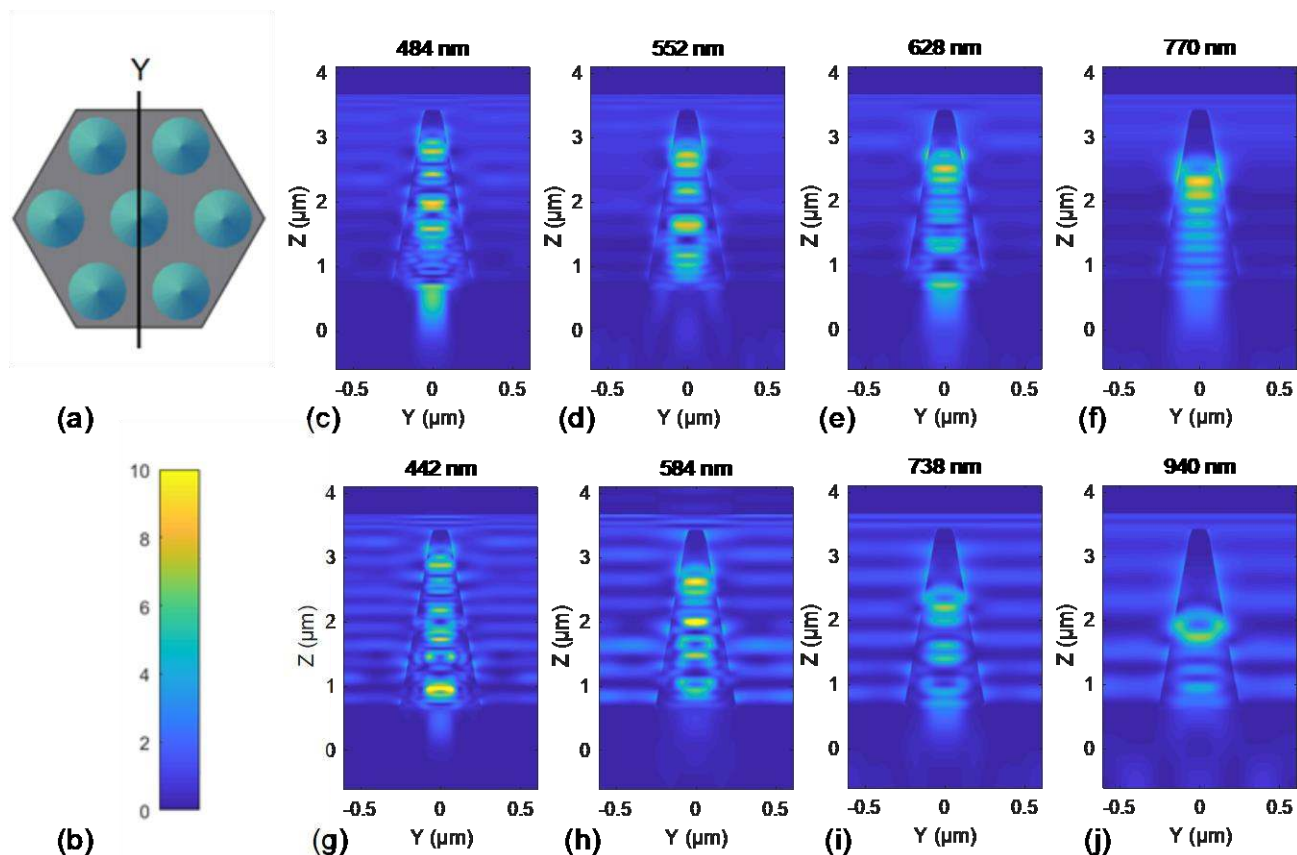


Figure 3: Simulated electric field profiles along the cross section of a TiO₂ nanocone on a Si substrate. (a) Cross section and (b) scale for the relative electric field intensity for the profile plots. (c-f) Profiles for wavelengths of 484 nm, 552 nm, 628 nm, and 770 nm, respectively, which correspond to the maxima in the transmission spectra shown in Figure 2b. (g-j) Profiles for wavelengths of 442 nm, 584 nm, 738 nm, and 940 nm, respectively, which correspond to minima in the transmission spectrum in Figure 2b.

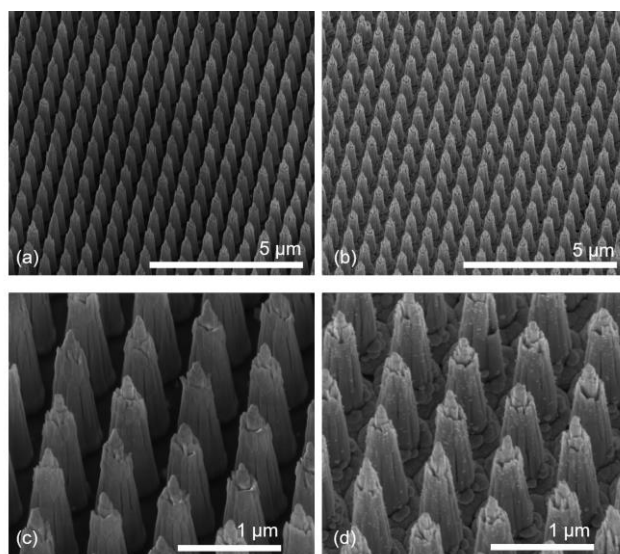
Depending on the dimensions of the nanocones and the background index of refraction, simulations indicated that the electric fields associated with some wavelengths of light were highly confined inside the TiO₂ nanocone, while the electric fields associated with other wavelengths

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3 were only partially confined. Simulation results with varying dimensions of cones are presented in
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5 Figure S4. In contrast, the optical absorption in the Ni was enhanced for the wavelengths of light
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7 that were not completely confined within the nanocones. The wavelength-dependent variation in
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9 the confinement of the electric field within TiO₂ nanocones cannot be explained using effective
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11 medium theory. Instead, wave-optic simulations showed that the nanocones acted as antennae for
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13 the incoming radiation, coupling the light to waveguide modes, and providing a route for the light
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15 to reach the underlying Si substrate even though 54 % of the surface was covered by Ni.
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21 The optimal structures revealed by simulation were fabricated and investigated in detail. To
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23 experimentally demonstrate the enhancement in photocurrent density obtainable by utilizing TiO₂
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25 nanocone arrays, planar p⁺n Si homojunction photoanodes were prepared by doping n-type Si with
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27 boron (B). Briefly, electron-beam evaporation was used to deposit 5 - 10 nm of SiO₂ over the Si
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29 photoanodes, prior to deposition of 2.3 μm of TiO₂. Electron-beam evaporation depletes the TiO₂
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31 source of oxygen and thus increases the conductivity of the resulting films, so the 5 – 10 nm thick
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33 SiO₂ was deliberately incorporated to electrically isolate the TiO₂ from making an electrical
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35 contact to the highly doped p⁺-Si surface, while minimally affecting the optical behavior. The
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37 refractive index *n*, *k* of TiO₂ was characterized using ellipsometry (J.A. Woollam Co. model
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39 VASE). Electron-beam lithography was used to pattern spin-coated polymethyl methacrylate
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41 (PMMA) with a hexagonal array of 100 nm diameter circular holes with a 700 nm pitch. 200 nm of
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43 Cr was evaporated onto these samples, followed by liftoff, resulting in a hexagonal array of Cr
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45 circles that was used as an etching mask. An SF₆ / C₄F₈ etching recipe was developed to fabricate
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47 TiO₂ nanocones by inductively coupled plasma reactive-ion etching (ICP-RIE). These samples
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49 were made into electrodes and Ni was electrodeposited between the TiO₂ nanocones until ~ 300
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51 mC cm⁻² of cathodic charge had been passed. Charge normalization to the exposed Si area between
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3 nanocones indicated an equivalent of an ~ 70 nm thick flat Ni layer, which is slightly higher than
4 the 50 nm value used in the simulations. Experimental details are included in Supporting
5 information, and an illustration of the process flow for fabrication of the desired structures is
6 shown in Figure S5.
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14 Figure 4 shows scanning-electron micrographs (SEMs), before and after electrodeposition
15 of Ni, for samples of dry-etched TiO_2 nancone arrays on planar $\text{p}^+\text{n-Si}$ substrates. The EDS
16 mappings are included in Figure S6. The TiO_2 nanocones were ~ 2.3 μm tall and had base radii of
17 ~ 250 nm. Discontinuities in the taper of the nanocones were evident, particularly near the vertex
18 of each cone. The radii at the vertices of the nanocones were < 50 nm. Figures 4b and 4d show that
19 the Ni predominantly deposited onto the Si surface in the spaces between the TiO_2 nanocones, as
20 expected because the insulating 5-10 nm layer of SiO_2 beneath the base of the cones should
21 prevent electrodeposition onto the TiO_2 . The Ni layer was ~ 70 nm thick as estimated based on the
22 charge passed during electrodeposition. The SEM image of a 50 nm thick Ni hole array fabricated
23 via electron-beam patterning and dry etching is shown in Figure S7.
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3 **Figure 4:** Scanning-electron micrographs of dry-etched TiO₂ nanocones on p⁺n-Si substrates
4 before (a, c) and after (b, d) electrodeposition of Ni.
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10 Figure S8 compares the real component of the complex refractive index measured by
11 ellipsometry for the electron-beam-evaporated amorphous TiO₂ used to make nanocones in this
12 work relative to the real component of the index of refraction of ideal rutile TiO₂ tabulated in
13 standard reference data.⁴⁹ The real component of the refractive index for the electron-beam-
14 evaporated TiO₂ was substantially lower ($n = 2.05 - 2.3$) than for the standard value ($n = 2.7 - 3.3$),
15 presumably due to oxygen depletion during evaporation and the amorphous phase of the TiO₂ film.
16 Figure 5a shows the reflection, transmission, and absorption spectra calculated for TiO₂ nanocones
17 with 50 nm Ni using the experimentally measured refractive index data for electron-beam-
18 evaporated TiO₂, while Figure 5b shows the simulated transmitted photon flux along with the AM
19 1.5G spectrum. The estimated attainable photocurrent density calculated from these revised
20 simulations for a Si solar cell covered with the TiO₂ nanocone array and Ni was $J_{\text{ph,max}} = 29.8 \text{ mA}$
21 cm^{-2} , after correcting for losses due to reflection at the air/glass/water interfaces that are
22 unavoidable in an electrochemical cell configuration. This estimated maximum photocurrent
23 density ($J_{\text{ph,max}} = 29.8 \text{ mA cm}^{-2}$) was substantially lower than the current density that could be
24 obtained with ideal TiO₂ ($J_{\text{ph,max}} = 36.5 \text{ mA cm}^{-2}$), but is still larger than the value expected for a
25 bare, planar Si surface ($J_{\text{ph,max}} \sim 28 \text{ mA cm}^{-2}$).
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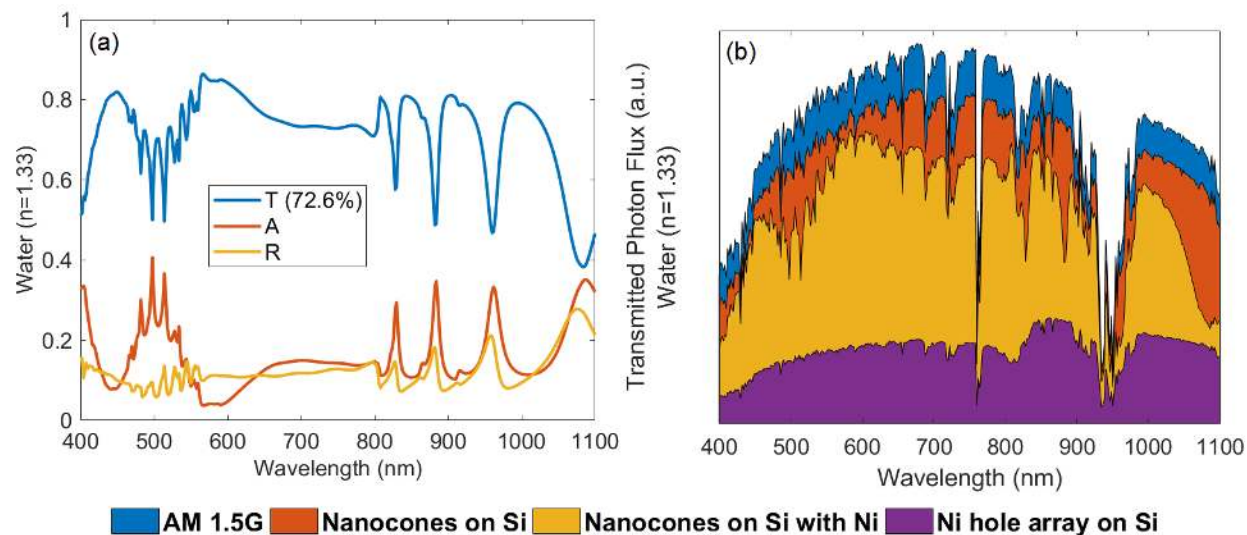


Figure 5. Transmission (T), absorption (A), and reflection (R) plots for Si with TiO₂ nanocones and 50 nm thick Ni calculated with evaporated TiO₂ refractive index data are shown in (a). (b) shows the area plot overlapped over the AM 1.5G spectrum for the three different cases, as shown in Fig.1, using the refractive index data for amorphous TiO₂ deposited by e-beam evaporation.

Figure 6 compares simulated and experimentally measured reflectance spectra for a TiO₂ nanocone array on Si, a TiO₂ nanocone array with Ni on Si, and for a 50 nm layer of Ni with an array of holes. The experimental and theoretical spectra are in good mutual agreement, with certain differences readily ascribed to technical differences between the simulation and experimental conditions. For example, the simulations were performed using a coherent illumination source, whereas experimental measurements were not. Moreover, the simulations used smoothly tapering nanocones and a flat layer of Ni, whereas the samples did not have either smoothly tapering cones or a perfectly flat Ni layer (Figure 4).

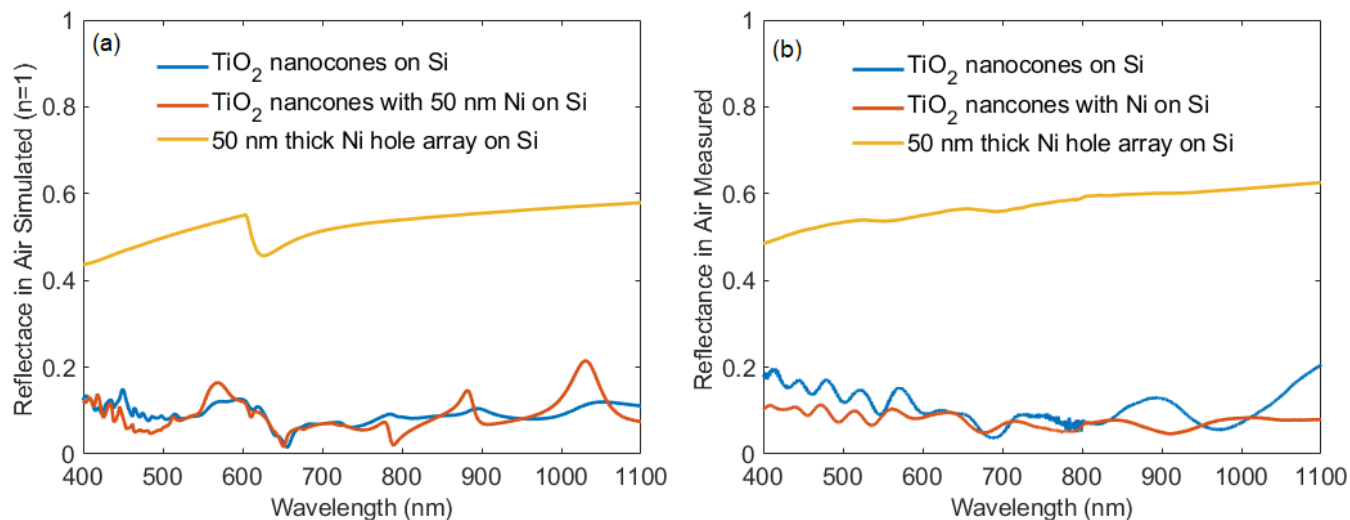


Figure 6: Reflection spectra (a) simulated and (b) measured for samples consisting of an array of TiO₂ nanocones on Si (blue), an array of TiO₂ nanocones with Ni on Si (red), an array of holes in a Ni layer on Si (yellow).

Figure 7 shows the current density versus potential behavior, in the dark and under 100 mW cm⁻² of simulated AM1.5 illumination, respectively, while in contact with 1.0 M KOH(aq), for a photoanode made from a p⁺n-Si substrate covered with an array of TiO₂ nanocones and a layer of Ni (Figures 4b and 4d). The light-limited photocurrent density, obtained by subtracting the current density measured in the dark at ~ 1 V vs the saturated calomel electrode (SCE) from the current density measured in the light at the same potential, was $\sim J_{\text{ph,max}} = 28 \text{ mA cm}^{-2}$, and matched well with the value estimated ($J_{\text{ph,max}} = 29.8 \text{ mA cm}^{-2}$) from the simulations. The current density at the formal potential for water oxidation, $E^{\circ}(\text{O}_2/\text{H}_2\text{O})$ was 2 - 7 mA cm⁻². The observed light-limited photocurrent density was comparable to the photocurrent density normally measured for a bare planar Si surface, consistent with the TiO₂ nanocones serving as antireflective structures that can couple to incoming light to enable transmission of light into the Si substrate even when ~ 54 % of the Si surface was covered with ~70 nm of Ni.

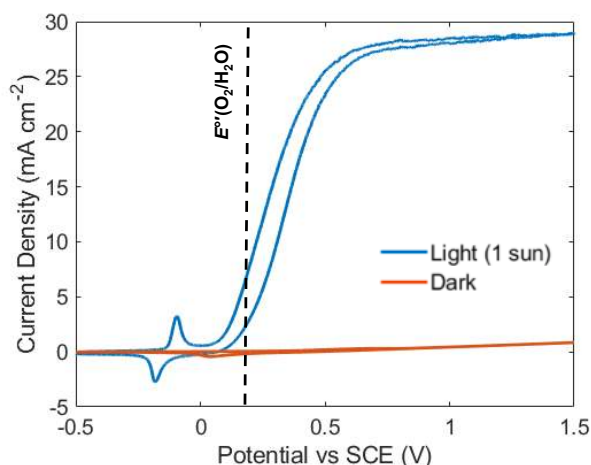


Figure 7: Current-density versus potential behavior, in the dark and under 100 mW cm^{-2} of simulated AM1.5 solar illumination, respectively, for a p^+n -Si sample covered by an array of TiO_2 nanocones and 300 mC cm^{-2} of electrodeposited Ni while in contact with 1.0 M KOH(aq) . The scan rate was 50 mV s^{-1} .

Si photoanodes with a uniform 2 nm layer of Ni have been reported previously to exhibit a light-limited photocurrent density of $J_{\text{ph,max}} \sim 55 \text{ mA cm}^{-2}$ under ~ 2.25 Suns equivalent of illumination, whereas increasing the Ni thickness to 20 nm reduced $J_{\text{ph,max}}$ to $\sim 32 \text{ mA cm}^{-2}$.⁵⁰ These results translate at 1 Sun intensity into $J_{\text{ph,max}} < 25 \text{ mA cm}^{-2}$ for 2 nm Ni and $< 15 \text{ mA cm}^{-2}$ with 20 nm Ni, whereas for comparison, the p^+n -Si photoanodes investigated herein exhibited $J_{\text{ph,max}} \sim 28 \text{ mA cm}^{-2}$. Although thick Ni catalysts are not required to lower the overpotential for water oxidation,⁵¹ the use of thick electrocatalyst layers can minimize performance degradation associated with catalyst detachment.

A wide range of alternate approaches to efficient photoelectrode performance have been demonstrated, especially when active catalysts for the desired water-splitting half-reactions are used.²⁰ For example, p^+n -Si(111) photoanodes decorated with 15 nm thick Ni islands that covered

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3 18% of the photoelectrode surface have demonstrated a light-limited current density of 20.4 mA
4 cm⁻².⁵¹ Modeling has shown that the optimal efficiency of a water-splitting system using a light-
5 facing photocathode patterned with Pt islands covering 5% of the optical plane closely approaches
6 that of a system using a photocathode patterned with a hypothetical transparent catalyst with the
7 same activity as Pt.⁵² Furthermore, photoanodes do not require reflective metallic catalyst coatings;
8 indeed, p⁺n-Si(100) photoanodes coated with 75 nm of sputtered NiO_x have been shown to be
9 stable for 1200 h of continuous oxygen evolution in contact with 1.0 M KOH(aq) and exhibit a
10 light-limited photocurrent density > 30 mA cm⁻². The TiO₂ nanocone array structure can
11 effectively optimize light transmission and catalysis simultaneously in a variety of possible
12 materials systems, and would be especially beneficial for chemical reactions that require very high
13 mass loadings of catalysts, such as O₂ evolution or CO₂ reduction using earth-abundant
14 electrocatalyst materials.
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32 Dielectric nanocone arrays thus provide an additional option to a growing toolbox of
33 strategies for directing broadband light around opaque top contacts to PV or PEC cells. The
34 approach ought to be generally applicable for any combination of semiconductor and metal, and in
35 principle is scalable; however, arbitrary combinations of semiconductors and metals may not be
36 compatible with electrodeposition of the metal onto the semiconductor as used in the fabrication
37 process described herein. Furthermore, the fabrication process developed herein for a proof-of-
38 concept experimental demonstration of a device that makes use of a TiO₂ nanocone array for light
39 management was complex relative to other known options for light management, such as
40 antireflective catalyst coatings or deposition of a controlled density and diameter of catalyst
41 islands. The value of the dielectric nanocone approach to light management can be increased by
42 developing a simplified fabrication process and by developing synthetic methods that yield TiO₂
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3 nanocones with a refractive index that approaches the index for ideal TiO₂. Modeling and
4 simulation efforts that compare attainable efficiencies for application-specific devices across
5 relevant light-management strategies will prove valuable for identifying the strategies that are most
6 promising for a given application.
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Supporting Information Available: Methods, simulated spectra of the TiO₂ film, simulated transmitted spectral photon flux, lateral distribution of transmitted light intensities, dimension variation effect on transmission, process flow diagram, EDS mapping of the TiO₂ nanocones with Ni sample, SEM image of the Ni hole array, and refractive index for TiO₂. This material is available free of charge *via* the Internet at <http://pubs.acs.org>.

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