Defect-rich decorated TiO$_2$ nanowires for super-efficient photoelectrochemical water splitting driven by visible light†

Md Anisur Rahman, Samad Bazargan, Saurabh Srivastava, Xiong Yao Wang, Marwa Abd-Ellah, Joseph P. Thomas, Nina F. Heinig, Debabrata Pradhan‡ and Kam Tong Leung*

Oxygen vacancy defects are highly desirable for photoelectrochemical water splitting reactions of TiO$_2$ nanomaterials because they act as electron donors and thereby enhance the electrical conductivity and charge transport property of TiO$_2$. For TiO$_2$ nanowires reported to date, oxygen vacancies are mainly generated by post-treatment of the as-synthesized nanowires. This comes with a disadvantage that oxygen vacancies are found to form just within a few tens of nanometers at the outer surface of these nanowires, and the photocurrent density is significantly reduced by two to three orders of magnitude when ultraviolet light is filtered out from the AM 1.5G light. Here, we demonstrate, for the first time, the controlled growth of 1D TiO$_2$ nanostructures with different morphologies and with incorporation of oxygen vacancy defects on a Si substrate by a single-step, catalyst-assisted pulsed laser deposition (PLD) method. Photoelectrochemical water splitting measurements under simulated sunlight show that the decorated nanowires exhibit one of the highest photoactivity values in the visible region (430 nm) reported to date, which represents 87% of the overall photocurrent. The higher activity in the visible region can be attributed to more conductive TiO$_2$ nanostructures (i.e., with a larger amount of oxygen vacancy defects), and the enhanced charge transfer from the nanocrystallites to the core of the decorated nanowires.

Broader context

Engineering the defects in wide band gap semiconducting transparent conductive oxide nanostructures is crucial in governing the physical and chemical properties of these structures. Compared to defect-free oxides, defect-rich oxides are more attractive for photovoltaics, photocatalysis, and fuel cell applications because of their narrower band gaps, which enable absorption of visible light, and a relatively high electrical conductivity. Enormous efforts have been made to narrow the band gap and extend the working spectrum to the visible light region, and these efforts include doping, defect creation by hydrogen treatment, and plasmonic nanoparticle sensitization. Unfortunately, all of these efforts provide two to three orders less photoactivity when ultraviolet light (<430 nm) is filtered out from the AM 1.5G spectrum. Moreover, synthesis of one-dimensional defect-rich TiO$_2$ nanostructures on conductive substrates by vapour deposition methods is extremely difficult due to the high melting temperature of TiO$_2$. The dependence of photoelectrochemical activity on the surface morphology of TiO$_2$ and the amount of oxygen vacancy defects in the 1D nanostructures is also not well understood. Despite recent developments, a simple method to fabricate defect-rich oxide semiconductors for efficient visible-light-driven photocatalysis remains elusive. We have developed a simple one-step method using pulsed laser deposition to fabricate defect-rich 1D TiO$_2$ nanostructures, which show excellent photoelectrochemical activity under the visible light illumination.

Introduction

Over the past two decades, TiO$_2$ has been extensively studied as a photoanode for photoelectrochemical water splitting reaction due to its compatible band-edge positions, high photocatalytic activity, high resistance to photocorrosion, low cost, and lack of toxicity. However, TiO$_2$ has a too wide band gap (3.0 eV) to absorb sunlight in the visible region, which limits its photocatalytic activity to ultraviolet illumination. Several attempts
have been made to extend the light absorption of this catalyst, and they include doping, hydrogen treatment, and plasmonic nanoparticle sensitization. All of these efforts have only managed to produce a photocurrent density not greater than 0.1 mA cm\(^{-2}\) in the visible region (>430 nm). The dependence of photoelectrochemical activity on the surface morphology and oxygen vacancies of these 1D TiO\(_2\) nanostructures is also not well understood. As the surface morphology and electronic properties of TiO\(_2\) nanostructures can affect the space charge regions differently, they are especially important for the overall charge collection efficiency by influencing the recombination velocity and the chemical reaction dynamics. Furthermore, these nanostructures (such as nanobelts and nanowires) can also be used to enhance light harvesting and suppress charge carrier recombination while maintaining a high surface area necessary to improve the photoreponse.

There are a variety of techniques to synthesize 1D TiO\(_2\) nanostructures, including anodization of titanium foil or wires, electro deposition or solution precipitation, hydrothermal methods, thermal evaporation, and chemical vapour deposition. One major limitation of wet-chemistry methods is that the precursor materials are often incorporated into the final structure as impurities. As a result, the charge transport efficiency and material stability are significantly reduced due to poor crystallinity, and grain boundaries. However, large-scale controlled synthesis of 1D TiO\(_2\) nanostructures by vapour deposition is challenging due to the extremely low vapour pressures and high melting points of Ti and TiO\(_2\). A protective buffer layer such as SiO\(_2\), TiO\(_2\) or TiN is often employed to activate the substrate-sensitive catalyst, including Ni, Cu, or Au, in order to promote vapour–liquid–solid (VLS) growth of TiO\(_2\) nanowires. In the absence of a buffer layer, the catalyst would quickly become poisoned, thus inhibiting VLS growth. However, the presence of a dielectric or insulating buffer layer that is too thick on a conductive substrate has adverse effects on the growth characteristics and charge collection efficiency, which negatively impact the electronic properties of the nanodevices. A simple, alternative vapour deposition method to enable controlled synthesis of a 1D TiO\(_2\) nanostructure on a conductive substrate with a buffer layer, of an appropriately optimized thickness (<50 nm), could therefore significantly advance future technological applications.

Unlike thermal evaporation and chemical vapour deposition, pulsed laser deposition (PLD) involves direct laser ablation of the target material, without affecting its stoichiometry, into the gaseous form, which is then exposed to the substrate held at a specified temperature. The absorption of a high-intensity laser energy pulse by a small volume of material leads to vaporization in the thermally non-equilibrium regime. As a result, activation of the gold catalyst could occur at a lower temperature, thus allowing the formation of 1D TiO\(_2\) nanostructures at a lower temperature compared to other vapour deposition methods. Furthermore, variable substrate temperature, oxygen partial pressure and reductive growth environment during PLD can be used to control not only the rate of deposition but also the crystallinity, morphology and the amount of oxygen-related defects. Oxygen vacancies are highly desirable for metal oxides because oxygen vacancy defects increase light absorption, act as electron donors and therefore enhance the electrical conductivity and charge transport property, which can significantly improve their catalytic performance for photoelectrochemical water splitting reactions.

Here, we use catalyst-assisted pulsed laser deposition (PLD) to synthesize defect-rich 1D TiO\(_2\) nanostructures with a wide range of morphologies on a Si substrate by controlling a SiO\(_2\) buffer layer of an appropriately optimized thickness and the growth temperature. We further demonstrate the remarkable photoelectrochemical catalytic performance of these defect-rich nanostructures for the first time in the visible light region (>430 nm) in a water splitting reaction.

**Experimental**

The catalyst-assisted PLD technique used to synthesize the 1D TiO\(_2\) nanostructures has been described in detail elsewhere. Briefly, the NanoPLD system (PVD Products) used in the present study was equipped with a KrF excimer laser (248 nm wavelength) and operated at a fluence of 350 mJ per pulse with a repetition rate of 5 Hz. The TiO\(_2\) target was prepared by coldpressing rutile TiO\(_2\) powders (Aldrich, 99.99% purity) at a pressure of 25 MPa, followed by sintering in air at 900 °C for 12 h. The temperature of the substrate could be varied from room temperature to 900 °C by radiative heating from infrared heat lamps. The target-to-substrate distance was maintained at 25 mm with the substrate temperature kept at 675, 700, 720 or 750 °C to facilitate growth of nanostructures with different morphologies. Argon gas was let into the growth chamber at a constant flow rate of 19.8 scm by using a mass flow controller to maintain a pressure of ~180 mTorr.

To evaluate the effect of the surface SiO\(_2\) layer, we modified commercial p-type Si(100) chips (resistivity 0.001–0.002 ohm cm, Siegert Wafer) to produce three different substrates: (RCA-Si) chemically oxidized Si obtained after RCA cleaning; (H-Si) H-terminated Si obtained by etching with hydrofluoric acid; and (Ox-Si) thermally oxidized Si by annealing H-Si in O\(_2\) at 850 °C for 120 min. Using a Filmetrics F-40 UV reflectometer, we estimated the respective oxide layer thicknesses for H-Si, RCA-Si and Ox-Si to be 1 nm, 3 nm and 30 nm. Gold nanoslands (GNIs) were produced on the three modified Si(100) substrates by magnetron sputtering a gold target for 4 s followed by annealing in N\(_2\) at 500 °C for 30 min and the resulting templates were designated as GNI/RCA-Si, GNI/H-Si, and GNI/Ox-Si. The size distributions of the GNIs were measured by processing their SEM images using the ImageJ software.

The surface morphologies of the as-grown TiO\(_2\) nanostructures on the three templates were characterized by field-emission scanning electron microscopy (SEM) using a Zeiss Merlin microscope. The crystal structures of the nanostructures were analyzed by glancing-incidence X-ray diffraction at an incidence angle of 0.3° using a PANalytical X’Pert Pro MRD diffractometer with Cu K\(_\alpha\) radiation (1.54 Å). The transmission electron microscopy (TEM) study of the as-deposited structures was conducted using a Zeiss Libra 200 MC microscope. Reflectance spectra were...
recorded using a Perkin-Elmer Lambda 950 UV-Vis-NIR spectro-
meter equipped with a Labsphere integrating sphere detector.
The chemical-state compositions of the nanostructures were
characterized by X-ray photoelectron spectroscopy (XPS) using a
VG Scientific ESCALab 250 microprobe equipped with a mono-
chromatic Al Kα X-ray source (1486.6 eV).

Photoelectrochemical measurements for the water splitting
reaction using the TiO2 nanostructures as the photocatalysts were
carried out using an electrochemical station (CH Instruments, CHI
660E). We employed a standard three-electrode configuration, in
which the TiO2 nanostructures grown on the aforementioned
templates, a saturated Ag/AgCl electrode, and a platinum wire
were used as the working, reference, and counter electrodes,
respectively, and a 1.0 M KOH solution was used as the electrolyte.
A 300 W solar simulator (Newport-Oriel Instruments, Model 68811)
was used to provide the AM 1.5G solar spectral illumination.

As short-pass (< 400 nm) or a long-pass (> 430 nm) filter (Oriel) was
coupled with the AM 1.5G filter to isolate the UV or visible part of
the simulated sunlight spectrum. Before each measurement, the
electrolyte was thoroughly flushed with N2 gas to remove any
dissolved oxygen. The same electrochemical station was also used
for the electrical impedance measurement by electrochemical
impedance spectroscopy.

Results and discussions

Growth of defect-rich 1D nanostructures

The SEM images shown in Fig. 1 illustrate the effect of a SiO2
buffer layer with different thicknesses on PLD growth of TiO2
nanostructures at 700 °C. On a pristine H-Si substrate, laser
ablation of the rutile TiO2 target for 90 min produces nano-
bricks with an edge length of 150–250 nm and a thickness of
80–150 nm (Fig. 1a1). A similar film morphology is also
observed on pristine RCA-Si (Fig. 1b1) and Ox-Si substrates
(Fig. 1c1), which indicates that the presence of a SiO2 layer,
irrespective of its thickness, appears to have no significant
effect on the TiO2 film growth. In Fig. 1, we show that the mean
diameters of the GNIs as-formed on the respective pristine
substrates [4 ± 3 nm for H-Si (Fig. 1a2), 8 ± 3 nm for RCA-Si
(Fig. 1b2), and 11 ± 3 nm for Ox-Si (Fig. 1c2)] increase with the
increasing SiO2 buffer layer thickness. The formation of much
smaller GNIs on H-Si than RCA-Si and Ox-Si is due to the
relative ease of Au silicide formation on the H-Si surface with
the thinnest SiO2 layer.27 PLD growth of TiO2 on the GNI/H-Si
template for 90 min at 700 °C produces mainly flake-like
nanostructures (Fig. 1a3), 300–400 nm long and 3–8 nm thick.
The corresponding back-scattered electron images show that
no GNI is present at the edges of these nanoflakes (Fig. 1a4).

On the other hand, PLD growth on the GNI/RCA-Si template under
the same deposition conditions produces TiO2 nanowires that
are notably different from flake-like nanostructures (Fig. 1b3 and b4).
The surfaces of these straight nanowires appear to be smooth,
and each individual wire has a cross-sectional diameter of 10–15 nm along its entire length of several hundred nanometers. The length of the nanowires can be controlled by changing the deposition time. Evidently, the GNIs have been detached from the substrate and stay at the tips of individual nanowires, indicating a vapour–liquid–solid (VLS) growth mechanism for these nanowires. However, the presence of a small amount of Au at the RCA-Si substrate interface (Fig. 1b4, inset), as in the case of GNI/H-Si (Fig. 1a4, inset), suggests that a fraction of Au has diffused through the interfacial SiO₂ layer at high temperature during the GNI formation and/or during TiO₂ deposition, producing Au-silicides at the interface. Interestingly, PLD growth on the GNI/Ox-Si template at 700 °C produces TiO₂ nanobelts, typically 10–20 nm thick, 50–80 nm wide and several hundred nm long (Fig. 1c3 and c4). The nanobelts have a pointy, triangular tip, with periodic sawtooth faceting along the sidewalls, the latter reflecting a remarkable oscillatory growth process. Unlike the RCA-Si and H-Si templates, the thicker SiO₂ layer on the Ox-Si template prevents Au diffusion and the subsequent Au–silicide formation, as supported by the absence of Au at the interface (Fig. 1c4, inset).

We have also studied the effect of deposition (substrate) temperature on the nanostructure growth. Fig. 2 shows the SEM images of TiO₂ nanostructures grown on the three templates at 675 °C, 720 °C, and 750 °C, in addition to those obtained at 700 °C (already shown in Fig. 1a1, b1, and c1). Deposition at 675 °C produces, on all three templates, tapered corrugated nanowires with stacking faults distributed along the growth direction (Fig. 2a1, b1, and c1). Similar types of structures have also been reported for SiC and ZnO nanowires. On the other hand, deposition at 720 °C on GNI/H-Si produces pebble-like particles (Fig. 2a3), which is likely caused by complete consumption of the thin SiO₂ layer (~1 nm) via silicide formation. As reported in earlier studies, annealing SiO₂ on Si under high vacuum conditions leads to decomposition of SiO₂ via the interfacial reaction: Si + SiO₂ = 2SiO(g), and the decomposition rate is further enhanced by the presence of Au. The surfaces of these pebble-like particles are decorated with small nanoparticles. Interestingly, PLD growth at the same temperature (720 °C) on GNI/RCA-Si (Fig. 2b3) and GNI/Ox-Si templates (Fig. 2c3) leads to tapered nanowires also decorated with nanocrystallites on the surface, in marked contrast to the straight nanowires with smooth surfaces found on GNI/RCA-Si at 700 °C (Fig. 2b2). These decorated nanowires are found to be 0.8–1.5 μm long with an average diameter of 50–70 nm. A closer examination reveals that the nanocrystallites on these decorated nanowires are more concentrated at the base, and the surface of the decorated nanowires grown on GNI/Ox-Si (Fig. 2c3) appears to be rougher than that of the decorated nanowires on GNI/RCA-Si (Fig. 2b3). Deposition on the GNI/H-Si template at a higher temperature (750 °C) produces pebble-like structures (Fig. 2a4) similar to those obtained at 720 °C (Fig. 2a3). On GNI/RCA-Si, nanoflakes and pebble-like particles are observed at 750 °C (Fig. 2b4) and 770 °C (not shown), respectively, likely due to the gradual consumption of a thin SiO₂ layer (3 nm) via the interfacial reaction. In contrast to the GNI/H-Si (Fig. 2a4) and GNI/RCA-Si templates (Fig. 2b4), nanowires decorated with larger nanocrystallites grown on GNI/Ox-Si at 750 °C (Fig. 2c4) or higher temperatures are observed. In Fig. 3, we schematically summarize the different 1D TiO₂ nanostructures obtained on the three templates: GNI/RCA-Si, GNI/H-Si and GNI/Ox-Si, with the respective estimated thicknesses for the SiO₂ buffer layer of 1 nm, 3 nm, and 30 nm, at different growth temperatures.

Fig. 4 shows the corresponding transmission electron microscopy (TEM) images of representative TiO₂ nanostructures, including corrugated nanowires (Fig. 2b1), straight nanowires (Fig. 2b2), decorated nanowires (Fig. 2b3), and nanobelts (Fig. 2c2).
The rugged edges of the nanobelts (Fig. 4a) and corrugated nanowires (Fig. 4b) are clearly observed, while the surface of the straight nanowires appears to be smooth (Fig. 4c). For the decorated nanowires (Fig. 4d), the outer shell consists of nanocrystallites of 3–5 nm in size. The corresponding high-resolution TEM images (Fig. 4, insets) show that all the nanostructures are single-crystalline and have an interplanar spacing of 3.2 Å, corresponding to the (110) plane of bulk rutile TiO$_2$. Interestingly, the same rutile TiO$_2$ interplanar spacing is also found for individual nanocrystallites on the decorated nanowires (Fig. 4d, top inset). The corresponding lattice planes appear to be not perfectly aligned and disordered at the edges of the nanocrystallites (Fig. 4d, top inset), indicating the presence of crystalline defects, including dislocations and local strains.$^{37}$ To further investigate the nature of crystallinity of the predominant nanostructures, we compare the glancing-incidence X-ray diffraction (XRD) patterns of the as-deposited nanostructures in Fig. S1 (ESI†). The prominent diffraction peaks are in good accord with the typical rutile structure of TiO$_2$ (PDF2 00-021-1276) and the FCC phase of metallic Au (PDF2 00-004-0784). Of particular interest is the remarkably different relative peak intensities of the prominent peaks at 27.4° (110), 36° (101) and 54.3° (211) with respect to the reference pattern of powder TiO$_2$ (PDF2 00-021-1276). Evidently, the higher intensity ratios of the (110) peak to (101) peak in all the nanowires and of the (110) peak to (211) peak in nanobelts than those in the reference pattern indicate that they have a preferred (110) growth orientation (in good accord with our TEM data).

As noted previously for other material systems,$^{38,39}$ the growth temperature can affect the catalyst state and, consequently, the predominant growth mode, i.e. vapour–solid growth below the eutectic temperature or VLS growth at or above the eutectic temperature, which ultimately governs the length and diameter of the nanowires. It has been observed that both vapour–solid and VLS growth can occur simultaneously, with the vapour–solid growth generally 10–100 times slower than VLS growth at the same precursor partial pressure and temperature.$^{39}$ In the present study, the growth temperature (675–750 °C) for the nanowires is lower than the lowest eutectic temperature in the bulk Au–Ti binary system (832 °C).$^{40}$ It should be noted that the actual eutectic temperature of a nanoscale material is expected to be lower than that of the bulk under the same pressure conditions.$^{41}$ We therefore expect that the growth of these nanowires occurs by both vapour–solid and VLS mechanisms as the catalyst state changes from a solid state to a liquid state throughout the temperature range. While both vapour–solid and VLS growth could occur concurrently, the VLS growth predominates at the higher growth temperature and the slower vapour–solid growth at a particular growth temperature could perturb and thus introduce variations into the general morphology of the nanowires. The formation of the tapered shape for the decorated nanowires has been attributed to the additional uncatalyzed vapour–solid growth occurring at the sidewalls, and to the longer exposure of the vapour to the base area compared to the tip area that ultimately affects the cross sectional shape of the nanowires.$^{42}$ The presence of a greater number of nanocrystallites on the decorated nanowires as-grown on GNI/Ox-Si than those on GNI/RCA-Si at a particular growth temperature suggests that the thicker, thermally grown SiO$_2$ layer (on Ox-Si) is rougher and has a different heat transfer efficiency than RCA-grown SiO$_2$, which ultimately affects the surface mobility, nucleation sites, and supersaturation rate of TiO$_2$, all of which control the morphology of the 1D nanostructures at a given temperature.$^{43}$ Our results also suggest that a minimum SiO$_2$ layer thickness of 3 nm (as formed on the RCA-Si substrate) is necessary for enabling VLS nanostructure growth in the PLD method, and a thicker SiO$_2$ or protective buffer layer is required for the growth of nanowires at a higher temperature. A buffer layer has been used in thermal evaporation and other methods for similar reasons,$^{44}$ but the
thickness of the buffer layer so employed has been considerably larger than 3–5 nm. For example, TiO$_x$ nanowires on Si were obtained by thermal evaporation (at 1100 °C) and a SiO$_2$ layer thickness of 65–120 nm was found to be necessary for efficient VLS growth. In atmospheric pressure chemical vapor deposition, a 200 nm thick SiO$_2$ layer was coated with a 50 nm thick Ti layer for TiO$_2$ nanowire growth on Si(110) at 950 °C. The SiO$_2$ buffer layer is used to modify the interaction between GNIs and the Si substrate for Au silicide formation and to provide a source of oxygen during growth in ambient Ar atmosphere. The thickness of the SiO$_2$ buffer layer therefore plays a critical role in the growth of TiO$_2$ nanowires on a Si substrate. The formation of different 1D nanostructures at different growth temperatures on GNI/RCA-Si (corrugated nanowires at 675 °C, straight nanowires at 700 °C, and decorated nanowires at 720 °C) and on GNI/Ox-Si (corrugated nanowires at 675 °C, nanobelts at 700 °C, and decorated nanowires at 720 °C or higher temperature) therefore confirms that both the growth temperature and the thickness of the SiO$_2$ buffer layer can be used complementarily to control the morphology of the 1D nanostructures.

In Fig. 5a, we show the changes in the colour of the as-deposited nanostructured films from blue (corrugated nanowires) to deep blue (straight nanowires) to greyish black (decorated nanowires), and then to lighter blue (nanobelts and nanobricks). It should be noted that the colours so observed for these nanostructured films remain unchanged for the respective films obtained by deposition for longer than 40 min. Moreover, the samples retain their individual colour upon storage in ambient atmosphere for over a year, indicating the robustness of these nanostructured films and that Ti$^{3+}$ and/or oxygen vacancy defects are located in the bulk and not just at the surface of these nanostructures. Similar colour changes in TiO$_2$ due to difference in growth temperature and oxygen partial pressure as employed in the flame reduction method have also been reported. Furthermore, hydrogen treatment has been used to create a high density of oxygen vacancies, which changed the colour of rutile TiO$_2$ from white to yellowish green and finally to black. Recently, Ti$^{3+}$-related bulk defects in rutile TiO$_2$ have been found to exhibit five different colours, and the crystal colour appeared to correlate directly with the amount of defects. Based on these studies and our experimental results, we hypothesize that the different colours for corrugated (light blue), straight (dark blue) and decorated nanowires (greyish black) are due to the differences in the amount of defects.

This series of colours should correlate with the respective degree of sub-stoichiometry of TiO$_2$ in these nanostructured films, which is in good accord with our X-ray photoelectron data shown in Fig. 5b. For all the samples, the prominent Ti 2P$_{3/2}$ Peak at 459.4 eV corresponds to the Ti$^{4+}$ state attributable to TiO$_2$, while the shoulder at 458.0 eV could be assigned to the Ti$^{3+}$ state in TiO$_x$ ($2 > x > 1$). Four O 1s peaks at 530.7, 531.1, 532.6 and 533.3 eV correspond to TiO$_2$, TiO$_x$, SiO$_2$, and

![Fig. 5](image-url)
SiO₂, respectively. The fitted O 1s intensity ratios for TiO₂/ TiO₂ and SiO₂/SiO₂ of the nanowires prepared on the GNI/RCA-Si template follow the order: decorated nanowires (720 °C) > straight nanowires (700 °C) > corrugated nanowires (675 °C), in close correlation with the growth temperature and sample colour (Fig. 5a). The Si 2p ½ (103.5) eV correspond to SiO₂ and SiO₂, respectively. For decorated nanowires, the Ti 2p ½ peak width is found to be discernibly larger (Fig. S2, ESI†), which further supports the presence of a larger amount of oxygen vacancy defects in decorated nanowires than the other nanostructures. The higher the growth temperature, the more reduced TiO₂ has become under the present synthesis conditions. On the other hand, the O 1s intensity ratio for TiO₂/TiO₂ of the nanobelts, deposited at the same temperature as that for straight nanowires on GNI/RCA-Si (700 °C) but on a GNI/Ox-Si template, is found to be smaller, which is consistent with the thicker SiO₂ layer on the GNI/Ox-Si template serving as a source of oxygen during growth in an Ar atmosphere. Less oxygen vacancy defects can therefore be expected in nanobelts than the nanowires grown on the GNI/RCA-Si template. As a result, the colour of the nanobelt film is lighter than the nanowire film (Fig. 5a). The corresponding reflectance spectra of the nanostructures all exhibit broadband absorption, starting at 330 nm and extending into the visible region of the spectrum (Fig. S3, ESI†). The intensity of the reflectance band increases with decreasing growth temperature for the nanowires, and with a larger interfacial SiO₂ layer thickness for the nanobelts, which is also consistent with the colour change of the samples. The visible light absorbance of the TiO₂ nanowires could be mainly attributed to the existence of defect states in the TiO₂ band gap, likely due to the presence of Ti³⁺ defects and oxygen vacancies in accordance with the XPS analysis.

The slight deviation from perfect stoichiometry could result in a significant change in the electrical properties of the TiO₂ nanostructured films. Fig. S4a (ESI†) shows the corresponding Nyquist plots for the nanostructured films under simulated sunlight illumination obtained by potentiostatic electrochemical impedance spectroscopy. Using the equivalent circuit model shown in Fig. S4b (ESI†), we determine the series resistance (Rₛ), the resistance (Rₒ) and chemical capacitance (CPEₒ) of the semiconductor depletion layer in an RC circuit, along with the charge transfer resistance in the Helmholtz layer (Rₜ), the Warburg diffusion impedance (Zₜ), and the capacitance of the electrochemical double layer (CPEₓ) in a second RC circuit in series. The electrical parameters obtained by fitting the experimental data with the equivalent circuit are summarized in Table S1 (ESI†). The fitted data shows that the charge transfer resistances (Rₛ, Rₒ, and Rₜ) increase (while the capacitance decreases) in the following order: decorated nanowires < straight nanowires < corrugated nanowires < nanobelts, in close correlation with the observed oxygen vacancies and crystal colour. The higher charge transfer resistances of nanobelts might also be caused by the thicker interfacial SiO₂ layer, which ultimately reduces the collection efficiency of photogenerated electrons. Interestingly, the charge transfer resistance (Rₜ) at the depletion layer of decorated nanowires has become significantly smaller while the corresponding capacitance (CPEₓ) has increased concomitantly, which suggests that the nanocrystallites of the decorated nanowires contain a large amount of oxygen vacancy defect states, likely in the band gap of the TiO₂ nanocrystallites. The sub-stoichiometric TiO₂ (2 > x > 1) therefore possesses numerous advantages over stoichiometric TiO₂ because reduced TiO₂ has higher absorbance, wettability, and conductivity that are important for photoelectrochemical applications.

**Photoelectrochemical properties**

To study the photocatalytic activity of the aforementioned nanostructures for photoelectrochemical water splitting reaction, we employ, as photoanodes, TiO₂ nanobricks (grown on a pristine RCA-Si substrate, Fig. 1b1), corrugated nanowires (on a GNI/RCA-Si template, Fig. 2b1), straight nanowires (on a GNI/RCA-Si template, Fig. 2b2) and decorated nanowires (on a GNI/RCA-Si template, Fig. 2b3), as well as nanobelts (produced on a GNI/Ox-Si template, Fig. 2c2). The photocurrent spectra have been obtained over an illuminated sample area of 0.2 cm² under simulated sunlight illumination at 100 mW cm⁻² using a 300 W xenon lamp coupled with an AM 1.5G filter. In situ quantification of the evolved gases by using an Universal Gas Analyser (Stanford Research Systems, SRS-UGA) confirms the stoichiometric splitting of water (Fig. S5, ESI†). The photocurrent density measured at 0.5 V (vs. Ag/AgCl) for the decorated nanowires (1.5 mA cm⁻²) is found to be 8.3, 6.0, 2.5, and 1.6 times those of nanobelts (0.18 mA cm⁻²), nanobricks (0.25 mA cm⁻²), straight nanowires (0.6 mA cm⁻²), and corrugated nanowires (0.94 mA cm⁻²), respectively (Fig. 6a). We also characterize and obtain essentially no photocatalytic activity for the pristine RCA-Si substrate and GNI/RCA-Si template under the same conditions (Fig. 6a). The photogenerated holes in Si cannot be easily transferred to the valence band of TiO₂, likely due to a significant barrier at the junction resulting in carrier recombination in Si. The higher photocurrent density observed for the decorated nanowires (and other nanostructures) can therefore be attributed only to the photogenerated charge carriers from the TiO₂ nanostructures themselves. The decorated nanowires provide one of the best photoelectrochemical performances among the TiO₂ nanostructures reported to date. The measured photocurrent density for the decorated nanowires (1.5 mA cm⁻² at 0.5 V) in the present work is higher than those for most TiO₂ nanomaterials, including a modified rutile TiO₂ nanowire array obtained by depositing an epitaxial rutile TiO₂ shell onto a hydrothermally prepared rutile TiO₂ nanowire array (1.1 mA cm⁻² at 0.5 V), a hierarchical branched rutile TiO₂ nanorod array with the surface of the TiO₂ nanorod branches covered by short needle-shaped TiO₂ branches (0.83 mA cm⁻² at 0.7 V), a N-modified rutile TiO₂ nanowire array with a cobalt cocatalyst (0.8 mA cm⁻² at 0.7 V), a TiO₂ nanoforest prepared by depositing dense TiO₂ nanorods along the entire TiO₂ nanotube trunk (0.75 mA cm⁻²), and an anatase TiO₂ nanotube array decorated with Ag nanoparticles (0.05 mA cm⁻²). Our current density is also comparable to that of flame-reduced TiO₂ nanowires (1.5 mA cm⁻² at 0.58 V), where a complicated flame reduction method was used to control the oxygen vacancies.
by manipulating a minute variation of reduction time (a few seconds) or by adjusting a slight change in the fuel-to-air ratio. To quantitatively evaluate the efficiency of photoelectrochemical hydrogen generation from our TiO\textsubscript{2} nanostructures, the photoconversion efficiency is calculated by using the equation,

$$\eta(\%) = \frac{j_p (1.23 - V)}{I_0} \times 100,$$

where \(j_p\) is the photocurrent density (in mA cm\(^{-2}\)) at the applied voltage \(V\) [vs. reversible hydrogen electrode (RHE)], and \(I_0\) is the illumination intensity (i.e. 100 mW cm\(^{-2}\) for AM 1.5G)\textsuperscript{3,4} A maximum photoconversion efficiency of 2.4\% at \(-0.3\) V vs. Ag/AgCl (or 0.7 V vs. RHE) is found for the decorated nanowires, followed by the corrugated nanowires (1.8\% at \(-0.4\) V vs. Ag/AgCl), straight nanowires (0.95\% at \(-0.33\) V vs. Ag/AgCl), nanobelks (0.32\% at \(-0.44\) V vs. Ag/AgCl), and nanobelts (0.11\% at \(-0.09\) V vs. Ag/AgCl), as shown in Fig. 6b. The lowest maximum photocurrent density found for the nanobelts can be attributed to the thicker SiO\textsubscript{2} buffer layer on the GNI/Ox-Si template, which impedes the photogenerated carrier transfer from the TiO\textsubscript{2} surface to the Pt counter electrode. The lower photocatalytic activity of the nanobelks on the RCA-Si template compared to nanowires is due to a shorter average length and a lower density of the as-grown nanobelks, and therefore a smaller specific surface area available for the water oxidation reaction. On the other hand, the higher photocatalytic activities of the decorated nanowires and corrugated nanowires compared to straight nanowires are attributed to the different morphologies of the nanowires. For the decorated nanowires, the shell consisting of densely packed ultrasmall nanocrystals (3–5 nm) introduces a jagged surface at the nanowires. The “bumpy” surface evidently provides extra surface area for the photoelectrochemical reaction, while the junctions between the nanocrystallites act as additional active sites for oxygen production reaction.\textsuperscript{61} Similarly, the rugged surface and nano-junctions in corrugated nanowires account for the observed higher catalytic activity than straight nanowires, but less than the decorated nanowires. Furthermore, to investigate the chemical and structural stabilities during photoelectrochemical water splitting, we perform chronoamperometric (current vs. time) studies with light on/off cycles at 100 mW cm\(^{-2}\) at 0 V vs. Ag/AgCl (or 1.0 V vs. RHE), the potential at which the photocurrent density has reached a plateau region (Fig. 6a). A typical measurement on the decorated nanowires shows a stable photocurrent density of 1.06 mA cm\(^{-2}\) with degradation of only 2.0\% after 9 on/off cycles (Fig. 6c). (The corresponding Faradaic efficiency is estimated to be 95.1\%). The catalysts remain active even after six hours of photoelectrochemical water-splitting reaction (Fig. S6, ESI\textsuperscript{†}). Similar stability tests have also been conducted on other nanostructures and they show virtually no degradation over repeated cycling and extended use.

Since TiO\textsubscript{2} is expected to be photoelectrochemically active mainly under UV light illumination due to its wide band gaps: 3.2 eV (388 nm) for anatase and 3.0 eV (410 nm) for rutile phases, and given that the AM 1.5G light contains only a small UV component, we determine the photocurrent densities arising from separate UV and visible spectral illuminations by coupling the AM 1.5G light with appropriate short-pass
<400 nm) and long-pass filters (>430 nm), respectively. As shown in Fig. 6d, the photocurrent density of decorated nanowires is reduced slightly from 1.5 mA cm\(^{-2}\) to 1.4 mA cm\(^{-2}\) when a long-pass filter is coupled with the AM 1.5G filter, and to effectively dark current density (0.18 mA cm\(^{-2}\)) when a shortpass filter is used. The photocurrent density observed for the decorated nanowire sample therefore mainly comes from the longer wavelength region (>430 nm), i.e., the visible light region. This is a significant result, because unlike the previously reported case for rutile TiO\(_2\) nanowire arrays decorated with Au nanoparticles,\(^5\) where the observed photocurrent density (1.8 mA cm\(^{-2}\)) in AM 1.5G light was found to reduce by nearly 50% to 0.96 mA cm\(^{-2}\) with the UV light component (<430 nm) and to 0.00267 mA cm\(^{-2}\) with the visible light component (>430 nm), we observe only a 13% reduction with just the visible light component in the present work. Our visible light current density is also significantly higher than those reported for highly dense Si core TiO\(_2\) shell nanowire arrays, obtained by depositing a polycrystalline anatase TiO\(_2\) layer on a Si nanowire array, which gave zero photocurrent density under visible light.\(^55\) Similarly, for H\(_2\)-treated\(^4\) and Sn-doped TiO\(_2\) nanowires,\(^62\) almost zero photocurrent density was observed in visible light (>430 nm). These results verify that our decorated nanowire sample is the top photoelectrochemical catalysis performer in visible light (>430 nm) reported to date.

It has been reported that the band gap of TiO\(_2\) and the amount of oxygen vacancy defects depend on the crystallite size. For example, when the crystallite size is decreased from 17 to 3 nm, the band gap is reported to increase from 3.2 to 3.6 eV and the deviation from stoichiometry (due to the presence of oxygen vacancies) has also increased with the increasing Ti\(^{3+}\) concentration.\(^45\) Meanwhile, oxygen vacancies are found to introduce defect states below the conduction band of TiO\(_2\).\(^22,52\) The smaller (3–5 nm) rutile nanocrystallites on the decorated nanowires would therefore have a larger band gap than the single-crystalline nanowire host but possess defect states close to the conduction band minimum. A schematic band alignment diagram representing the enhancement mechanism of photoelectrochemical properties of decorated nanowires is shown in Fig. 7. When the decorated nanowires are irradiated with AM 1.5G light, electron transfer takes place from both valence band (VB) and oxygen vacancy defect states to the conduction band (CB) of TiO\(_2\) nanocrystallites. The photon-excited electrons in the nanocrystallites are then injected into the conduction band of the core nanowires, while the photogenerated holes of nanocrystallites react with the donor species of the electrolyte. Owing to the single-crystalline nature of the nanowire core, the electrons in the conduction band of the nanowires could migrate easily to the Si substrate and ultimately to the counter electrode. The higher photocurrent density obtained from the decorated TiO\(_2\) nanowires can therefore be attributed to the dense mat of nanowires\(^63\) with densely packed TiO\(_2\) nanocrystallites at the outer surface. These nanocrystallites offer excellent light-trapping characteristics, a large contact area with the electrolyte, and a highly conductive pathway for charge carrier collection, while the presence of a large number of oxygen vacancy defects in these nanocrystallites provides superior photoelectrochemical performance in the visible region.

**Conclusion**

By tuning the interfacial SiO\(_2\) layer thickness and growth temperature, we have synthesized a variety of 1D nanostructured TiO\(_2\) films, including nanobelts, corrugated nanowires, straight nanowires, and decorated nanowires, by using the catalyst-assisted PLD method. The use of a high vacuum system and the precise control of growth temperature and Ar flow have enabled us to produce (oxygen vacancy) defect-rich TiO\(_2\) nanostructured films. We further demonstrate that the amount of oxygen vacancy defects depends on the growth temperature, and the electrochemical impedance measurement confirms the lower charge transfer resistances at the depletion layer of the decorated nanowires. The photoelectrochemical measurement under simulated sunlight (100 mW cm\(^{-2}\)) shows that these decorated nanowires exhibit a low onset potential of 0.3 V (vs. RHE) and a total energy photoconversion efficiency of 2.4%. More importantly, the photocurrent density of defect-rich decorated nanowires is reduced only slightly from 1.6 mA cm\(^{-2}\) to 1.4 mA cm\(^{-2}\) when the ultraviolet light component (<430 nm) is filtered out. Unlike the previously reported cases for sub-10 nm rutile nanoparticles,\(^64\) Fe\(_2\)TiO\(_5\) coated TiO\(_2\) nanotube arrays,\(^65\) (W, C) co-doped TiO\(_2\) nanowires,\(^66\) and Au nanoparticle decorated TiO\(_2\) nanowire arrays,\(^5\) where the observed photocurrent densities in AM 1.5G light were found to reduce by over 50% with just visible light illumination, we observe only a 13% reduction for the decorated nanowires. These defect-rich decorated nanowires therefore have the best photoelectrochemical catalytic performance in the visible region reported to date and are expected have a significant impact on the design of super-efficient photoanodes for photoelectrochemical applications driven by visible light.

The present photocurrent density of TiO\(_2\) nanowires can be further increased with a longer PLD deposition time. When the
deposition time for the decorated nanowires is increased from 90 minutes to 130 minutes, the current density increases from 1.6 to 2.2 mA cm$^{-2}$ (i.e. by 32%). This performance is especially remarkable considering the fact that both the length and density of the nanowires are smaller than most of the high-performance TiO$_2$ nanowire samples reported in the literature.$^{4,62}$ While the latter samples exhibit a current density of 2–3 mA cm$^{-2}$, these nanowires also have a higher aerial density and an average length of 5–15 μm, the larger amount of which inherently provides more active sites for the photoelectrochemical reaction. Furthermore, the present nanowires are prepared with one distinct advantage, i.e., no need for any post-synthesis modification or treatment, in marked contrast to most of the aforementioned TiO$_2$ nanowire samples, all of which required post-treatment (such as annealing in a reductive environment) or doping with secondary materials. In our case, the photocurrent density and hence the efficiency could easily be increased further by increasing the aerial density of the nanowires (e.g., by increasing the GNI density) and/or the length of the nanowires (e.g., by increasing the deposition time). An even higher efficiency can be achieved by controlling doping with a second material (e.g., Sn, Zn, Fe, or Cu) in the TiO$_2$ target. Furthermore, fabricating hybrid and/or core–shell nanowires and synthesizing binary or tertiary nanowires could also enhance the photoelectrochemical efficiency and can be easily accomplished by switching the targets (using a multi-target holder) during the growth of the TiO$_2$ nanowires. The present approach of intentionally growing defect-rich TiO$_2$ nanostructures by the catalyst-assisted PLD method could be extended to other wide-band gap semiconductors, which could offer viable alternatives for TiO$_2$ in a variety of solar energy driven applications, including photoelectrochemical water splitting, photocatalysis, and solar cells.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada.

References