Synthesis and Photocatalytic Activity of Highly Ordered TiO₂ and SrTiO₃/TiO₂ Nanotube Arrays on Ti Substrates

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Highly ordered TiO₂ nanotube arrays (TiO₂-NTAs) are produced by electrochemical anodization of a Ti foil in ammonium fluoride (NH₄F)–ethylene glycol solution. Photocatalytic (PC) investigations indicate that the length of the NTAs plays an important role in their photoactivity. The PC activity increases initially with the NT length and then decreases and the optimum length that yields the highest PC is 6.2 μm for TiO₂-NTAs. The TiO₂-NTAs are further converted to heterojunction strontium titanate (SrTiO₃)/TiO₂-NTAs by a hydrothermal reaction in Sr(OH)₂ solution. As the hydrothermal reaction proceeds, more TiO₂ is converted into SrTiO₃ and the thickness of the SrTiO₃ layer increases. The SrTiO₃/TiO₂-NTAs exhibit variable PC activities that depend on the hydrothermal reaction time, and the SrTiO₃/TiO₂-NTAs hydrothermally treated for 1 h or less have enhanced PC properties. The advantage of combining TiO₂ and SrTiO₃ stems from the difference in the flatband potential, thereby improving the separation of the photogenerated electron–hole pairs and consequently the PC activity.

1. Introduction

The use of semiconductor photocatalysts for photocatalytic (PC) degradation of environmental organic pollutants and toxins has received considerable attention.¹ Among the various semiconductor photocatalysts used, nanosized titanium oxide (TiO₂) is widely studied because of its unique properties such as high photosensitivity, strong oxidizing activity, as well as biological and chemical stability. The nanosized TiO₂ species used in environmental control is mainly suspended zero-dimensional (0D) nanoparticles.³⁻⁴ However, recovery of the suspended TiO₂ nanoparticles from the treated water is very difficult and energy consuming and hence their usefulness is limited in practical applications. Immobilization of TiO₂ nanoparticles has been carried out on different substrates to counter this problem.²⁻⁸ Unfortunately, the efficiency of the immobilization system is much lower than that of the corresponding slurries due to the inevitable reduction of the surface area associated with nanoparticle immobilization.⁹ In addition, owing to the lack of continuous conducting pathways, photogenerated carriers are transferred by a hopping mechanism due to the energy barriers between nanoparticles,⁴⁻¹⁰ resulting in a rapid recombination of the photogenerated electron (e⁻) and hole (h⁺) and consequently low quantum yield. One-dimensional (1D) TiO₂ nanostructures such as nanotubes (NTs) and nanowires, especially substrate-anchored 1D TiO₂ NT arrays (TiO₂-NTAs), have improved charge transport properties due to the direct conduction pathways of the NT walls versus electron hopping in the nanoparticle systems.¹¹⁻¹² At the same time, a large active surface area and multiple diffusion pathways for reaction species are provided. Hence, 1D TiO₂-NTAs display interesting PC properties and are promising in the photodegradation of environmental pollutants. Anodization is a relatively simple and efficient method to fabricate highly ordered TiO₂-NTAs on Ti substrates such as sheets, foils, wires, and so on.¹³ The anodized TiO₂-NTAs grow directly and adhere strongly to the underlying Ti substrate. This factor thus allows easy recovery of the photocatalyst and also can give rise to enhanced photovoltaic properties by applying a potential to the conducting Ti substrate.¹⁴⁻¹⁶

Recent investigations suggest that the PC activity of TiO₂-NTAs depends very much on the length and pore diameter.¹³,¹⁵ Larger diameter NTs can degrade pollutants more quickly due to the improved accessibility to pollutants. However, if the diameter of the NT is over a certain value, e.g. 75 nm,¹³ the PC efficiency cannot be further improved. Therefore, the influence of the NT length on the PC activity is important. Longer NTs have larger surface areas enabling more light harvesting and larger active sites accessible to pollutants in the aqueous environment. These factors lead to a higher PC activity. However, the light intensity is usually attenuated sharply as it penetrates into the solid photocatalyst film.¹⁸ It means that light harvesting by the NTAs does not necessarily increase when the length of the NTAs exceeds a certain value. On the other hand, diffusion and transport of pollutant species from the solution are also affected by the length of the NTs due to the capillary structure. The longer NTs have a longer diffusion path and diffusion of reactants into the NTs is slower. This may instead lead to a decrease in the PC degradation rate.¹⁹ In other words, there should be an optimal length for the best PC activity. However, the effects of the NT length on the PC activity have not been investigated in detail and systematically and it is the motivation of the work presented here.

Very recently, heterostructure photocatalysts such as heterojunction ZnO/TiO₂ or CdS/TiO₂-NTAs have attracted much interest due to the improved charge separation efficiency and visible-light photoactivity.²⁰⁻²¹ Strontium titanate (SrTiO₃) with a perovskite structure is an important functional electronic ceramic material. It is widely used in capacitors, transducers, actuators, nonlinear optical devices, nonvolatile random-access memory devices, and so on because of unique properties such as high ferroelectric response, high dielectric constant, and large nonlinear optical coefficients.²²⁻²⁵ Besides the good electric and optical properties, SrTiO₃ is an efficient n-type semiconductor photocatalyst with a band gap of about 3.2 eV.²⁶⁻²⁹ Although the band gaps of SrTiO₃ and TiO₂ are similar, SrTiO₃ has a slightly higher flatband potential²⁹ and it is thus expected that a proper combination of SrTiO₃ and TiO₂ can lead to enhanced...
PC activity due to the improved separation between photogenerated electrons ($e^-$) and holes ($h^-$). Although the PC properties of TiO$_2$ and SrTiO$_3$ have been investigated, there have been very few reports on the PC activity of heterojunction SrTiO$_3$/TiO$_2$-NTAs. According to our knowledge, only one paper reported the improved photoelectrochemical performance of TiO$_2$–SrTiO$_3$ heterostructure NTAs. The heterostructure NTAs consisting of SrTiO$_3$ nanoparticle-coated TiO$_2$-NTAs were prepared by a hydrothermal treatment involving anatase TiO$_2$-NTAs in Sr(OH)$_2$ solution. In comparison, the heterojunction SrTiO$_3$/TiO$_2$-NTAs presented here are fabricated by hydrothermal treatment of amorphous TiO$_2$-NTAs in Sr(OH)$_2$ solution. The amorphous characteristics provide a facile substitution of Sr by the hydrothermal reaction resulting in the formation of heterojunction SrTiO$_3$/TiO$_2$-NTAs with a core-shell structure. The PC activity of the SrTiO$_3$/TiO$_2$-NTAs is evaluated by monitoring the photodegradation of methyl blue (MB) and the influence of the structure and composition on the PC activity is also investigated. This paper describes a feasible and facile method to improve the PC activity of TiO$_2$-NTAs by incorporating photoactive 0D nanoparticle layers and the results improve our understanding and design of new functional nanocomposite photocatalysts.

II. Experimental Procedure

The highly ordered TiO$_2$-NTAs were fabricated by electrochemical anodization of a Ti metal foil in ammonium fluoride (NH$_4$F)-ethylene glycol solution. Anodization was carried out at room temperature in a conventional two-electrode cell using a direct current power supply (IT6834, ITECH, Nanjing, China). A graphite foil and Ti foil (99.6% purity, 20 mm x 10 mm x 1 mm) served as the cathode and anode, respectively. The electrolyte was ethylene glycol containing 0.3 wt% NH$_4$F and 5 vol% distilled water. Anodization was conducted at 40 V for 40 min, 2, 4, and 7 h to prepare TiO$_2$-NTAs with different lengths. In the anodization process, the electrolyte was continuously agitated using a magnetic stirrer. After anodization, the samples were rinsed in distilled water and dried in air. Heterojunction SrTiO$_3$/TiO$_2$-NTAs were synthesized hydrothermally by reacting the as-anodized TiO$_2$-NTAs in Sr(OH)$_2$ solution. The anodized samples were placed vertically in 40 mL of Sr(OH)$_2$ solution (0.02 M) in a 60 mL Teflon-lined autoclave using a holder. The autoclave was sealed and heated in an oven to 200°C for different reaction times. After the hydrothermal reaction, the specimens were removed from the vessel, ultrasonically washed with 1 M HCl solution for 5 min to remove residual Sr(OH)$_2$, rinsed with distilled water, and dried in air. Afterwards, the SrTiO$_3$/TiO$_2$-NTAs and TiO$_2$-NTAs were annealed at 450°C in air for 3 h (heating rate of 10°C/min).

The samples were characterized by X-ray diffraction (XRD, Philips X’ Pert Pro, Eindhoven, the Netherlands) with CuKz radiation ($\lambda$ = 1.5418 Å), field-emission scanning electron microscopy (FE-SEM, FEI Nova 400 Nano, Eindhoven, the Netherlands), energy-dispersive X-ray spectroscopy (EDS, Oxford INCA 200, Oxford Instruments, Oxfordshire, U.K.), and X-ray photoelectron spectroscopy (XPS, ESCALB MK-II, VG Instruments, U.K.).

The PC activity of the TiO$_2$-NTAs and heterojunction SrTiO$_3$/TiO$_2$-NTAs was evaluated using MB in an aqueous solution as the probing molecule. The sample sealed with a size of 1 cm x 1 cm was immersed in 20 mL of MB aqueous solution with an initial concentration of 10 mg/mL. The solution was stirred in the dark for 2 h to saturate the photocatalyst with MB. The photodegradation experiments were performed at the natural pH of the MB dye. The solution was aspirated continuously with air during the PC reaction. A high-pressure mercury lamp (500 W, primary wavelength of 365 nm) was used as the UV irradiation source. The distance between the light source and sample was about 120 mm and the average UV intensity impacting the samples surface was measured to be 4.0 mW/cm$^2$ using irradiance meters (Model: UV-A, Beijing Normal University, China). The change in the MB concentration with PC time was measured using a UV-Vis spectrophotometer (TU-1810SPC, Beijing PGENERAL, Beijing, China).

III. Results and Discussion

Figure 1(a) shows the top-view FE-SEM images of the anodized product prepared in NH$_4$F-ethylene glycol at 40 V for 40 min

![Fig. 1. Top view and side view of field-emission scanning electron microscopic images of the titanium oxide (TiO$_2$) nanotube arrays (TiO$_2$-NTA) prepared by electrochemical anodization of Ti foils in an ammonium fluoride-ethylene glycol solution for different times: (a) top view (40 V—40 min), (b)–(e) side view SEM images of TiO$_2$-NTA prepared by different anodization time. (b) 40 V—40 min, (c) 40 V—2 h, (d) 40 V—4 h, and (e) 40 V—7 h. The inset in (a) is the enlarged top-view image of NTs and the scale bar is 100 nm.](image-url)
resembling uniform NTs with an inner diameter of 90 nm and a wall thickness of 10 nm. The 1.2-μm-long NTs are perpendicular to the Ti foil as shown in the FE-SEM side-view image (Fig. 1(b)). If the anodization time is prolonged to 2, 4, and 7 h with the electrolyte and applied potentials unchanged, the NTA lengths increase to 3, 6.2, and 10 μm, respectively, as shown in Figs. 1(b)–(e), but the other dimensions remain almost the same. XRD results (Fig. 2) suggest that the anodized NTAs are amorphous (curve 1). They could be crystallized into anatase structure (curve 2), the higher catalytic activity of the TiO2 crystal structures, by thermal treatment of the anodized amorphous NTAs at 450°C for 3 h in air. The PC activity of the TiO2-NTAs with different lengths is evaluated using aqueous MB as the probing molecule under UV illumination. MB is a nonbiodegradable dye used in the textile industry and often considered the standard dye in the determination of PC activity. The highest absorbance wavelength of MB is measured at 664 nm. The photodegradation experiments were performed at the natural pH of MB and the incident UV intensity is about 4 mW/cm². Direct photolysis is carried out without using the photocatalyst of TiO2-NTAs. Figure 3(a) shows the plot of concentration of MB in the aqueous solution against UV illumination time. The PC activity increases initially with NTA lengths from 1.2 to 6.2 μm and then decreases for longer NTAs (10 μm). The fastest PC degradation of MB is observed on the 6.2-μm-long TiO2-NTAs and almost 90% of the MB is photodegraded within 100 min. The photodegradation of MB on the TiO2-NTAs obeys the first-order reaction kinetics (Fig. 3(b)). The first-order photodegradation reaction rate and associated kinetics may be expressed as

\[ \ln(C/ C_0) = k t \]

where \( k \) is the apparent rate constant, \( t \) is the irradiation time, and \( C_0 \) and \( C \) are the initial and reaction concentrations of the MB aqueous solution, respectively. The calculated \( k \) values of the TiO2-NTAs with different lengths are listed in Fig. 3(b) showing the magnitude of the overall photodegradation rate. The \( k \) value of the 6.2-μm-long NTAs is about 2.6 times larger than that of the 1.2-μm-long ones, suggesting that the tube length plays an important role in the PC activity of the TiO2-NTAs.

We further investigate the PC activity of the SrTiO3/TiO2-NTAs. Heterojunction SrTiO3/TiO2-NTAs consisting of TiO2-NTAs and the SrTiO3 nanoparticle layers are prepared by the hydrothermal treatment of as-anodized amorphous TiO2-NTAs in Sr(OH)2 solution at 200°C followed by thermal annealing at 450°C for 3 h in air. Figures 4(a)–(d) depict the top-view images of SrTiO3/TiO2-NTAs after undergoing the hydrothermal reaction for 0.5, 1, 3, and 6 h. After the hydrothermal reaction and thermal treatment, the morphology of the highly ordered NTAs is retained. The spacing between the original TiO2-NTAs shown in Fig. 1(a) is no longer apparent and the NT walls thicken from 10 to 12 nm after the 30-min reaction and to 21 nm after 6 h due to crystal cell expansion induced by the transformation from TiO2 to SrTiO3. This suggests that more TiO2 is converted to SrTiO3 by increasing the hydrothermal reaction time. XRD patterns obtained from the SrTiO3/TiO2-NTAs formed using different hydrothermal time are displayed in Fig. 4(e). No diffraction peaks related to SrTiO3 species can be observed from the sample reacted for 0.5 h (curve 1). It may be due to the small amount of SrTiO3. The enhanced SrTiO3 diffraction peaks and reduced anatase TiO2 peak observed when the reaction time is lengthened further indicate that more TiO2 is converted to SrTiO3. The presence of SrTiO3 suggests that the hydrothermal treatment may not be sufficient and the remaining NT walls that have not reacted in the hydrothermal reaction turn into anatase TiO2 after annealing. The remaining TiO2-NTAs are in conjunction with the in situ generated SrTiO3 nanoparticle layer resulting in the formation of the heterojunction SrTiO3/TiO2-NTAs.

The XPS results further confirm the SrTiO3/TiO2 nanojunction structure. Figure 5(a) shows the Sr, Ti, and O elemental distributions of the 1.2-μm-long anodized NTAs after hydrothermal reaction in the Sr(OH)2 solution for 6 h without further annealing. A high Sr content is observed on the surface and the Sr concentration decreases gradually with depth. After sputtering for about 65 min at an approximate sputtering rate of 20.6 nm/min, nearly no Sr and O signals can be detected. It suggests
that Sr is distributed along the entire NT length although the absolute concentration decreases with depth. The high-resolution Ti 2p spectra obtained at different sputtering time are shown in Fig. 5(c). The observed binding energy of Ti 2p varies with depth. At the near surface, the Ti 2p peaks are centered at about 463.5 and 457.8 eV corresponding to Ti in SrTiO₃.35 After 3 and 30 min of sputtering, three other peaks ascribed to three chemical states of Ti, namely Ti²⁺/TiO (Ti 2p₁/₂, 455.3 eV; Ti 2p₃/₂, 461.5 eV), Ti³⁺/Ti₂O₃ (Ti 2p₁/₂, 457 eV; Ti 2p₃/₂, 463.1 eV), and Ti⁴⁺/TiO₂ (Ti 2p₁/₂, 459.3 eV; Ti 2p₃/₂, 464.8 eV) exist.36,37 After 60 min of sputtering, peaks form pure Ti (Ti 2p₁/₂, 454.5 eV; Ti 2p₃/₂, 454.5 eV; Ti 2p₃/₂, 460.5 eV) appear. The XPS results indicate that the top of the hydrothermally treated NTAs may be composed of SrTiO₃ and the rest consists of mainly TiOₓ-NTAs and SrTiO₃ nanoparticles, which can be further converted into crystallized heterojunction SrTiO₃/TiO₂ by annealing at 450°C for
3 h in air, as suggested by the XRD results in Fig. 4(e). Elemental depth profiles and Ti 2p fine spectra of the as-anodized amorphous NTAs are also presented for comparison (Figs. 5(b) and (d)). The surface of the NTAs contains a high content of O (about 68 at.%) and the Ti 2p signal can be attributed to Ti\(^{4+}/\)TiO\(_2\) (Ti 2p\(_{1/2}\), 459.3 eV; Ti 2p\(_{3/2}\), 464.8 eV). After sputtering for 3 min at a sputtering rate of about 20.6 nm/min, the Ti and O signals are stable with the atomic content being about 42% and 58%, respectively. The Ti 2p peaks that correspond to Ti\(^{2+/3+}/\)TiO\(_2\) and Ti\(^{2+/3+}/\)Ti\(_2\)O\(_3\) can also be identified (Fig. 5(d)), suggesting incomplete oxidization during anodization of the Ti foil. As a result, the anodized NTs are composed of not only TiO\(_2\) but also other forms of titanium oxide such as TiO and Ti\(_2\)O\(_3\). The large amounts of Ti\(_2\)O\(_3\) and TiO render the anodized NT amorphous. These amorphous suboxides can further be transformed into anatase TiO\(_2\) by annealing in air at 450°C for 3 h (Fig. 2(a)).

The perovskite-type SrTiO\(_3\) is similar to the amorphous TiO\(_2\) comprising corner-sheared TiO\(_6\) octahedrons in structure. The formation of perovskite SrTiO\(_3\) by the TiO\(_2\) precursor in the alkaline solution is proposed to be due to a dissolution and precipitation mechanism that involves the dissolution of titanium oxide followed by nucleation and growth of the perovskite SrTiO\(_3\) crystal.\(^{26,38,39}\) In our experiments, the TiO\(_2\) species on the inner wall of the as-anodized NTs first dissolves in the alkaline solution to form [Ti(OH)\(_6\)]\(^{2-}\) and then reacts with Sr\(^{2+}\) to form SrTiO\(_3\) that precipitates onto the remaining NT wall. As the reaction proceeds, the generated SrTiO\(_3\) nanoparticles accumulate in the NT wall forming the SrTiO\(_3\) nanoparticle layer. Finally, the heterojunction SrTiO\(_3\)/TiO\(_2\)-NTAs are produced.
The reduced tube inner diameter and enlarged wall thickness of the SrTiO$_3$/TiO$_2$-NTAs are due to the volume expansion during the conversion of TiO$_2$ into SrTiO$_3$. The Sr concentration decrease with depth is attributed to the decreased Sr$^{2+}$ and OH$^-$ concentration along the NT. Owing to the small diameter of the NTs, transportation or diffusion of Sr$^{2+}$ and OH$^-$ to the reaction sites of the NTs away from the mouth is more difficult, resulting in decreasing concentration grades along the NT. Hence, the heterojunction SrTiO$_3$/TiO$_2$-NTAs have gradually decreasing Sr concentrations with the NT depth as revealed by the XPS depth profiles. In other words, the layer containing the SrTiO$_3$ nanoparticles has decreased thickness along the depth. On the other hand, the hydrothermal reaction time has an important influence on the wall thickness of SrTiO$_3$/TiO$_2$-NTAs, as suggested by Figs. 4(a)–(d). As the reaction proceeds, more SrTiO$_3$ is formed and the thickness of SrTiO$_3$ layer in the SrTiO$_3$/TiO$_2$-NTAs increases. The transformation of TiO$_2$-NTAs into heterojunction SrTiO$_3$/TiO$_2$-NTAs during the hydrothermal reaction is schematically illustrated in Fig. 6.

The PC activities of the SrTiO$_3$/TiO$_2$-NTAs prepared for different hydrothermal time are evaluated using MB in an aqueous solution as the probing molecule. The 6.2-μm-long SrTiO$_3$/TiO$_2$-NTAs are selected because this length is shown to have the highest PC activity in our study. Figure 7(a) plots the photodegradation fraction of the MB versus the UV illumination time in the presence of the photocatalysts of SrTiO$_3$/TiO$_2$-NTAs. It can be clearly observed that SrTiO$_3$/TiO$_2$-NTAs prepared by hydrothermally reacting for 0.5 and 1 h exhibit enhanced PC activity. However, if the hydrothermal reaction time is further extended to 3–6 h, the PC photodegradation rate diminishes instead, and even becomes smaller than that of the TiO$_2$-NTAs. The photodegradation of MB on SrTiO$_3$/TiO$_2$-NTAs obeys the first-order reaction kinetics and the estimated $k$ values are listed in Fig. 7(b). The $k$ value of SrTiO$_3$/TiO$_2$-NTAs hydrothermally treated for 1 h is about twice that of TiO$_2$-NTAs confirming the enhanced PC properties.

The PC experiments suggest that the SrTiO$_3$/TiO$_2$-NTAs have fluctuating PC activity with hydrothermal reaction time and the SrTiO$_3$/TiO$_2$-NTAs hydrothermally treated for 1 h have the highest PC activity. PC degradation of MB on a photocatalyst is an interface reaction. The photogenerated $e^-$ and $h^+$ under UV irradiation either recombine inside the photocatalyst or diffuse to its surface. Depending upon the type of dye, positively charged $h^+$ can oxidize the organic molecules or react with OH$^-$ or water to form hydroxyl radicals, HO$^*$. Negatively charged $e^-$ in the conduction band (CB) reduces dissolved molecular oxygen to create superoxide $^*$O$_2$. Organic molecules such as MB in the solution then react with these oxidizing agents to induce oxidative degradation to inorganic compounds of CO$_2$ and H$_2$O$^{40}$ In order to achieve maximum degradation efficiency, rapid charge separation is desired besides adequate band-edge positions and a large active surface area. The principle of PC decomposition of pollutants via heterojunction SrTiO$_3$/TiO$_2$ photocatalyst is illustrated in Fig. 8. Under UV
irradiation, the photogenerated $e^-$ can transfer from the CB of SrTiO$_3$ to the CB of TiO$_2$, and conversely $h^+$ transfer from the valence band (VB) of TiO$_2$ to VB of SrTiO$_3$ because the SrTiO$_3$ has a slightly higher flatband potential although they have similar electronic structure and band gap. This high interfacial charge transfer and separation ability enhances the redox reaction of the absorbed MB. Hence, the elevated PC activity of coupled SrTiO$_3$/TiO$_2$ nanocomposites can be ascribed to the enhanced charge separation derived from the coupling effect in the TiO$_2$ and SrTiO$_3$ nanocomposite. However, if the SrTiO$_3$ nanoparticle layer is too thick (long hydrothermal reaction time), the photogenerated carriers accumulated in the TiO$_2$ underlayer may not be able to participate in the PC reactions. Thus, the corresponding quantum efficiency may be lower and the PC activity diminishes. Therefore, The PC activity of the SrTiO$_3$/TiO$_2$-NTAs exhibits a decreasing trend with reaction time after 1-h reaction as indicated by Fig. 7. For the 0.5-h sample, the SrTiO$_3$ content is too small, and hence no diffraction peaks related to SrTiO$_3$ can be observed from the XRD pattern (Fig. 4(e)). Thus, the synergistic effect rendered by SrTiO$_3$ and TiO$_2$ in this sample is not clear and a lower PC activity in comparison with the 1-h SrTiO$_3$/TiO$_2$-NTAs is observed, although the PC activity is still better than that of the corresponding TiO$_2$-NTAs.

**IV. Conclusion**

Anatase TiO$_2$-NTAs with different lengths are fabricated on Ti substrates by electrochemical anodization and subsequent thermal annealing. The effect of the length of the NTAs on the PC activity is evaluated. The PC activity increases initially and then decreases with length and the optimum length that yields the highest PC activity is 6.2 μm for TiO$_2$-NTAs with a diameter of 90 nm and a wall thickness of 10 nm. The anodized TiO$_2$-NTAs constitute a good template or precursor to prepare hetero-junction SrTiO$_3$/TiO$_2$-NTAs consisting of TiO$_2$-NTAs and a self-assembled SrTiO$_3$ nanoparticle layer by a hydrothermal reaction in Sr(OH)$_2$ solution. The SrTiO$_3$/TiO$_2$ heterostructures retain the morphology of the highly ordered NTAs although they have thicker walls compared with the TiO$_2$-NTAs. The SrTiO$_3$ is distributed along the entire NT length but has a decreasing concentration with depth. The formation mechanism of SrTiO$_3$/TiO$_2$ is proposed. The SrTiO$_3$/TiO$_2$-NTAs exhibit enhanced PC activity due to the synergistic effects rendered by the SrTiO$_3$/TiO$_2$ nanocomposites. The enhanced charge separation in the SrTiO$_3$/TiO$_2$ nanocomposite photocatalyst stems from the difference in the potentials of the CB and VB of the SrTiO$_3$ and TiO$_2$. However, if the SrTiO$_3$ nanoparticle layer is too thick (i.e., reaction time being too long), the quantum efficiency diminishes. Consequently, reduced PC activity is observed because the photogenerated carrier accumulated in the TiO$_2$ underlayer may not be able to participate in the PC reactions. The results reported here enable a better understanding of the PC mechanism of heteroconjugation semiconductor photocatalysts and may expedite the applications of ABO$_3$-NTAs such as SrTiO$_3$, BaTiO$_3$, and CaTiO$_3$-NTAs to photocatalysis.

**References**


