Journal of Solid State Electrochemistry (2023) 27:2289–2307
https://doi.org/10.1007/s10008-023-05538-2

REVIEW PAPER

A review on TiO_2 nanotubes: synthesis strategies, modifications, and applications

O. Zakir[1,2] · A. Ait-Karra[1] · R. Idouhli[1] · M. Khadiri[1] · B. Dikici[3] · A. Aityoub[1] · A. Abouelfida[1] · A. Outzourhit[2]

Received: 7 November 2022 / Revised: 11 May 2023 / Accepted: 12 May 2023 / Published online: 2 June 2023

Abstract
In the field of nanotechnology, titanium dioxide nanotubes (TiO_2 NTs) are one of the most valued inventions. They were discovered in 1996, and have since been used in several fields including photocatalytic degradation of pollutants, hydrogen production, and dye-sensitized solar cells. This review provides a comprehensive overview of TiO_2 NTs and their synthesis methods, highlighting recent progress and modifications that improve their properties. The influence of anodization parameters, the effect of annealing temperature, and modified TiO_2 NT arrays, including doping and heterostructure were discussed also in detail. In addition, this article summarizes some of the recent advances in the applications of TiO_2 nanotubes in photocatalysis, hydrogen production, dye-sensitized solar cells (DSSC), and the detection of heavy metal ions. Finally, the existing problems and further prospects of this renascent and rapidly developing field are also briefly addressed.

Keywords Electrochemical anodization · Doped nanotubes · Modified TiO_2 · Nanostructures · TiO_2 Nanotubes

Introduction

Nanotechnology has opened up new opportunities to design and develop materials with unique properties and applications. Recently, those materials have played an important role in new technologies to attain high-performance devices for various applications. The geometry, shape, and morphology of the used nanomaterials significantly determine the performance of these devices. Transition metal oxide nanomaterials such as titanium dioxide (TiO_2) [1–3] zinc oxide (ZnO) [4, 5], tungsten trioxide (WO_3) [6, 7], ferric oxide (Fe_2O_3) [8, 9], and copper/cuprous oxides (CuO/Cu_2O) [10] have extensively been investigated for various applications.

✉ O. Zakir
othmane.zakir@gmail.com

1 Laboratory of Applied Chemistry and Biomass, Department of Chemistry, Faculty of Science Semlalia, University Cadi Ayyad, BP 2390 Marrakech, Morocco

2 Laboratory of Nanomaterials for Energy and Environment, Department of Physics, Faculty of Science Semlalia, University Cadi Ayyad, BP 2390 Marrakech, Morocco

3 Department of Metallurgical and Materials Engineering, Faculty of Engineering, Ataturk University, 25240 Erzurum, Turkey

Among all transition metal oxides, TiO_2 is the most studied material because it has a wide range of functional properties. Various nanostructures of TiO_2 have been successfully synthesized including; nanowires [11], nanoparticles [12], nanorods [13], nanosheets [14], nanotubes [15], and microspheres [16] (Fig. 1). Nanotube structures have attracted significant research interest due to their high specific surface area, enhanced charge transfer, stability, and remarkable photo-catalytic and photo-electrocatalytic properties. These unique characteristics make them promising candidates for various applications, including but not limited to photo-catalytic [17–20], photo-electrochemical [21–23], water splitting [24–27], solar cells [28, 29], biomedicine [30], etc. The TiO_2-based nanotubes were first reported in 1996 by Hoyer using the template-assisted method [31].

To achieve the desired properties and characteristics of TiO_2 nanotubes, the synthesis method plays a critical role. Thus, several techniques have attracted considerable attention to synthesize the TiO_2 nanotubes and ameliorate their proprieties. The most used technics to elaborate TiO_2 nanotubes are the template-assisted method [32, 33], sol-gel process [34, 35], electrochemical anodization of titanium (Ti) [36–46], and the hydrothermal method [47]. Each technique has its own advantages and limitations. Therefore, it is essential to have a good understanding of the different methods and their influencing factors to obtain the desired nanotube structure.

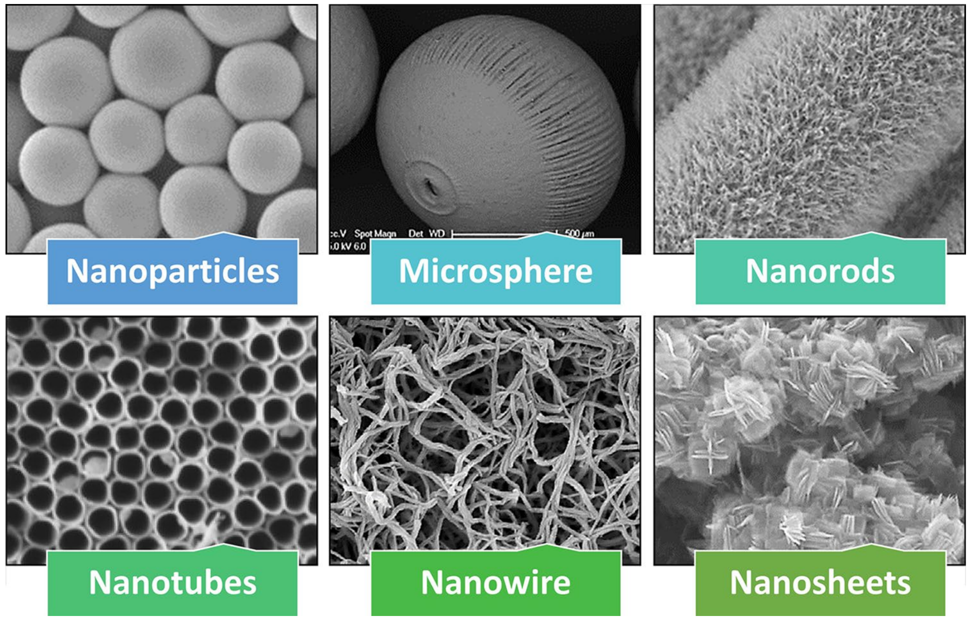

Fig. 1 Different nanostructures of TiO_2 (Derivated from refs. [11–16])

The fundamental principles of anodized TiO_2 nanotubes were proposed in 1999 and 2001 by Zwilling et al. [48, 49] and Gong et al. [50], respectively. Since then, several studies focused on the determination of the optimal experimental conditions have been performed to efficiently obtain high-quality TiO_2, such as smooth and high-aspect-ratio nanotubes [51], highly ordered nanotubes by multistep anodization [52], tapered and conical-shaped nanotubes [53], free-standing and open-ended nanotubes [54, 55], and transparent nanotubes [56]. Despite these efforts, the wide band gap (> 3 eV) and the recombination of photo-generated charges are major disadvantages of TiO_2. Several attempts to activate TiO_2 under visible light have been investigated. Many studies have reported that the absorption capacity of TiO_2 can be increased from UV to visible range by doping or coupling the TiO_2 with other semiconductors [57–60].

This review provides an analysis of the recent developments in TiO_2 NTs synthesis methods and modifications that enhance their performance. Besides, the review aims to provide an overall understanding of the current state of the art, the novelty, and the future perspectives of TiO_2 NTs, which can inspire further research and development of these materials for various practical applications.

Synthesis of TiO_2 nanotubes

The synthesis of TiO_2 nanotubes has been the subject of extensive research over the past few decades. Several methods have been developed to fabricate these nanotubes up to now, as shown in Fig. 2. The first method developed was the template-assisted method in 1996, followed by the sol-gel method in 1998, the hydrothermal method in 1999, and the currently used electrochemical anodization method performed in 2001 [61, 62].

Each of these methods has its advantages and disadvantages, and the choice of method depends on the specific application and desired properties of the nanotubes. In the following sections, details of the methods used to synthesize TiO_2 nanotubes and the parameters that influence their growth and properties were discussed.

Template-assisted method

Template-assisted synthesis is an easy, cost-effective approach to fabricating TiO_2 nanotubes. Porous materials, usually anodic aluminum oxide, were used as a template,

Fig. 2 The chronology of fabrication methods for TiO_2 nanotubes

and TiO_2 layers were deposited on their bottom. Firstly, the template surface is covered with a thin layer of gold, then the pores of the treated aluminum oxide are entirely filled with a poly(methyl)methacrylate polymer. Finally, the polymeric block is separated from the Al_2O_3 mold and used as the secondary template for the growth of the TiO_2 nanotube arrays. After the deposition of TiO_2, the second template is removed to obtain the TiO_2 nanotubes. A template-assisted method is a mainly used technic to synthesize the TiO_2 nanotube arrays. Michailowski et al. [33] synthesized a TiO_2 nanotube material via an impregnation-decomposition of titanium (IV) isopropoxide to TiO_2 at 500 °C using anodic Al_2O_3 as a template. Additionally, Yuan et al. [63] revealed the synthesis of TiO_2 nanotubes by template-based $Ti(OC_4H_9)_4$ hydrolysis process using an anodic Al_2O_3 membrane as a template between H_2O and the $Ti(OC_4H_9)_4$ solution. Similar results are reported by immerging anodic Al_2O_3 in an aqueous $(NH_4)_2TiF_6$ solution [64]. Liang et al. showed the synthesis of TiO_2 nanotubes by deposing the $TiCl_4$ on anodic Al_2O_3 using atomic layer deposition [65]. Liu et al. [66, 67] have produced a very innovative class of TiO_2 photonic crystals functionalized nanoporous anodic alumina broadband-distributed Bragg reflectors for visible-light-driven photocatalysis.

Sol-gel method

The sol-gel method has been widely used to produce TiO_2 materials of high purity and homogeneity. In this method, a titanium precursor undergoes hydrolysis/condensation to form a sol, which then transforms into a gel. The solvent is then evaporated, and a xerogel is obtained. The xerogel is further processed through milling and heat treatment to produce highly crystalline TiO_2.

To produce highly ordered TiO_2 nanotubes, the sol-gel method is usually combined with another process, such as the hydrothermal or the template-assisted method. For instance, Pang et al. [68] have successfully obtained TiO_2 nanotubes via the sol-gel process in conjunction with the hydrothermal method to degrade Rhodamine B in an aqueous solution. Similarly, Liu et al. [69] used the nanorods of ZnO as a template to elaborate TiO_2 nanotube arrays by the sol-gel process. The combination of the sol-gel method with other techniques has provided an effective means of producing highly ordered and functional TiO_2 nanotubes for various applications.

Hydrothermal method

Hydrothermal treatment has received wider attention because it gave pure TiO_2 nanotubes with a high crystallinity [70]. It consisted of mixing titanium dioxide powder and highly concentrated sodium hydroxide solution at a temperature below 150 °C and under high pressure using a Teflon-sealed autoclave [71, 72]. Using this method, the properties of the formed TiO_2 nanotubes depend on many parameters, such as the starting materials [73], hydrothermal temperature [74], and post-treatment [75]. Xu et al. [76] obtained TiO_2 nanotubes with a diameter of about 10 nm using the hydrothermal process at 110 °C after approximately 20 h. In another study, Dong et al. [77] successfully produced TiO_2 nanotubes with multilayered sheets and an outer diameter varying from 10 to 15 nm. Tsai and Teng [78] investigated the role of post-treatment acidity on the properties of TiO_2 nanotubes. It is found that with the increase in acidity, the TiO_2 layer transformed into nanotubes and eventually into the anatase phase during the post-treatment acid wash. In addition, it was reported that the main factor in the formation of the nanotubes is the acid-washing process [35, 79, 80]. Nevertheless, other researchers concluded that acid washing does not affect the properties of TiO_2 nanotubes [81]. Tsai and Teng postulated that the contradiction observed between these studies is due to the synthesis conditions such as the time and temperature of NaOH treatment [78].

Anodization: an electrochemical synthesis strategy

Recently, the electrochemical technique has been the commonly used method to elaborate TiO_2 nanotube layers. This method has many advantages, such as good mechanical adhesion strength and high electronic conductivity since the layer grows directly on the titanium metal substrate [82]. This method offers easy control of the thickness and morphology of the TiO_2 by adjusting the anodization parameters such as applied voltage, anodization time, electrolyte composition, and the temperature of the solution. The anodization method can obtain a layer of TiO_2 nanotubular with a controlled and uniform diameter. It has been demonstrated that different morphologies of TiO_2 can be obtained depending on the anodization parameters (Fig. 3). Compact TiO_2 films are generally obtained in fluoride-free electrolytes, whereas nanoporous/nanotubular films can be prepared in electrolytes containing fluoride ions [83, 84]. Using the anodization method, Kulkarni et al. successfully obtained thick and adherent TiO_2 nanotubes on the titanium surface. They showed that the thickness and diameter of the nanotubes depend on the anodization time and applied voltage [85]. However, Jankulovska et al. [86] successfully fabricated TiO_2 nanotubes with an internal diameter of 90 nm, an external diameter of 120 nm, and a length of approximately 4 µm. In another study, Ghicov et al. [87] fabricated TiO_2 nanotubes in a fluoride-ion-containing phosphate electrolyte with diameters varied between 40 and 100 nm and lengths between 100 nm and 4 µm.

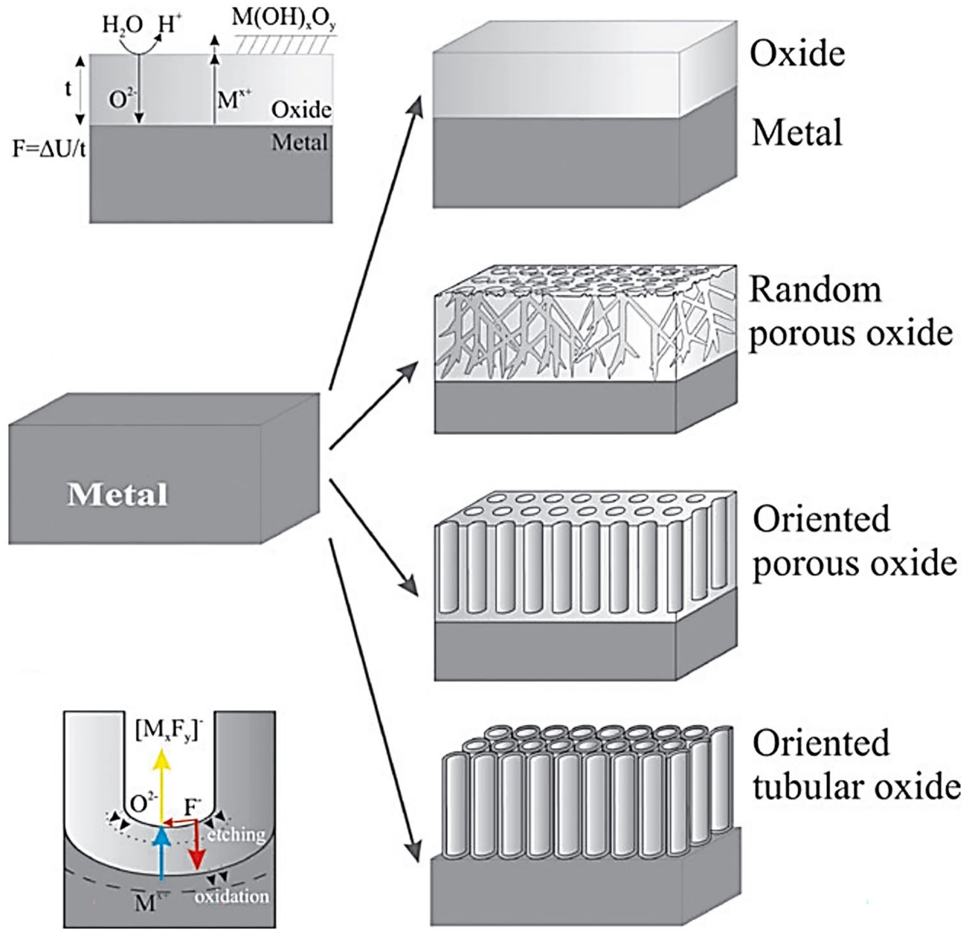

Fig. 3 The schematic illustration of anodization setup (Reprinted with permission from ref. [88], Copyright 1996, Royal Society Of Chemistry)

Among all these methods, electrochemical anodization is the most effective way to produce highly ordered nanotubular TiO_2 films.

Influence of anodization parameters

The anodization method has focused on the formation of TiO_2 nanotubes. All these showed that the synthesis of TiO_2 nanotubes is strongly influenced by anodization parameters, which have a significant impact on their morphology, composition, and structure. The ability to control these parameters has been a major focus of research to achieve desirable properties and performance of TiO_2 nanotubes for various applications. In this section, the influence of these parameters on the formation of TiO_2 nanotubes and their properties were reported with recent literature.

Effect of electrolyte composition

The composition and concentration of electrolytes significantly affect the formation of nanotube arrays. Based on the electrolyte we use, the nanotubes are essentially classified into four generations: 1st generation of nanotubes prepared in hydrofluoric acid, which were only 0.5 µm long and characterized as poorly self-organized [50, 89–91]. Second generation of nanotubes up to 5 µm long grown in an aqueous solution containing fluoride ions. 3rd generation of smooth and longer nanotubes, up to 100–1000 µm grown in organic solvents such as ethylene glycol [40, 92–94], glycerol [36, 51, 95–97], dimethyl sulfoxide [98], formamide or diethylene glycol [99], containing fluoride species (NH_4F, NaF, and KF) and small amounts of water. The 4th generation nanotubes and nanopores have been developed in the last few years. A highly ordered hexagonal structure characterizes this generation. Yeonmi and Seonghoon [100] have improved the regular nanopores structure using two-step anodization. Macak et al. [101] developed highly hexagonal TiO_2 nanotubes using a multi-step approach in other studies. Similar results have also been achieved by Albu et al. [102]. They produced the hexagonal self-ordered TiO_2 nanotube of about 250 µm by operating within optimal anodization parameters (F^- concentration, anodizing voltage, and time). Table 1 summarizes the anodization conditions and the characteristics diameter (D), and length (L) of the

Table 1 Evolution of TiO_2 nanotubes from the 1st to 4th generation

	Electrolyte	Anodization conditions	Characteristics of NTs	Ref
1st Generation	- Aqueous solution + 0.5 wt% HF	20 V 20 mins	D = 60 nm L = 250 nm	[50]
2nd Generation	- Aqueous solutions of fluoride salts; (0.5 wt% NaF + 0.5 M H_3PO_4 + 0.5 M Na_2SO_4 + 0.2 M sodium citrate)	20 V 18 h	Organized nanotube D = 110 nm L = 2.6 µm	[103]
3rd Generation	- Glycerol + 1.48 wt% NH_4F	60 V 1 h	Organized nanotube D = 128 nm L = 1.5 µm	[36]
	- Ethylene glycol + 0.3 wt % NH_4F + 2 vol.% H_2O	60 V 18 h	Organized nanotube D = 100 nm L = 45 µm	[104]
	- Glycerol + 0.3 wt% NH_4HF_2	30 V 2 h Annealing (500 °C)	D = 100 nm	[105]
4th Generation	Ethylene glycol + 0.3 wt% NH_4F + 2 vol% H_2O	Pure Ti Two-step anodization 50 V **1st step;** • Freshly electrolyte • 1 h **2nd step;** • Freshly electrolyte • 30 minutes	Hexagonal shape D = 75 nm L = 6 µm	[24]

resulting TiO_2 nanotubes in different generations. Figure 4 shows the morphology of TiO_2 nanotubes depending on the generation.

Effect of applied voltage

The anodic charge is the critical factor controlling film thickness and pore diameter. Several studies showed that the diameter and length of the nanotube vary linearly with the electric charge applied during the anodization process [106–108]. For this reason, the morphology of the nanotube arrays can be predicted by applying the suitable voltage (Fig. 5) [36, 109–111]. The applied voltage usually ranges from 10 to 60 V and 5 to 30 V in organic and aqueous solutions, respectively [112, 113]. At low applied voltage, tubes of a few nanometers in diameter and a few hundred nanometers in length were obtained. At intermediary voltage, the ordered nanotubes are formed. If a higher voltage is applied, the dissolution rate is too high, resulting in high dissolution of the oxide layer and no tube formation could be observed [114]. Zakir et al. [36] reported that the highly ordered nanotubes are formed at 60 V, and the mean inner diameter of TiO_2 nanotubes increased from 59 to 128 nm when the applied voltage was increased from 30 to 60 V. Other studies suggested that the linear relation between the inter-tube distance and anodization voltage is limited to low voltages [115], whereas at higher voltages, the dependence is not linear [116, 117].

On the other hand, the anodization voltage affects the photo-electrochemical and photo-catalytic activity of the TiO_2 nanotubes. Sun et al. [44] investigated the effect of anodization voltage on photo-electrochemical properties and hydrogen production. The hydrogen production rate increased by increasing anodization voltage, and a maximum rate was denoted at 93.6 µmol/h.cm^2 with photo-conversion efficiency of 3.51% for TiO_2 formed at 50 V. Atyaoui et al. [118]. studied the photocatalytic activity of TiO_2 nanotubes arrays on the degradation of Black Amido and shown that the photo-decolorization efficiency of about 100% is achieved after 30 min of irradiation using a nanotube formed at the optimal voltage of about 60 V.

Effect of anodization time

The duration of anodization affects the nanotubes principally in two aspects. Firstly, the formation or not of the nanotube structure, and secondly, the length of the nanotubes [119]. At the beginning of the anodization, a thin and compact TiO_2 film is formed. In this case, if the duration is too short, a disordered porous layer is formed at the substrate surface. In addition, with an increase in the anodization time, porous structures progressively become thicker, converting into the TiO_2 nanotube array [112, 120]. If the duration is sufficient, highly nanotube arrays can be formed [109]. If the other anodization parameters are kept constant, the length of the nanotubes increases over time

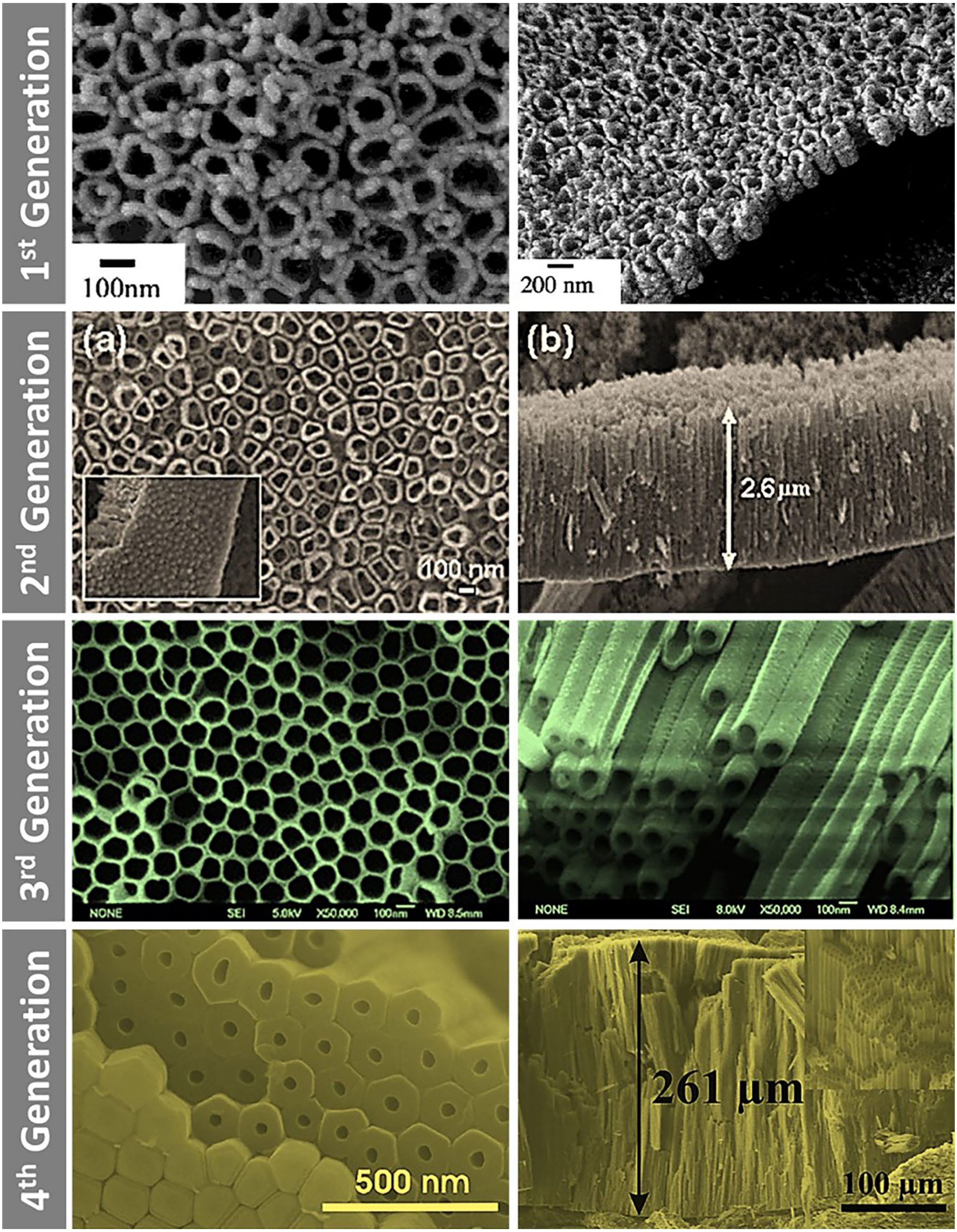

Fig. 4 Evolution of the anodized TiO_2 nanotube from 1st to 4th generation (Derivated from refs. [50, 102–104] with permission from their publishers)

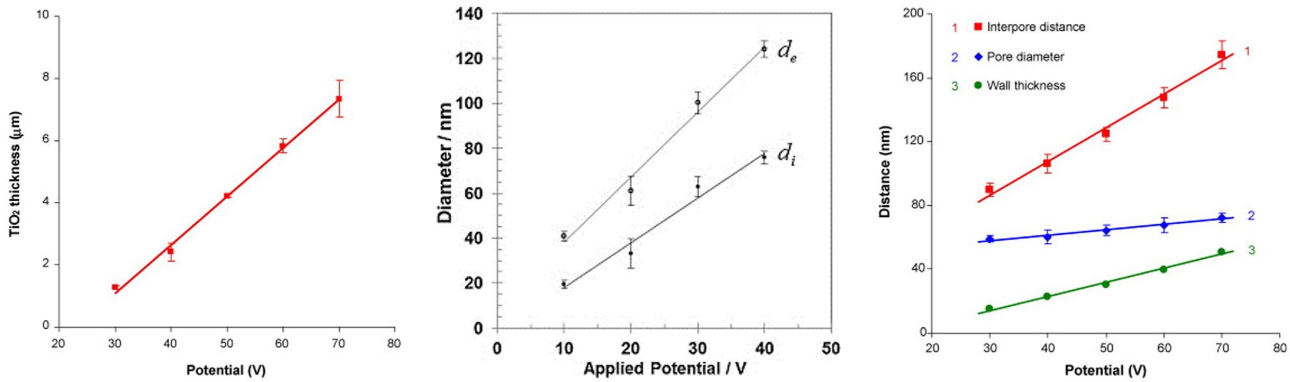

Fig. 5 Linear relationship between the applied voltage and nanotube parameters (Reprinted with permission from refs. [95, 111], Copyright 2010 and 2012, Elsevier)

[88, 109, 121]. However, the growth rate of nanotubes is reduced with anodization time because of the decreasing diffusion rate of $[TiF_6]^{2-}$ within the nanotube [112]. Ghicov et al. [87] also suggested that after reaching a stable condition between nanotube growth at the metal/TiO_2 interface and electrochemical/chemical dissolution at the top of the tube, we will no longer find an increase in nanotube length (Fig. 6a). Macak et al. [101] showed that the wall thickness and inner tube diameter is not a constant along the TiO_2 nanotube and that the inner tube diameter increases from 50 nm at the bottom to 110 nm at the tube top, while the wall thickness decreased from 65 to 12 nm. Bervian et al. [122] have suggested that the anodization duration is less than 30 min, a compact TiO_2 structure will occur and the nanotube structure is not yet formed until reaching 60 min of anodization time, using a mixture of fluorinated glycerol and ethylene glycol electrolyte. The average length of the nanotubes was varied between 650 nm to 6 μm by changing the anodization time from 1 to 3 h. This study also shows that the length of the nanotubes plays a crucial role in the photo-electrochemical water splitting properties of TiO_2 and that the best performance is obtained using nanotubes formed at 120 min. Figure 6b show that the photo-current response increases with anodization duration to reach a maximum for TiO_2 nanotubes formed at 60 min, while the photocurrent response decreased when the anodization duration reached to 120 min. This result was explained by a simple transfer of photo-generated electrons from TiO_2 to the counter electrode in the TiO_2 NTs formed at 60 min.

Effect of electrolyte temperature

The electrolyte temperature affects the growth and quality of TiO_2 nanotube arrays by affecting the oxide growth rate and, consequently, the wall thickness and the length of the nanotubes [28, 45, 123]. Wang and Lin published the first

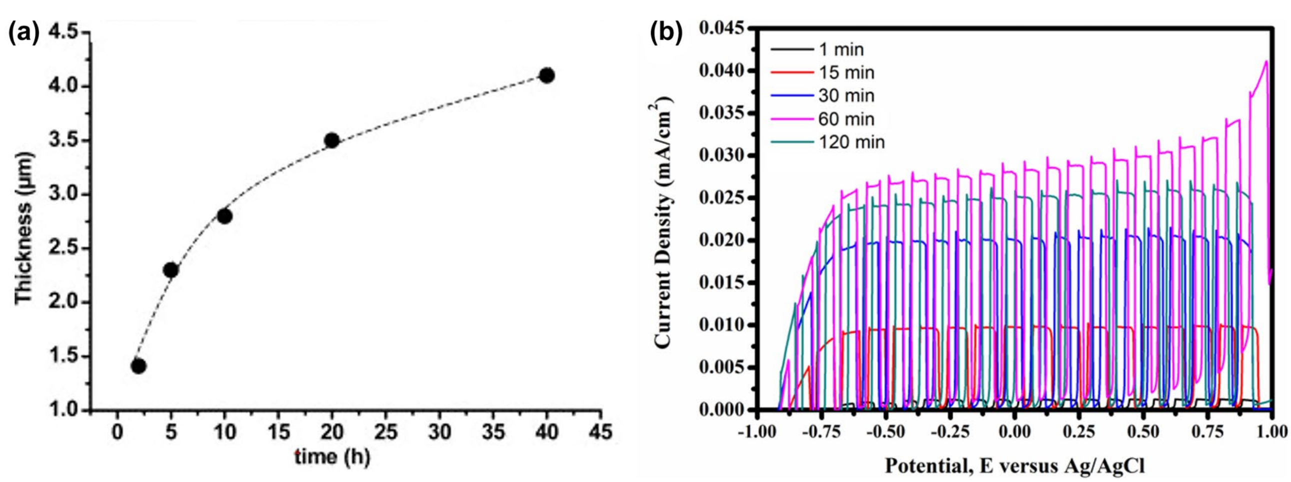

Fig. 6 Evolution of length (**a**) and photo-current responses (**b**) of TiO_2 nanotubes prepared at different anodization duration (Reprinted with permission from ref. [21, 87])

work demonstrating the effect of electrolyte temperature in an aqueous and non-aqueous electrolyte on the anodic TiO_2 properties [91]. In an aqueous electrolyte, a slight decrease in internal diameter was observed with increasing temperature while the external diameters remained unchanged [124]. This can be due to the fact that the etching of TiO_2 induced by the electric field and fluoride ions is similar, while the rate of oxide formation is higher than at low temperatures [91]. Prida et al. suggest that in aqueous solutions, low temperatures inhibit the growth of TiO_2 nanotubes [45]. In organic electrolytes containing fluoride ions, the temperature between 0 and 40 °C is the most range of temperature suitable for the growth of highly ordered TiO_2 nanotubes [125]. In addition, the outer diameter of the nanotubes fabricated in glycerol/NH_4F (0.14 M) electrolyte was significantly increased by increasing the temperature of the electrolyte from 0 °C to 40 °C [126]. These suggestions can be explained by the fact that at low temperatures, the ionic mobility of fluorine in some organic electrolytes is reduced, resulting in a slower dissolution of the formed TiO_2 and, consequently, a smaller nanotube diameter [91].

Effect of fluoride ion (F^-) concentration

The presence of fluorides in the electrolyte affects strongly the anodization process. On one hand, complexation occurs with Ti^{4+} ions that are ejected at the TiO_2/electrolyte interface to form a water-soluble complex $[TiF_6]^{2-}$ and on the other hand by chemical attack of the formed TiO_2 [127–129]. Various studies showed that three different electrochemical characteristics can be obtained depending on the fluoride concentration [88, 95, 130–132]. At low fluoride concentrations, a stable compact oxide layer is formed after anodization [133]. At higher fluoride concentrations, the Ti^{4+} formed immediately reacts with the abundant fluoride to form soluble $[TiF_6]^{2-}$ and no oxide formation can be observed [134]. For the intermediate fluoride concentrations, the growth of the NTs layers is controlled by a competition between the formation of a compact oxide layer and the chemical dissolution of the oxide by F^- ions [135–137].

Effect of water content

In addition to the applied voltage and the anodization time, the water content is another crucial factor in the electrochemical anodization process of titanium because the growth of one-dimensional nanotubes can be accelerated by enhancing the corrosive effect [138]. Water is the source of oxygen to form efficiently TiO_2 during the anodization process, but it is also an essential factor for the formation of tubes rather than pores [139]. The effect of water on oxide formation has been studied by many researchers. Wei et al. [140] suggested that the transition from nanopores to nanotubes is favored by increasing the water content from 0 to 0.7% in NH_4F (0.05 M) -containing ethylene glycol electrolyte at an anodization voltage of 20 V. Yin et al. [141] showed that when the water content is in the range of 4–12%, the TiO_2 NTs are growth with a reasonable rate and that the barrier layer thickness increases while the growth rate decreases with increasing water content in NH_4F (0.25 wt.%)-containing ethylene glycol electrolyte. When the water content is beyond 12%, compact titania is formed.

Effect of annealing temperature

The morphology and crystallinity of the TiO_2 nanotube arrays, as well as their optical and electrical properties, depend on the annealing temperature [142–146]. Varghese et al. [147] published the first comprehensive study demonstrating the effect of annealing temperature on anodized TiO_2 nanotubes, demonstrating that the NTs were stable up to 580 °C when annealed in an oxygen atmosphere. Other previous studies showed that the as-prepared TiO_2 is amorphous and could be transformed to anatase or rutile phase, or mixtures of the phases relying when be annealed on specific temperature [120, 148, 149]. The amorphous character of mesoporous TiO_2 results in low thermal stability and limits their applications. In contrast, the crystallized structures offer enhanced thermal properties and improved electrical, optical, and catalytic properties [150]. Sun et al. [151] showed that at a temperature less than 450 °C, the TiO_2 nanotubes consist of a pure anatase phase, while the rutile phase starts to appear at 550 °C so that a mixture of anatase and rutile phases are detected between 550 °C and 750 °C (Fig. 7a). Recently, Gavrilin et al. [152] studied the influence of thermal treatment in vacuum and air on the structural properties of multi-walled anodic TiO_2 NTs. It was found that the composition of samples annealed in the air was different from those annealed in a vacuum. Talla et al. [153] synthesized TiO_2 NTs and annealed them in different atmospheres, such as air, nitrogen, oxygen, and vacuum at 450 °C. They reported that the atmosphere affected the phase composition of TiO_2 and that the transformation from the anatase into rutile is retarded in a vacuum and the anatase phase remained the dominant phase even at 800 °C.

Tighineanu et al. [154] have investigated the effect of annealing treatment on the conductivity of anodic TiO_2 nanotube arrays. This study demonstrates that the resistance of the TiO_2 layer decreases when the amorphous nanotube arrays are converted into the anatase phase at about 350–450 °C. Similar results are found by Bakri et al. [155], who show that the resistivity decreases from 1.40×10^5 to 7.19×10^2 Ω·cm by varying the annealing

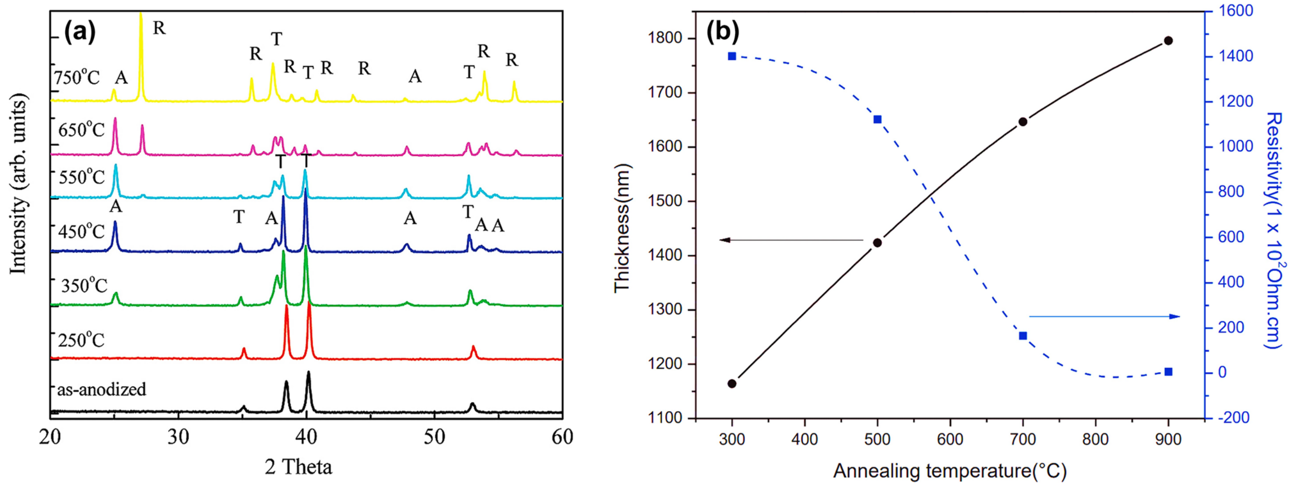

Fig. 7 Evolution of phase composition, thickness, and resistivity of TiO_2 after annealing at indicated temperatures (Reprinted with permission from refs. [151, 155], Copyright 2011 and 2017, American Chemical Society and AIP Publishing)

temperature between 300 and 900 °C (Fig. 7b). Zhao et al. [156] show that the extinction coefficient and the refractive index increase with the increase in the annealing temperature. This study also shows that the anatase is the dominant phase until the temperature lower than 900 °C above the rutile phase becomes the dominant crystal phase.

Modified TiO_2 nanotube arrays

Despite its excellent physical and chemical properties, the higher band gap of TiO_2 makes this material almost inactive under visible light (Fig. 8a). In this regard, several studies have been made to: firstly broaden the absorption of TiO_2

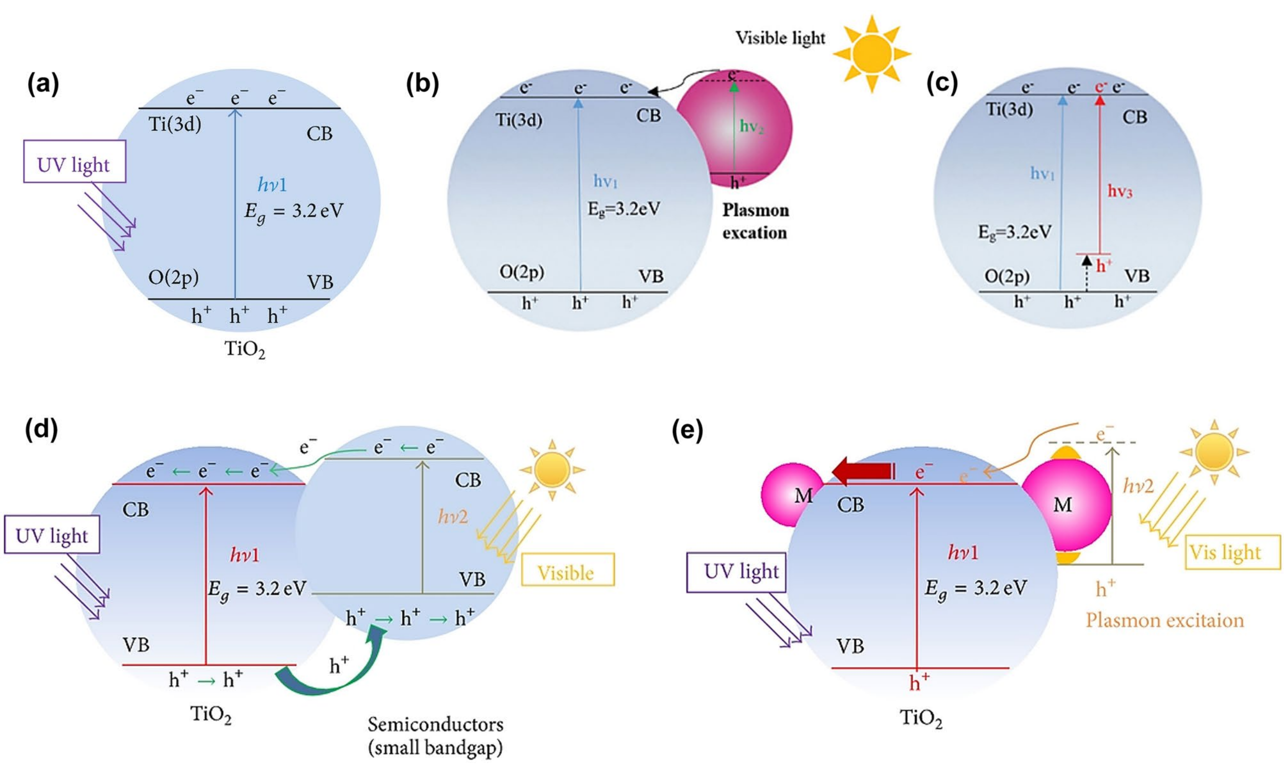

Fig. 8 Schematic of energy level and electron/hole separation of pure TiO_2 (**a**), doping with metal (**b**), non-metal (**c**), coupling with semiconductors (**d**), and noble metals (**e**) (Reprinted with permission from refs. [157, 158], Copyright 2013 and 2012, Hindawi and De Gruyder)

in the visible wavelength range and more efficient charge transfer by modifying its optical and electronic properties, and secondly to promote the separation between the electrons and holes photo-generated and inhibit their recombination. To achieve these objectives, different approaches are proposed such as; firstly, doping of TiO_2 with metal ions (Co^{2+}, Fe^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, etc.) or non-metallic (C, S, N, P, etc.) is one of the typical approaches that have been widely applied (Fig. 8b, c). Or coupling the TiO_2 with a semiconductor material with a narrow band gap (Fig. 8d). The decoration of TiO_2 with different noble metals (Ag, Pt, Au, Pd, etc.) represents another approach (Fig. 8e). In the below subsections, some of the modifications were made to TiO_2 nanotube arrays, including doping and heterostructure formation. These modifications have shown promising results in improving the properties and expanding the applications of TiO_2 nanotubes.

Doping

Asahi et al. [159] reported for the first time the doping of TiO_2 with nitrogen by sputtering in a nitrogen-containing gas mixture and showed that N-doped TiO_2 exhibits photo-electrochemical activity under visible light irradiation. Recently, other doping species, such as several non-metals such as fluorine [160–162], carbon [163, 164], phosphor [165, 166], sulfur [167–169], and boron [170, 171] have been inserted into TiO_2 using different methods. These studies show that the visible-light activities of doped TiO_2 were not only influenced by the value of the energy gap, the distribution of impurity level, and the property of impurity levels but were also affected by the location of Fermi level and the energy in the edges of the band gap [172, 173]. It was found that doping TiO_2 nanotubes with nitrogen received significant attention because of their improved charge transfer properties. Different approaches have been published concerning the doping of TiO_2, including the annealing of TiO_2 in gaseous atmospheres [174], sputtering [175], sol-gel [176], and anodization of titanium alloys [177]. Among these methods, heat treatment of TiO_2 in gaseous atmospheres of the dopant species is considered an easy one-step doping technique [174, 178]. Moreover, the surface of doped nanotubes exhibits significant photo-response in the visible range compared to undoped nanotubes. On the other hand, TiO_2 doped with transition metal ions (Cu [179–181], Cr [182], Ni [183, 184], Zn [185, 186], Ag [181], Co [187], Zr [188], and Fe [22, 187]) has also been reported to broaden the visible light absorption range, and improve the conversion efficiency by extending the lifetime of photo-generated electrons and holes. Choi et al. [189] studied the photoreactivity of quantum-sized TiO_2 doped with metal ions. Doping with Fe, Mo, Ru, Os, Re, V, and Rh significantly increased the photo-reactivity efficiency of TiO_2 nanotubes, while doping with Co and Al ions decreased the photoreactivity. In other studies, Momeni and Ghayeb [190] obtained Fe-TiO_2 nanotube composites using iron (potassium ferricyanide) to decorate anodic TiO_2 nanotubes. They indicated that Fe doping accelerates the photocatalytic performance of TiO_2 nanotubes for water splitting.

Heterostructure

In recent years, many attempts have been made to extend the light absorption range of TiO_2 nanotubes and reduce the charge carrier recombination, such as the formation of hetero-junctions between TiO_2 nanotubes and narrow band gap semiconductors [191]. In 1986, Gerischer and Lübke fabricated the TiO_2 photo-electrodes sensitized by thin deposit CdS semiconductor [192]. Recently, this approach is improved, and other semiconductors are used CdSe [193, 194], Cu_2O [195, 196], ZnO [197], WO_3 [198], and BiOI [199]. Indeed, all these semiconductors can absorb part of the visible light. One of the following schemes to elaborate the p-n heterojunction for highly efficient photo-electrocatalytic devices is the direct deposition of p-type semiconductors on TiO_2 nanotubes [196, 199]. Wang et al. [200] deposed p-type Cu_2O on n-type TiO_2 nanotube arrays to fabricate Cu_2O/TiO_2 p-n heterojunction photo-electrodes using ultrasonic-assisted sequential chemical bath deposition. This study shows that the Cu_2O/TiO_2 p-n photo-electrodes exhibited higher photoconversion capacity and higher photo-electrocatalytic activity in the degradation of rhodamine B compared to single TiO_2 nanotubes. This result was explained by the efficient separation of photo-generated electrons and holes. Similar results have also been achieved by Davaslıoğlu et al. [198] using WO_3/TiO_2 p-n heterojunction photo-electrodes prepared by electrochemical deposition of WO_3 on the TiO_2 nanotubes array by subsequent cycling the potential between -0.6 –1.0 V vs Ag/AgCl. However, the major disadvantage of this approach is that many narrow bandgap semiconductors are not stable, not only due to corrosion or photo-corrosion but also due to the instability of some of the materials under applied voltage.

Applications of TiO_2 nanotubes

TiO_2 nanotubes have attracted considerable attention due to their applications in photo-catalysis, water splitting, photovoltaic cells (solar cells), and other aspects.

This TiO_2 nanotube is a promising material for these applications due to its multifunctional semiconductor properties which are based on its excellent physical and chemical behavior, high specific surface area, and fast charge transfer [201].

Photocatalysis

Today, one of the most useful applications of TiO_2 is the photocatalytic degradation of toxic pollutants water contains [83, 202, 203]. It has been shown that TiO_2 nanotube layers can be more efficient photo-catalysts than comparable nanoparticle layers. After Fujishima and Honda demonstrated, for the first time, the photo-electrochemical decomposition of water on TiO_2 surfaces [204, 205]. TiO_2 has been investigated for applications in heterogeneous catalysis [206, 207]. On the other hand, TiO_2 has been used to convert carbon dioxide (CO_2) into energy-intensive hydrocarbon compounds [208, 209]. Savchuk et al. [210] are studied the efficient conversion of CO_2 in the gas phase to methane and methanol on the surface of TiO_2-Cu_xO NTs. In another study, Park et al. [211] successfully reduced the CO_2 to methane by photocatalysis using Cu_xO-TiO_2 hybrid heterostructures under solar irradiation. The basic mechanisms of the photo-catalytic process can be explained as follows:

When the TiO_2 is excited by UV light, the electrons of the valence band (VB) will move to the conduction band (CB). Then the holes and electrons photo-generated (Eq. 1) will be transported to the TiO_2/solution interface and react with the adsorbed molecules. The photo-generated e^-_{CB} could reduce the dye (Eq. 2) or react with electron acceptors such as adsorbed O_2 on the TiO_2 surface or dissolved in water, reducing it to the superoxide radical anion $O_2^{\bullet-}$ (Eq. 3). On the other hand, the photo-generated h^+_{VB} can oxidize the organic dye (Eq. 4), or react with H_2O (Eq. 5) or OH^- (Eq. 6) to form $OH^\bullet$ radicals. The resulting $OH^\bullet$ radical, being a very strong oxidizing agent, can oxidize most of the molecule dyes to the mineral end-products (Eq. 7) [14, 212–217].

$$TiO_2 + h\upsilon \rightarrow TiO_2\,(e^-_{CB} + h^+_{VB}) \quad (1)$$

$$Dye\ +\ e^-_{CB} \rightarrow \text{Reduction products} \quad (2)$$

$$TiO_2(e^-_{CB}) + O_2 \rightarrow TiO_2 + O_2^{\bullet-} \quad (3)$$

$$Dye + h^+_{VB} \rightarrow \text{Oxidation products} \quad (4)$$

$$TiO_2(h^+_{VB}) + H_2O \rightarrow TiO_2 + H^+ + OH^\bullet \quad (5)$$

$$TiO_2(h^+_{VB}) + OH^- \rightarrow TiO_2 + OH^\bullet \quad (6)$$

$$Dye + OH^\bullet \rightarrow \text{Degradation} \quad (7)$$

Hydrogen production

Today, hydrogen energy is expected as a new clean energy source. In this regard, various technologies are proposed to produce hydrogen, but only some of them can be considered environmentally friendly. Recently, solar hydrogen produced by photo-catalytic water splitting has attracted considerable attention and has been widely studied due to its great potential for low-cost clean hydrogen production [218]. For this purpose, low-dimensional semiconductor nanostructures are recently developed and applied to solar energy conversion fields [219–221]. The photocatalytic hydrogen production from water, alcohols, or organic pollutants with wide-gap semiconductors has been intensely studied [222]. TiO_2 nanotubes have been intensively studied as photoanodes in photo-electrochemical cells for hydrogen production due to their semiconductor properties, physical and chemical stability, abundance, and low cost [223, 224]. Theoretically, for efficient hydrogen production from water by photo-catalysis, the CB level should be negative than the hydrogen production level ($E(H_2O/H_2)$) while the VB should be positive than the water oxidation level ($E(O_2/H_2O)$) [225]. Recent studies show that the hydrogen production rate is highly dependent on the electrolyte, light intensity, external polarization, and the morphology and structure of TiO_2 [158]. Therefore, optimizing these parameters and fundamentally understanding their possible correlations is important to clarify approaches to constructing a highly efficient cell for hydrogen production. Hattori et al. [226] have successfully produced hydrogen from the photo-decomposition of ethanol using TiO_2 nanotubes. Moreover, they found that the length of the nanotubes is the most important factor in this process. They showed that the amount of hydrogen produced increases with the increase in the length of the nanotube. Mor et al. [227] found a hydrogen generation rate of 960 μmolcm^{-2} h^{-1} by using highly ordered TiO_2 nanotubes arrays of about 224 nm in length and 22 nm in diameter for water splitting under a constant voltage of -0.4 V. Recently, Li et al. [228] reported an enhanced hydrogen generation rate of 3.507 mmol h^{-1} g^{-1} under simulated solar light by a mesoporous-structured anatase TiO_2.

Solar cells applications

The TiO_2 nanotubes are one of the most promising materials for dye-sensitized solar cells (DSSCs) due to their improved charge-collection efficiency and enhanced separation of photo-generated electrons/holes [229–232]. For this reason, the ordered TiO_2 nanotubes significantly increase solar energy's conversion efficiency [233]. The DSSC consists of a layer of TiO_2 nanotubes deposited on a conductive substrate, a counter electrode (Pt), an adsorbed dye as a sensitizer, and an electrolyte. On the TiO_2 surface, adsorbed is a dye that serves as a light absorber and is attached to the TiO_2 surface by specific functional groups. For the choice of the dye molecule, the LUMO of the dye must be energetically placed slightly higher than the CB of TiO_2. Under solar irradiation, HOMO–LUMO transitions occur in the dye. Excited electrons can then be injected from the LUMO (of the Dye) into the CB of the TiO_2 electrode [158]. However, the overall power conversion efficiency of the dye-sensitized TiO_2 nanotubes solar cells remained relatively low. Paulose et al. [234] found a conversion efficiency of about 4.24% using highly-ordered TiO_2 nanotube films sensitized by a monolayer of N719 under AM 1.5 sunlight source. These results can be explained by the incomplete coverage of the dye molecules on the TiO_2 nanotubes and insufficient electrolyte infiltration into the nanotubes [235, 236]. In another study, Mor et al. [56] compared the photo-conversion of anodic TiO_2 nanotubes formed on titanium substrate and nanotubes formed on FTO glass. They found that solar cells fabricated with nanotubes formed on the titanium surface have higher charge transfer efficiency and dye absorption than solar cells fabricated with nanotubes formed on FTO glass. Tsvetkov et al. [34] compared the photoconversion of the pure and Nb-doped TiO_2 nanotubes and nanoparticles. They found that the doping of TiO_2 nanostructures leads to an additional about 14% in CPE and that DSSCs based on Nb-doped TiO_2 NTs have an efficiency of 8.1%, which is 35% higher than that of a cell using TiO_2 nanoparticles. An open-ended TiO_2 NT ordering by anodization of titanium for the application of PE of DSSCs was prepared by Zhu et al. [237] The device obtained by using this material showed a PCE of 7.7%. In another study, Peighambardoust et al. [238] examined the effect of some parameters such as; annealing temperature and dopant on the efficiency of TiO_2 NTs electrodes for DSSCs, they found that the increasing of annealing temperature from 480 to 520 °C and doping of NTs improve the cell efficiency up to 70% and 40%, respectively.

Detection of heavy metal ions and organic pollutants

Toxic heavy metal ions such as Pb^{2+} and As^{3+}, as well as organic pollutants present in water and soil, are a source of danger for the environment and human beings. Many methods have been developed to assess the environmental impact and control the amount of pollutants in water and soil, such as flame atomic absorption spectrometry, graphite furnace atomic absorption spectrometry, atomic fluorescence spectrometry, and inductively coupled plasma atomic emission spectrometry, etc. Recently, the sensors offered a new technique for monitoring heavy metals and organic pollutants. A modified TiO_2 nanotube array has been reported as a sensor for detecting heavy metals and organic pollutants in water. Liu et al. [239] have developed a DNA-modified TiO_2 nanotube array sensor to determine Pb^{2+} in water. The results showed that the concentrations detected by DNA-modified TiO_2 nanotubes were similar to those obtained by the atomic absorption spectrometry method. They also found that the modified TiO_2 nanotube sensor possesses a wide linear calibration between 0.01 nM and 160 nM with detection limits of about 3.3 pM. Yang et al. [240] fabricated Au shrub-modified TiO_2 nanotube arrays as a novel and useful sensor to determine the arsenic concentration in water. The results showed a high sensitivity between the current changes and the arsenic concentration with a value of 25.7 μA/cm^2 corresponding to 5 μg/L of As^{3+}. Cai et al. [241] reported molecularly imprinted polymer-modified TiO_2 nanotube arrays as a sensor to detect perfluorooctane sulfonate in water. The results showed that this sensor has good selectivity. Moreover, the direct detection of perfluorooctane sulfonate by electrocatalytic reduction reaction was achieved with a detection limit of 86 ng/mL.

Conclusion and future perspectives

The developments of the last decades have highlighted the importance of TiO_2-based materials. The different types of TiO_2 nanostructures, the synthesis strategies of TiO_2 nanotubes, and their applications in energy and environment fields have been discussed in this review. Ordered nanotubes have been synthesized by anodization and by regulating the operating conditions. These structures have considerably improved their performances and have found many applications in various fields. TiO_2-based materials have been widely used in photocatalytic applications, and solar-cell and continue to be active in other applications such as sensing, hydrogen production, etc.

As TiO_2 is a wide band gap (> 3 eV), the optimal use of solar energy is one of these materials' main challenges, reducing its photocatalytic performance. Therefore, doping with appropriate materials, development of composites, and new structural morphologies are expected to be developed in the coming days and will hopefully solve the problems mentioned above. Many innovative and cost-effective synthesis strategies are expected to emerge in the future. Preparing low-cost materials with high stability and environmentally friendly and with improved light adsorbed properties needs to be discovered to fulfill future needs. The development and commercialization of such light-harvesting materials will help to solve, to some extent, our ever-increasing energy needs and the environmental problems facing the world today.

In conclusion, TiO_2 nanotubes have demonstrated significant advantage in various technological fields, such as medicine, energy, and the environment. The review has discussed different synthesis methods and techniques for preparing highly ordered TiO_2 nanotubes with improved performance. However, there are still challenges to overcome, including reducing the band gap of TiO_2 for optimal use of solar energy and developing low-cost, stable, and environmentally friendly materials. The future of TiO_2 nanotubes looks promising, and further research and innovation are expected to improve their performance and commercialization, contributing to a more sustainable future for our energy needs and the environment.

Acknowledgements The authors are grateful to the Centre of Analysis and Characterization (CAC) of the Faculty of Sciences Semlalia in Marrakesh for research facilities, and the National Center for Scientific and Technical Research (CNRST) in Rabat for its financial support.

References

1. Dronov A, Gavrilin I, Kirilenko E et al (2018) Investigation of anodic TiO_2 nanotube composition with high spatial resolution AES and ToF SIMS. Appl Surf Sci 434:148–154. https://doi.org/10.1016/j.apsusc.2017.10.132
2. Devipriya SP, Yesodharan S (2010) Photocatalytic degradation of phenol in water using TiO_2 and ZnO. J Environ Biol 31:247–249
3. Dhanabalan SS, Avaninathan SR, Rajendran S, Carrasco MF (2020) Green Photocatalysts for Energy and Environmental Process. Springer International Publishing, Cham
4. Dong J, Liu Z, Dong J et al (2016) Self-organized ZnO nanorods prepared by anodization of zinc in NaOH electrolyte. RSC Adv 6:72968–72974. https://doi.org/10.1039/c6ra16995c
5. He S, Zheng M, Yao L et al (2010) Preparation and properties of ZnO nanostructures by electrochemical anodization method 256:2557–2562. https://doi.org/10.1016/j.apsusc.2009.10.104
6. Valerini D, Hernández S, Di Benedetto F et al (2016) Sputtered WO_3 films for water splitting applications. Mater Sci Semicond Process 42:150–154. https://doi.org/10.1016/j.mssp.2015.09.013
7. Qamar M, Gondal MA, Yamani ZH (2009) Synthesis of highly active nanocrystalline WO_3 and its application in laser-induced photocatalytic removal of a dye from water. Catal Commun 10:1980–1984. https://doi.org/10.1016/j.catcom.2009.07.014
8. Wang HG, Zhou Y, Shen Y et al (2015) Fabrication, formation mechanism and the application in lithium-ion battery of porous Fe_2O_3 nanotubes via single-spinneret electrospinning. Electrochim Acta 158:105–112. https://doi.org/10.1016/j.electacta.2015.01.149
9. Suman, Chahal S, Kumar A, Kumar P (2020) Zn doped α-Fe_2O_3: An efficient material for UV driven photocatalysis and electrical conductivity. Crystals 10. https://doi.org/10.3390/cryst10040273
10. Butmanov D, Savchuk T, Gavrilin I et al (2023) Temperature electrolyte influences on the phase composition of anodic CuO_x nanostructures. Phys E Low-dimensional Syst Nanostructures 146:115533. https://doi.org/10.1016/j.physe.2022.115533
11. Wu Y, Long M, Cai W et al (2009) Preparation of photocatalytic anatase nanowire films by in situ oxidation of titanium plate. Nanotechnology 20. https://doi.org/10.1088/0957-4484/20/18/185703
12. Zhang XL, Chen Y, Cant AM et al (2013) Crystalline TiO_2 nanorod aggregates: Template-free fabrication and efficient light harvesting in dye-sensitized solar cell applications. Part Part Syst Charact 30:754–758. https://doi.org/10.1002/ppsc.201300132
13. Yang Y, Qiu M, Liu L (2016) TiO_2 nanorod array@carbon cloth photocatalyst for CO_2 reduction. Ceram Int 42:15081–15086. https://doi.org/10.1016/j.ceramint.2016.06.020
14. Xu H, Ouyang S, Li P et al (2013) high-active anatase TiO_2 nanosheets exposed with 95% 100 facets toward efficient H_2 evolution and CO_2 photoreduction. ACS Appl Mater Interfaces 5:8262. https://doi.org/10.1021/am402298g
15. Cheng J, Zhang M, Wu G et al (2014) Photoelectrocatalytic reduction of CO_2 into chemicals using Pt-modified reduced graphene oxide combined with Pt-modified TiO_2 nanotubes. Environ Sci Technol 48:7076–7084. https://doi.org/10.1021/es500364g
16. Fang B, Bonakdarpour A, Reilly K et al (2014) Large-scale synthesis of TiO_2 microspheres with hierarchical nanostructure for highly efficient photodriven reduction of CO_2 to CH_4. ACS Appl Mater Interfaces 6:15488–15498. https://doi.org/10.1021/am504128t
17. Zhou X, Liu N, Schmuki P (2017) Photocatalysis with TiO_2 Nanotubes: "Colorful" Reactivity and Designing Site-Specific Photocatalytic Centers into TiO_2 Nanotubes. ACS Catal 7:3210–3235. https://doi.org/10.1021/acscatal.6b03709
18. Cao GJ, Cui B, Wang WQ et al (2014) Fabrication and photodegradation properties of TiO_2 nanotubes on porous Ti by anodization. Oral Oncol 50:2581–2587. https://doi.org/10.1016/S1003-6326(14)63386-0
19. Adán C, Marugán J, Sánchez E et al (2016) Understanding the effect of morphology on the photocatalytic activity of TiO_2 nanotube array electrodes. Electrochim Acta 191:521–529. https://doi.org/10.1016/j.electacta.2016.01.088
20. Naboulsi I, Lebeau B, Michelin L et al (2017) Insights into the Formation and Properties of Templated Dual Mesoporous Titania with Enhanced Photocatalytic Activity. ACS Appl Mater Interfaces 9:3113–3122. https://doi.org/10.1021/acsami.6b13269
21. Ayal AK (2019) Effect of Anodization Duration in the TiO_2 Nanotubes Formation on Ti Foil and Photoelectrochemical Properties of TiO_2 Nanotubes. Al-Mustansiriyah J Sci 29:77. https://doi.org/10.23851/mjs.v29i3.640
22. Xu Z, Yu J (2011) Visible-light-induced photoelectrochemical behaviors of Fe-modified TiO_2 nanotube arrays. Nanoscale 3:3138–3144. https://doi.org/10.1039/c1nr10282f
23. Wu H, Zhang Z (2011) Photoelectrochemical water splitting and simultaneous photoelectrocatalytic degradation of organic pollutant on highly smooth and ordered TiO_2 nanotube arrays. J Solid State Chem 184:3202–3207. https://doi.org/10.1016/j.jssc.2011.10.012
24. Zhang Z, Hossain MF, Takahashi T (2010) Photoelectrochemical water splitting on highly smooth and ordered TiO_2 nanotube arrays for hydrogen generation. Int J Hydrogen Energy 35:8528–8535. https://doi.org/10.1016/j.ijhydene.2010.03.032
25. Chaudhary D, Singh S, Vankar VD, Khare N (2017) A ternary Ag/TiO_2/CNT photoanode for efficient photoelectrochemical water splitting under visible light irradiation. Int J Hydrogen Energy 42:7826–7835. https://doi.org/10.1016/j.ijhydene.2016.12.036
26. Fu F, Cha G, Wu Z et al (2021) Photocatalytic Hydrogen Generation from Water-Annealed TiO_2 Nanotubes with White and Grey Modification. ChemElectroChem 8:240–245. https://doi.org/10.1002/celc.202001517
27. Zhao C, Luo H, Chen F et al (2014) A novel composite of TiO_2 nanotubes with remarkably high efficiency for hydrogen production in solar-driven water splitting. Energy Environ Sci 7:1700–1707. https://doi.org/10.1039/c3ee43165g
28. Mor GK, Varghese OK, Paulose M et al (2006) A review on highly ordered, vertically oriented TiO_2 nanotube arrays: Fabrication, material properties, and solar energy applications. Sol Energy Mater Sol Cells 90:2011–2075. https://doi.org/10.1016/j.solmat.2006.04.007
29. Naduvath J, Shaw S, Bhargava P, Mallick S (2014) Effect of nanograss and annealing temperature on TiO_2 nanotubes based dye sensitized solar cells. Mater Sci Forum 771:103–113. https://doi.org/10.4028/www.scientific.net/MSF.771.103
30. Kulkarni M, Mazare A, Gongadze E et al (2015) Titanium nanostructures for biomedical applications. Nanotechnology 26. https://doi.org/10.1088/0957-4484/26/6/062002
31. Hoyer P (1996) Formation of a Titanium Dioxide Nanotube Array. Langmuir 12:1411–1413. https://doi.org/10.1021/la9507803
32. Lee J, Kim DH, Hong SH, Jho JY (2011) A hydrogen gas sensor employing vertically aligned TiO_2 nanotube arrays prepared by template-assisted method. Sensors Actuator B Chem 160:1494–1498. https://doi.org/10.1016/j.snb.2011.08.001

33. Michailowski A, Almawlawi D, Cheng G, Moskovits M (2001) Highly regular anatase nanotubule arrays fabricated in porous anodic templates. Chem Phys Lett 349:1–5
34. Tsvetkov N, Larina L, Kang JK, Shevaleevskiy O (2020) Sol-gel processed TiO_2 nanotube photoelectrodes for dye-sensitized solar cells with enhanced photovoltaic performance. Nanomaterials 10. https://doi.org/10.3390/nano10020296
35. Kasuga T, Hiramatsu M, Hoson A et al (1998) Formation of Titanium Oxide Nanotube. Langmuir 14:3160–3163. https://doi.org/10.1021/la9713816
36. Zakir O, Idouhli R, Elyaagoubi M et al (2020) Fabrication of TiO_2 Nanotube by Electrochemical Anodization: Toward Photocatalytic Application. J Nanomater 2020. https://doi.org/10.1155/2020/4745726
37. Zakir O, Ait-Karra A, Idouhli R et al (2023) Effect of anodization time on the morphological, structural, electrochemical, and photocatalytic properties of anodic TiO_2 NTs. J Solid State Chem 322:123939. https://doi.org/10.1016/j.jssc.2023.123939
38. Guangzhong L, Wenyan Z, Jian Z et al (2011) A Novel Way to Fabricate Fe Doped TiO_2 Nanotubes by Anodization of TiFe Alloys. Rare Met Mater Eng 40:1510–1513. https://doi.org/10.1016/S1875-5372(11)60056-8
39. Alijani M, Sopha H, Ng S, Macak JM (2021) High aspect ratio TiO_2 nanotube layers obtained in a very short anodization time. Electrochim Acta 376:138080. https://doi.org/10.1016/j.electacta.2021.138080
40. Pishkar N, Ghoranneviss M, Ghorannevis Z, Akbari H (2018) Study of the highly ordered TiO_2 nanotubes physical properties prepared with two-step anodization. Results Phys 9:1246–1249. https://doi.org/10.1016/j.rinp.2018.02.009
41. Janekbary KK, Gilani N, Pirbazari AE (2020) One-step fabrication of Ag/RGO doped TiO_2 nanotubes during anodization process with high photocatalytic performance. J Porous Mater 27:1809–1822. https://doi.org/10.1007/s10934-020-00954-5
42. Zhang Z, Liu Q, He M et al (2020) Quantitative Analysis of Oxide Growth During Ti Galvanostatic Anodization. J Electrochem Soc 167:113501. https://doi.org/10.1149/1945-7111/aba00b
43. Sreekantan S, Saharudin KA, Wei LC (2011) Formation of TiO_2 nanotubes via anodization and potential applications for photocatalysts, biomedical materials, and photoelectrochemical cell. IOP Conf Ser Mater Sci Eng 21. https://doi.org/10.1088/1757-899X/21/1/012002
44. Sun Y, Yan KP (2014) Effect of anodization voltage on performance of TiO_2 nanotube arrays for hydrogen generation in a two-compartment photoelectrochemical cell. Int J Hydrogen Energy 39:11368–11375. https://doi.org/10.1016/j.ijhydene.2014.05.115
45. Prida VM, Manova E, Vega V et al (2007) Temperature influence on the anodic growth of self-aligned Titanium dioxide nanotube arrays. J Magn Magn Mater 316:110–113. https://doi.org/10.1016/j.jmmm.2007.02.021
46. Khadiri M, Elyaagoubi M, Idouhli R et al (2020) Electrochemical Study of Anodized Titanium in Phosphoric Acid. Adv Mater Sci Eng 2020:1–11. https://doi.org/10.1155/2020/5769071
47. Li N, Li Y, Li W et al (2016) One-Step Hydrothermal Synthesis of TiO_2@MoO_3 Core-Shell Nanomaterial: Microstructure, Growth Mechanism, and Improved Photochromic Property. J Phys Chem C 120:3341–3349. https://doi.org/10.1021/acs.jpcc.5b10752
48. Zwilling V, Darque-Ceretti E, Boutry-Forveille A et al (1999) Structure and physicochemistry of anodic oxide films on titanium and TA6V alloy. Surf Interface Anal 27:629–637. https://doi.org/10.1002/(SICI)1096-9918(199907)27:7%3c629::AID-SIA551%3e3.0.CO;2-0
49. Zwilling V, Aucouturier M, Darque-ceretti E (1999) Anodic oxidation of titanium and TA6V alloy in chromic media. An electrochemical approach 45:921–929
50. Gong D, Grimes CA, Varghese OK et al (2001) Titanium oxide nanotube arrays prepared by anodic oxidation. J Mater Res 16:3331–3334. https://doi.org/10.1557/JMR.2001.0457
51. Macak JM, Tsuchiya H, Taveira L et al (2005) Smooth anodic TiO_2 nanotubes. Angew Chemie Int Ed 44:7463–7465. https://doi.org/10.1002/anie.200502781
52. Zhang G, Huang H, Zhang Y et al (2007) Highly ordered nanoporous TiO_2 and its photocatalytic properties. 9:2854–2858. https://doi.org/10.1016/j.elecom.2007.10.014
53. Mor GK, Varghese OK (2003) Fabrication of tapered , conical-shaped titania nanotubes. 18–20. https://doi.org/10.1557/JMR.2003.0362
54. Albu SP, Ghicov A, Macak JM et al (2007) Self-Organized, Free-Standing TiO_2 Nanotube Membrane for Flow-through Photocatalytic Applications. Nano Lett 7:1286–1289. https://doi.org/10.1021/nl070264k
55. Paulose M, Prakasam HE, Varghese OK et al (2007) TiO_2 Nanotube Arrays of 1000 μm Length by Anodization of Titanium Foil: Phenol Red Diffusion. 14992–14997. https://doi.org/10.1021/jp075258r
56. Mor GK, Shankar K, Paulose M et al (2006) Use of highly-ordered TiO_2 nanotube arrays in dye-sensitized solar cells. Nano Lett 6:215–218. https://doi.org/10.1021/nl052099j
57. Etacheri V, Seery MK, Hinder SJ, Pillai SC (2010) Highly Visible Light Active $TiO_{2-x}N_x$ Heterojunction Photocatalysts. Chem Mater 22:3843–3853. https://doi.org/10.1021/cm903260f
58. Etacheri V, Seery MK, Hinder SJ, Pillai SC (2012) Nanostructured $Ti_{1-x}S_xO_{2-y}N_y$ heterojunctions for efficient visible-light-induced photocatalysis. Inorg Chem 51:7164–7173. https://doi.org/10.1021/ic3001653
59. Doong RA, Chen CH, Maithreepala RA, Chang SM (2001) The influence of pH and cadmium sulfide on the photocatalytic degradation of 2-chlorophenol in titanium dioxide suspensions. Water Res 35:2873–2880. https://doi.org/10.1016/S0043-1354(00)00580-7
60. Kang MG, Han HE, Kim KJ (1999) Enhanced photodecomposition of 4-chlorophenol in aqueous solution by deposition of CdS on TiO_2. J Photochem Photobiol A Chem 125:119–125. https://doi.org/10.1016/S1010-6030(99)00092-1
61. Ou HH, Lo SL (2007) Review of titania nanotubes synthesized via the hydrothermal treatment: Fabrication, modification, and application. Sep Purif Technol 58:179–191. https://doi.org/10.1016/j.seppur.2007.07.017
62. Abdullah M, Kamarudin SK (2017) Titanium dioxide nanotubes (TNT) in energy and environmental applications: An overview. Renew Sustain Energy Rev 76:212–225. https://doi.org/10.1016/j.rser.2017.01.057
63. Yuan L, Meng S, Zhou Y, Yue Z (2013) Controlled synthesis of anatase TiO_2 nanotube and nanowire arrays via AAO template-based hydrolysis. J Mater Chem A 1:2552–2557. https://doi.org/10.1039/c2ta00709f
64. Jiang WF, Ling YH, Hao SJ et al (2007) In Situ Template Synthesis of TiO_2 Nanotube Array Films. Key Eng Mater 336–338:2200–2202. https://doi.org/10.4028/www.scientific.net/KEM.336-338.2200
65. Liang Y, Wang C, Kei C et al (2011) Photocatalysis of Ag-Loaded TiO_2 Nanotube Arrays Formed by Atomic Layer Deposition. J Phys Chem C 115:9498–9502. https://doi.org/10.1021/jp202111p
66. Liu L, Lim SY, Law CS et al (2020) Engineering of Broadband Nanoporous Semiconductor Photonic Crystals for Visible-Light-Driven Photocatalysis. ACS Appl Mater Interfaces 12:57079–57092. https://doi.org/10.1021/acsami.0c16914
67. Lim SY, Hedrich C, Jiang L et al (2021) Harnessing Slow Light in Optoelectronically Engineered Nanoporous Photonic Crystals for Visible Light-Enhanced Photocatalysis. ACS Catal 11:12947–12962. https://doi.org/10.1021/acscatal.1c03320
68. Pang YL, Bhatia S, Abdullah AZ (2011) Process behavior of TiO_2 nanotube-enhanced sonocatalytic degradation of Rhodamine B in aqueous solution. Sep Purif Technol 77:331–338. https://doi.org/10.1016/j.seppur.2010.12.023

69. Liu Z, Liu C, Ya J, Lei E (2011) Controlled synthesis of ZnO and TiO_2 nanotubes by chemical method and their application in dye-sensitized solar cells. Renew Energy 36:1177–1181. https://doi.org/10.1016/j.renene.2010.09.019
70. Swami N, Cui Z, Nair LS (2011) Titania nanotubes: Novel nanostructures for improved osseointegration. J Heat Transfer 133:1–7. https://doi.org/10.1115/1.4002465
71. Abida B, Lotfi C, Baranton S et al (2011) Preparation and characterization of Pt /TiO_2 nanotubes catalyst for methanol electro-oxidation. Appl Catal B Environ 106:609–615. https://doi.org/10.1016/j.apcatb.2011.06.022
72. Abdallah H, Moustafa AF, Alhathal A, El-sayed HEM (2014) Performance of a newly developed titanium oxide nanotubes / polyethersulfone blend membrane for water desalination using vacuum membrane distillation. Desalination 346:30–36. https://doi.org/10.1016/j.desal.2014.05.003
73. Park J, Ryu Y, Kim H, Yu C (2009) Simple and fast annealing synthesis of titanium dioxide nanostructures and morphology transformation during annealing processes. Nanotechnology 20. https://doi.org/10.1088/0957-4484/20/10/105608
74. Yuan ZY, Su BL (2004) Titanium oxide nanotubes, nanofibers and nanowires. Colloids Surfaces A Physicochem Eng Asp 241:173–183. https://doi.org/10.1016/j.colsurfa.2004.04.030
75. Erjavec B, Kaplan R, Pintar A (2015) Effects of heat and peroxide treatment on photocatalytic activity of titanate nanotubes. Catal Today 241:15–24. https://doi.org/10.1016/j.cattod.2014.04.005
76. Xu J, Lu M, Guo X, Li H (2005) Zinc ions surface-doped titanium dioxide nanotubes and its photocatalysis activity for degradation of methyl orange in water. J Mol Catal A Chem 226:123–127. https://doi.org/10.1016/j.molcata.2004.09.051
77. Dong B, He B, Huang J et al (2008) High dispersion and electrocatalytic activity of Pd/titanium dioxide nanotubes catalysts for hydrazine oxidation. J Power Sources 175:266–271. https://doi.org/10.1016/j.jpowsour.2007.08.090
78. Tsai C, Teng H (2006) Structural Features of Nanotubes Synthesized from NaOH Treatment on TiO_2 with Different Post-Treatments. Chem Mater 18:367–373. https://doi.org/10.1021/cm0518527
79. Yuan ZY, Zhou W, Su BL (2002) Hierarchical interlinked structure of titanium oxide nanofibers. Chem Commun 11:1202–1203. https://doi.org/10.1039/b202489f
80. Tsai CC, Teng H (2004) Regulation of the physical characteristics of titania nanotube aggregates synthesized from hydrothermal treatment. Chem Mater 16:4352–4358. https://doi.org/10.1021/cm049643u
81. Chen Q, Du GH, Zhang S, Peng L-M (2002) The structure of trititanate nanotubes. Acta Crystallogr Sect B Struct Sci 58:587–593. https://doi.org/10.1107/S0108768102009084
82. Aliofkhazraei M, Makhlouf ASH (2016) Handbook of Nanoelectrochemistry: Electrochemical Synthesis Methods. Springer International Publishing, Cham, Properties and Characterization Techniques
83. Su Z, Zhou W (2011) Formation, morphology control and applications of anodic TiO_2 nanotube arrays. J Mater Chem 21:8955. https://doi.org/10.1039/c0jm04587j
84. Zhang S-Y, Yu D L, Li D-D et al (2014) Forming Process of Anodic TiO_2 Nanotubes under a Preformed Compact Surface Layer. J Electrochem Soc 161. https://doi.org/10.1149/2.0661410jes
85. Kulkarni M, Mazare A, Schmuki P, Iglic A (2016) Influence Of Anodization Parameters On Morphology Of TiO_2 Nanostructured Surfaces. Adv Mater Lett 7:23–28. https://doi.org/10.5185/amlett.2016.6156
86. Jankulovska M, Lana-Villarreal T, Gómez R (2010) Hierarchically organized titanium dioxide nanostructured electrodes: Quantum-sized nanowires grown on nanotubes. Electrochem Commun 12:1356–1359. https://doi.org/10.1016/j.elecom.2010.07.019
87. Ghicov A, Tsuchiya H, MacAk JM, Schmuki P (2005) Titanium oxide nanotubes prepared in phosphate electrolytes. Electrochem Commun 7:505–509. https://doi.org/10.1016/j.elecom.2005.03.007
88. Ghicov A, Schmuki P (2009) Self-ordering electrochemistry: a review on growth and functionality of TiO_2 nanotubes and other self-aligned MOx structures. Chem Commun 2791. https://doi.org/10.1039/b822726h
89. Zhao J, Wang X, Chen R, Li L (2005) Fabrication of titanium oxide nanotube arrays by anodic oxidation. Solid State Commun 134:705–710. https://doi.org/10.1016/j.ssc.2005.02.028
90. Beranek R, Hildebrand H, Schmuki P (2003) Self-Organized Porous Titanium Oxide Prepared in H_2SO_4/HF Electrolytes. Electrochem Solid-State Lett 6:B12. https://doi.org/10.1149/1.1545192
91. Wang J, Lin Z (2009) Anodic Formation of Ordered TiO_2 Nanotube Arrays: Effects of Electrolyte Temperature and Anodization Potential. J Phys Chem C 113:4026–4030. https://doi.org/10.1021/jp811201x
92. Quiroz HP, Quintero F, Arias PJ et al (2015) Effect of fluoride and water content on the growth of TiO_2 nanotubes synthesized via ethylene glycol with voltage changes during anodizing process. J Phys 614:012001. https://doi.org/10.1088/1742-6596/614/1/012001
93. Arenas-Hernandez A, Zúñiga-Islas C, Mendoza-Cervantes JC (2020) A study of the effect of morphology on the optical and electrical properties of TiO_2 nanotubes for gas sensing applications. EPJ Appl Phys 90:1–9. https://doi.org/10.1051/epjap/2020190267
94. Antony RP, Mathews T, Ajikumar PK et al (2012) Electrochemically synthesized visible light absorbing vertically aligned N-doped TiO_2 nanotube array films. Mater Res Bull 47:4491–4497. https://doi.org/10.1016/j.materresbull.2012.09.061
95. Regonini D, Satka A, Jaroenworaluck A et al (2012) Factors influencing surface morphology of anodized TiO_2 nanotubes. Electrochim Acta 74:244–253. https://doi.org/10.1016/j.electacta.2012.04.076
96. Kapusta-Kołodziej J, Syrek K, Pawlik A et al (2017) Effects of anodizing potential and temperature on the growth of anodic TiO_2 and its photoelectrochemical properties. Appl Surf Sci 396:1119–1129. https://doi.org/10.1016/j.apsusc.2016.11.097
97. Valota A, LeClere DJ, Skeldon P et al (2009) Influence of water content on nanotubular anodic titania formed in fluoride/glycerol electrolytes. Electrochim Acta 54:4321–4327. https://doi.org/10.1016/j.electacta.2009.02.098
98. Paulose M, Shankar K, Yoriya S et al (2006) Anodic Growth of Highly Ordered TiO_2 Nanotube Arrays to 134 μm in Length. J Phys Chem B 110:16179–16184. https://doi.org/10.1021/jp064020k
99. Shankar K, Mor GK, Fitzgerald A, Grimes CA (2007) Cation effect on the electrochemical formation of very high aspect ratio TiO_2 nanotube arrays in formamide-water mixtures. J Phys Chem C 111:21–26. https://doi.org/10.1021/jp066352v
100. Yeonmi S, Seonghoon L (2008) Self-organized regular arrays of anodic TiO_2 nanotubes. Nano Lett 8:3171–3173. https://doi.org/10.1021/nl801422w
101. Macak JM, Albu SP, Schmuki P (2007) Towards ideal hexagonal self-ordering of TiO_2 nanotubes. Phys Status Solidi Rapid Res Lett 1:181–183. https://doi.org/10.1002/pssr.200701148
102. Albu SP, Ghicov A, Macak JM, Schmuki P (2007) 250 μm long anodic TiO_2 nanotubes with hexagonal self-ordering. Phys Status Solidi Rapid Res Lett 1:R65–R67. https://doi.org/10.1002/pssr.200600069
103. Kang SH, Kim JY, Kim HS, Sung YE (2008) Formation and mechanistic study of self-ordered TiO_2 nanotubes on Ti substrate. J Ind Eng Chem 14:52–59. https://doi.org/10.1016/j.jiec.2007.06.004
104. Wan J, Yan X, Ding J et al (2009) Self-organized highly ordered TiO_2 nanotubes in organic aqueous system. Mater Charact 60:1534–1540. https://doi.org/10.1016/j.matchar.2009.09.002
105. Wang N, Li H, Lü W et al (2011) Effects of TiO_2 nanotubes with different diameters on gene expression and osseointegration of

implants in minipigs. Biomaterials 32:6900–6911. https://doi.org/10.1016/j.biomaterials.2011.06.023
106. Yasuda K, Schmuki P (2007) Control of morphology and composition of self-organized zirconium titanate nanotubes formed in $(NH_4)_2SO_4/NH_4F$ electrolytes. 52:4053–4061. https://doi.org/10.1016/j.electacta.2006.11.023
107. Javier F, Cortes Q, Arias-monje PJ et al (2016) Empirical kinetics for the growth of titania nanotube arrays by potentiostatic anodization in ethylene glycol. JMADE 96:80–89. https://doi.org/10.1016/j.matdes.2016.02.006
108. Sapoletova NA, Kushnir SE, Napolskii KS (2018) Anodic titanium oxide photonic crystals prepared by novel cyclic anodizing with voltage versus charge modulation. Electrochem Commun 91:5–9. https://doi.org/10.1016/j.elecom.2018.04.018
109. Macak JM, Hildebrand H, Marten-Jahns U, Schmuki P (2008) Mechanistic aspects and growth of large diameter self-organized TiO_2 nanotubes. J Electroanal Chem 621:254–266. https://doi.org/10.1016/j.jelechem.2008.01.005
110. Bauer S, Kleber S, Schmuki P (2006) TiO_2 nanotubes: Tailoring the geometry in H_3PO_4/HF electrolytes. Electrochem Commun 8:1321–1325. https://doi.org/10.1016/j.elecom.2006.05.030
111. Sulka GD, Kapusta-Kołodziej J, Brzózka A, Jaskuła M (2010) Fabrication of nanoporous TiO_2 by electrochemical anodization. Electrochim Acta 55:4359–4367. https://doi.org/10.1016/j.electacta.2009.12.053
112. Macak JM, Tsuchiya H, Ghicov A et al (2007) TiO_2 nanotubes: Self-organized electrochemical formation, properties and applications. Curr Opin Solid State Mater Sci 11:3–18. https://doi.org/10.1016/j.cossms.2007.08.004
113. Regonini D, Satka A, Allsopp DWE, Jaroenworaluck A (2009) Anodised Titania Nanotubes Prepared in a Glycerol / NaF Electrolyte. 4410–4416. https://doi.org/10.1166/jnn.2009.M69
114. Indira K, Mudali UK, Nishimura T, Rajendran N (2015) A Review on TiO_2 Nanotubes: Influence of Anodization Parameters, Formation Mechanism, Properties, Corrosion Behavior, and Biomedical Applications. J Bio- Tribo-Corrosion 1:28. https://doi.org/10.1007/s40735-015-0024-x
115. Lee K, Mazare A, Schmuki P (2014) One-Dimensional Titanium Dioxide Nanomaterials: Nanotubes. Chem Rev 114:9385–9454. https://doi.org/10.1021/cr500061m
116. Vega V, Montero-moreno JM, García J et al (2016) Long-Range Hexagonal Arrangement of TiO_2 Nanotubes by Soft Lithography-Guided Anodization. Electrochim Acta 203:51–58. https://doi.org/10.1016/j.electacta.2016.04.016
117. Sapoletova NA, Kushnir SE, Napolskii KS (2022) Polarization-enhanced cell walls etching of anodic titanium oxide. Nanotechnology 33:065602. https://doi.org/10.1088/1361-6528/ac345c
118. Atyaoui A, Cachet H, Sutter EMM, Bousselmi L (2013) Effect of the anodization voltage on the dimensions and photoactivity of titania nanotubes arrays. Surf Interface Anal 45:1751–1759. https://doi.org/10.1002/sia.5317
119. Ruan C, Paulose M, Varghese OK et al (2005) Fabrication of Highly Ordered TiO_2 Nanotube Arrays Using an Organic Electrolyte. J Phys Chem B 109:15754–15759. https://doi.org/10.1021/jp052736u
120. Roy P, Berger S, Schmuki P (2011) TiO_2 nanotubes: Synthesis and applications. Angew Chemie Int Ed 50:2904–2939. https://doi.org/10.1002/anie.201001374
121. Zhang S, Li Y, Xu P, Liang K (2017) Effect of anodization parameters on the surface morphology and photoelectrochemical properties of TiO_2 nanotubes. Int J Electrochem Sci 12:10714–10725. https://doi.org/10.20964/2017.11.80
122. Bervian A, Coser E, Khan S et al (2017) Evolution of TiO_2 nanotubular morphology obtained in ethylene glycol/glycerol mixture and its photoelectrochemical performance. Mater Res 20:962–972. https://doi.org/10.1590/1980-5373-MR-2016-0878
123. Sulka GD, Kapusta-Kołodziej J, Brzózka A, Jaskuła M (2013) Anodic growth of TiO_2 nanopore arrays at various temperatures. Electrochim Acta 104:526–535. https://doi.org/10.1016/j.electacta.2012.12.121
124. Enachi M, Tiginyanu I, Sprincean V, Ursaki V (2010) Self-organized nucleation layer for the formation of ordered arrays of double-walled TiO_2 nanotubes with temperature controlled inner diameter. Phys Status Solidi Rapid Res Lett 4:100–102. https://doi.org/10.1002/pssr.201004069
125. Macak JM, Schmuki P (2006) Anodic growth of self-organized anodic TiO_2 nanotubes in viscous electrolytes. Electrochim Acta 52:1258–1264. https://doi.org/10.1016/j.electacta.2006.07.021
126. Macák J (2008) Growth of anodic self-organized titanium dioxide nanotube layers. Universität Erlangen-Nürnberg
127. Kowalski D, Kim D, Schmuki P (2013) TiO_2 nanotubes, nanochannels and mesosponge: Self-organized formation and applications. Nano Today 8:235–264. https://doi.org/10.1016/j.nantod.2013.04.010
128. Albu SP, Roy P, Virtanen S, Schmuki P (2010) Self-organized TiO_2 nanotube arrays: Critical effects on morphology and growth. Isr J Chem 50:453–467. https://doi.org/10.1002/ijch.201000059
129. Zhou X, Nguyen NT, Özkan S, Schmuki P (2014) Anodic TiO_2 nanotube layers: Why does self-organized growth occur - A mini review. Electrochem Commun 46:157–162. https://doi.org/10.1016/j.elecom.2014.06.021
130. Wang X, Li Y, Song H et al (2016) Fluoride concentration controlled TiO_2 nanotubes: The interplay of microstructure and photocatalytic performance. RSC Adv 6:18333–18339. https://doi.org/10.1039/c5ra24732b
131. Quiroz HP, Quintero F, Arias PJ et al (2015) Effect of fluoride and water content on the growth of TiO_2 nanotubes synthesized via ethylene glycol with voltage changes during anodizing process. J Phys Conf Ser 614:1–8. https://doi.org/10.1088/1742-6596/614/1/012001
132. Hossain MF, Ahosan MS (2015) Investigation of NH_4F concentration effects on TiO_2 nanotube arrays fabricated by anode oxidation method. 2nd Int Conf Electr Eng Inf Commun Technol iCEEiCT 2015 1–5. https://doi.org/10.1109/ICEEICT.2015.7307430
133. Deen KM, Farooq A, Raza MA, Haider W (2014) Effect of electrolyte composition on TiO_2 nanotubular structure formation and its electrochemical evaluation. Electrochim Acta 117:329–335. https://doi.org/10.1016/j.electacta.2013.11.108
134. Nyamukamba P, Okoh O, Mungondori H et al (2018) Synthetic Methods for Titanium Dioxide Nanoparticles: A Review. In: Titanium Dioxide - Material for a Sustainable Environment. InTech
135. Zhong X, Yu D, Song Y et al (2014) Fabrication of large diameter TiO_2 nanotubes for improved photoelectrochemical performance. Mater Res Bull 60:348–352. https://doi.org/10.1016/j.materresbull.2014.09.011
136. Heidari Khoee M, Khoee S, Lotfi M (2019) Synthesis of titanium dioxide nanotubes with liposomal covers for carrying and extended release of 5-FU as anticancer drug in the treatment of HeLa cells. Anal Biochem 572:16–24. https://doi.org/10.1016/j.ab.2019.02.027
137. Raja KS, Misra M, Paramguru K (2005) Formation of self-ordered nano-tubular structure of anodic oxide layer on titanium. Electrochim Acta 51:154–165. https://doi.org/10.1016/j.electacta.2005.04.011
138. Nirmal KA, Nhivekar GS, Khot AC et al (2022) Unraveling the Effect of the Water Content in the Electrolyte on the Resistive Switching Properties of Self-Assembled One-Dimensional Anodized TiO_2 Nanotubes. J Phys Chem Lett 13:7870–7880. https://doi.org/10.1021/acs.jpclett.2c01075
139. Regonini D, Bowen CR, Jaroenworaluck A, Stevens R (2013) A review of growth mechanism, structure and crystallinity of anodized TiO_2 nanotubes. Mater Sci Eng R Reports 74:377–406. https://doi.org/10.1016/j.mser.2013.10.001

140. Wei W, Berger S, Hauser C et al (2010) Transition of TiO_2 nanotubes to nanopores for electrolytes with very low water contents. Electrochem Commun 12:1184–1186. https://doi.org/10.1016/j.elecom.2010.06.014
141. Yin L, Ji S, Liu G et al (2011) Understanding the growth behavior of titania nanotubes. Electrochem Commun 13:454–457. https://doi.org/10.1016/j.elecom.2011.02.019
142. Zakir O, mountassir El Mouchtari E, Elyaagoubi M et al (2022) Anodic TiO_2 nanotube: influence of annealing temperature on the photocatalytic degradation of carbamazepine. J Aust Ceram Soc. https://doi.org/10.1007/s41779-022-00752-z
143. Ghicov A, Tsuchiya H, Macak JM, Schmuki P (2006) Annealing effects on the photoresponse of TiO_2 nanotubes. Phys Status Solidi Appl Mater Sci 203:28–30. https://doi.org/10.1002/pssa.200622041
144. Regonini D, Jaroenworaluck A, Stevens R, Bowen CR (2010) Effect of heat treatment on the properties and structure of TiO_2 nanotubes: phase composition and chemical composition. Surf Interface Anal 42:139–144. https://doi.org/10.1002/sia.3183
145. Mathews NR, Morales ER, Cortés-Jacome MA, Toledo Antonio JA (2009) TiO_2 thin films - Influence of annealing temperature on structural, optical and photocatalytic properties. Sol Energy 83:1499–1508. https://doi.org/10.1016/j.solener.2009.04.008
146. Muaz AKM, Hashim U, Arshad MKM et al (2016) Effect of annealing temperature on structural, morphological and electrical properties of nanoparticles TiO_2 thin films by sol-gel method. AIP Conf Proc 1733. https://doi.org/10.1063/1.4948905
147. Varghese OK, Gong D, Paulose M et al (2003) Crystallization and high-temperature structural stability of titanium oxide nanotube arrays. J Mater Res 18:156–165. https://doi.org/10.1557/JMR.2003.0022
148. Tayade RJ, Surolia PK, Kulkarni RG, Jasra RV (2007) Photocatalytic degradation of dyes and organic contaminants in water using nanocrystalline anatase and rutile TiO_2. Sci Technol Adv Mater 8:455–462. https://doi.org/10.1016/j.stam.2007.05.006
149. Fu Y, Mo A (2018) A Review on the Electrochemically Self-organized Titania Nanotube Arrays: Synthesis, Modifications, and Biomedical Applications. Nanoscale Res Lett 13:187. https://doi.org/10.1186/s11671-018-2597-z
150. Kondo JN, Domen K (2007) Crystallization of Mesoporous Metal Oxides. 835–847. https://doi.org/10.1021/cm702176m
151. Sun Y, Yan K, Wang G et al (2011) Effect of Annealing Temperature on the Hydrogen Production of TiO_2 Nanotube Arrays in a Two-Compartment Photoelectrochemical Cell. J Phys Chem C 115:12844–12849. https://doi.org/10.1021/jp1116118
152. Gavrilin I, Dronov A, Volkov R et al (2020) Differences in the local structure and composition of anodic TiO_2 nanotubes annealed in vacuum and air. Appl Surf Sci 516:146120. https://doi.org/10.1016/j.apsusc.2020.146120
153. Talla A, Suliali NJ, Goosen WE et al (2022) Effect of annealing temperature and atmosphere on the structural, morphological and luminescent properties of TiO_2 nanotubes. Phys B Condens Matter 640:414026. https://doi.org/10.1016/j.physb.2022.414026
154. Tighineanu A, Ruff T, Albu S et al (2010) Conductivity of TiO_2 nanotubes: Influence of annealing time and temperature. Chem Phys Lett 494:260–263. https://doi.org/10.1016/j.cplett.2010.06.022
155. Bakri AS, Sahdan MZ, Adriyanto F et al (2017) Effect of annealing temperature of titanium dioxide thin films on structural and electrical properties. In: International Conference on Engineering, Science and Nanotechnology 2016. p 030030
156. Zhao B, Zhou J, Chen Y, Peng Y (2011) Effect of annealing temperature on the structure and optical properties of sputtered TiO_2 films. J Alloys Compd 509:4060–4064. https://doi.org/10.1016/j.jallcom.2011.01.020
157. Ge MZ, Cao CY, Huang JY et al (2016) Synthesis, modification, and photo/photoelectrocatalytic degradation applications of TiO_2 nanotube arrays: A review. Nanotechnol Rev 5:75–112. https://doi.org/10.1515/ntrev-2015-0049
158. Huang JY, Zhang KQ, Lai YK (2013) Fabrication, modification, and emerging applications of TiO_2 nanotube arrays by electrochemical synthesis: A review. Int J Photoenergy 2013. https://doi.org/10.1155/2013/761971
159. Asahi R, Morikawa T, Ohwaki T et al (2001) Visible-Light Photocatalysis in Nitrogen-Doped Titanium Oxides. Science (80-) 293:269–271. https://doi.org/10.1126/science.1061051
160. Gao Q, Si F, Zhang S et al (2019) Hydrogenated F-doped TiO_2 for photocatalytic hydrogen evolution and pollutant degradation. Int J Hydrogen Energy 44:8011–8019. https://doi.org/10.1016/j.ijhydene.2019.01.233
161. Trapalis C, Todorova N, Giannakopoulou T et al (2008) Preparation of fluorine-doped TiO_2 photocatalysts with controlled crystalline structure. Int J Photoenergy 2008. https://doi.org/10.1155/2008/534038
162. Li D, Haneda H, Labhsetwar NK et al (2005) Visible-light-driven photocatalysis on fluorine-doped TiO_2 powders by the creation of surface oxygen vacancies. Chem Phys Lett 401:579–584. https://doi.org/10.1016/j.cplett.2004.11.126
163. Yuferov YV, Popov ID, Zykov FM et al (2022) Study of the influence of anodizing parameters on the photocatalytic activity of preferred oriented TiO_2 nanotubes self-doped by carbon. Appl Surf Sci 573:151366. https://doi.org/10.1016/j.apsusc.2021.151366
164. Park JH, Kim S, Bard AJ (2006) Novel Carbon-Doped TiO_2 Nanotube Arrays with High Aspect Ratios for Efficient Solar Water Splitting. Nano Lett 6:24–28. https://doi.org/10.1021/nl051807y
165. Lin L, Lin W, Zhu Y et al (2005) Phosphor-doped titania - A novel photocatalyst active in visible light. Chem Lett 34:284–285. https://doi.org/10.1246/cl.2005.284
166. Lin L, Lin W, Xie JL et al (2007) Photocatalytic properties of phosphor-doped titania nanoparticles. Appl Catal B Environ 75:52–58. https://doi.org/10.1016/j.apcatb.2007.03.016
167. Momeni MM, Ghayeb Y, Ghonchegi Z (2015) Visible light activity of sulfur-doped TiO_2 nanostructure photoelectrodes prepared by single-step electrochemical anodizing process. J Solid State Electrochem 19:1359–1366. https://doi.org/10.1007/s10008-015-2758-2
168. Umebayashi T, Yamaki T, Itoh H, Asai K (2002) Band gap narrowing of titanium dioxide by sulfur doping. Appl Phys Lett 81:454–456. https://doi.org/10.1063/1.1493647
169. Hamadanian M, Reisi-Vanani A, Majedi A (2009) Preparation and characterization of S-doped TiO_2 nanoparticles, effect of calcination temperature and evaluation of photocatalytic activity. Mater Chem Phys 116:376–382. https://doi.org/10.1016/j.matchemphys.2009.03.039
170. Szkoda M, Lisowska-Oleksiak A, Siuzdak K (2016) Optimization of boron-doping process of titania nanotubes via electrochemical method toward enhanced photoactivity. J Solid State Electrochem 20:1765–1774. https://doi.org/10.1007/s10008-016-3185-8
171. Lu N, Quan X, Li JY et al (2007) Fabrication of boron-doped TiO_2 nanotube array electrode and investigation of its photoelectrochemical capability. J Phys Chem C 111:11836–11842. https://doi.org/10.1021/jp071359d
172. Yu J, Zhou P, Li Q (2013) New insight into the enhanced visible-light photocatalytic activities of B-, C- and B/C-doped anatase TiO_2 by first-principles. Phys Chem Chem Phys 15:12040–12047. https://doi.org/10.1039/c3cp44651d
173. Zhou P, Yu J, Wang Y (2013) The new understanding on photocatalytic mechanism of visible-light response NS codoped anatase TiO_2 by first-principles. Appl Catal B Environ 142–143:45–53. https://doi.org/10.1016/j.apcatb.2013.04.063
174. Vitiello RP, Macak JM, Ghicov A et al (2006) N-Doping of anodic TiO_2 nanotubes using heat treatment in ammonia.

Electrochem Commun 8:544–548. https://doi.org/10.1016/j.elecom.2006.01.023
175. Prabakar K, Takahashi T, Nezuka T et al (2008) Visible light-active nitrogen-doped TiO_2 thin films prepared by DC magnetron sputtering used as a photocatalyst. Renew Energy 33:277–281. https://doi.org/10.1016/j.renene.2007.05.018
176. Pomoni K, Vomvas A, Trapalis C (2008) Electrical conductivity and photoconductivity studies of TiO_2 sol-gel thin films and the effect of N-doping. J Non Cryst Solids 354:4448–4457. https://doi.org/10.1016/j.jnoncrysol.2008.06.069
177. Kim D, Fujimoto S, Schmuki P, Tsuchiya H (2008) Nitrogen doped anodic TiO_2 nanotubes grown from nitrogen-containing Ti alloys. Electrochem Commun 10:910–913. https://doi.org/10.1016/j.elecom.2008.04.001
178. Hahn R, Ghicov A, Salonen J et al (2007) Carbon doping of self-organized TiO_2 nanotube layers by thermal acetylene treatment. Nanotechnology 18. https://doi.org/10.1088/0957-4484/18/10/105604
179. Sreekantan S, Zaki SM, Lai CW, Tzu TW (2014) Copper-incorporated titania nanotubes for effective lead ion removal. Mater Sci Semicond Process 26:620–631. https://doi.org/10.1016/j.mssp.2014.05.034
180. Momeni MM, Ghayeb Y, Ghonchegi Z (2015) Fabrication and characterization of copper doped TiO_2 nanotube arrays by in situ electrochemical method as efficient visible-light photocatalyst. Ceram Int 41:8735–8741. https://doi.org/10.1016/j.ceramint.2015.03.094
181. Zakir O, Ait Karra A, Idouhli R et al (2022) Fabrication and characterization of Ag- and Cu-doped TiO_2 nanotubes (NTs) by in situ anodization method as an efficient photocatalyst. J Solid State Electrochem 26:2247–2260. https://doi.org/10.1007/s10008-022-05237-4
182. Ghicov A, Schmidt B, Kunze J, Schmuki P (2007) Photoresponse in the visible range from Cr doped TiO_2 nanotubes. Chem Phys Lett 433:323–326. https://doi.org/10.1016/j.cplett.2006.11.065
183. Zhang H, Xing Z, Zhang Y et al (2015) Ni^{2+} and Ti^{3+} co-doped porous black anatase TiO_2 with unprecedented-high visible-light-driven photocatalytic degradation performance. RSC Adv 5:107150–107157. https://doi.org/10.1039/c5ra23743b
184. Li Z, Ding D, Liu Q et al (2014) Ni-doped TiO_2 nanotubes for wide-range hydrogen sensing. Nanoscale Res Lett 9:118. https://doi.org/10.1186/1556-276X-9-118
185. Benjwal P, Kar KK (2015) One-step synthesis of Zn doped titania nanotubes and investigation of their visible photocatalytic activity. Mater Chem Phys 160:279–288. https://doi.org/10.1016/j.matchemphys.2015.04.038
186. Loan TT, Huong VH, Tham VT, Long NN (2018) Effect of zinc doping on the bandgap and photoluminescence of Zn^{2+}-doped TiO_2 nanowires. Phys B Condens Matter 532:210–215. https://doi.org/10.1016/j.physb.2017.05.027
187. Bharti B, Kumar S, Lee HN, Kumar R (2016) Formation of oxygen vacancies and Ti^{3+} state in TiO_2 thin film and enhanced optical properties by air plasma treatment. Sci Rep 6:1–12. https://doi.org/10.1038/srep32355
188. Liu H, Liu G, Zhou Q (2009) Preparation and characterization of Zr doped TiO_2 nanotube arrays on the titanium sheet and their enhanced photocatalytic activity. J Solid State Chem 182:3238–3242. https://doi.org/10.1016/j.jssc.2009.09.016
189. Choi W, Termin A, Hoffmann MR (1994) The Role of Metal Ion Dopants in Quantum-Sized TiO_2: Correlation between Photoreactivity and Charge Carrier Recombination Dynamics. J Phys Chem 98:13669–13679. https://doi.org/10.1021/j100102a038
190. Momeni MM, Ghayeb Y (2015) Fabrication, characterization and photoelectrochemical behavior of Fe–TiO_2 nanotubes composite photoanodes for solar water splitting. J Electroanal Chem 751:43–48. https://doi.org/10.1016/j.jelechem.2015.05.035
191. Naushad M, Rajendran S, Lichtfouse E (2020) Green Photocatalysts. Springer International Publishing, Cham
192. Gerischer H, Lübke M (1986) A particle size effect in the sensitization of TiO_2 electrodes by a CdS deposit. J Electroanal Chem 204:225–227. https://doi.org/10.1016/0022-0728(86)80520-4
193. Chong B, Zhu W, Hou X (2017) Epitaxial hetero-structure of CdSe/TiO_2 nanotube arrays with PEDOT as a hole transfer layer for photoelectrochemical hydrogen evolution. J Mater Chem A 5:6233–6244. https://doi.org/10.1039/c6ta10202f
194. Guijarro N, Lana-Villarreal T, Mora-Seró I et al (2009) CdSe Quantum Dot-Sensitized TiO_2 Electrodes: Effect of Quantum Dot Coverage and Mode of Attachment. J Phys Chem C 113:4208–4214. https://doi.org/10.1021/jp808091d
195. Konstantinova E, Savchuk T, Pinchuk O et al (2022) Photoelectron Properties and Organic Molecules Photodegradation Activity of Titania Nanotubes with Cu_xO Nanoparticles Heat Treated in Air and Argon. Molecules 27:8080. https://doi.org/10.3390/molecules27228080
196. Hou Y, Li X, Zou X et al (2009) Photoeletrocatalytic Activity of a Cu_2O-Loaded Self-Organized Highly Oriented TiO_2 Nanotube Array Electrode for 4-Chlorophenol Degradation. Environ Sci Technol 43:858–863. https://doi.org/10.1021/es802420u
197. Shen K, Wu K, Wang D (2014) Band alignment of ultra-thin hetero-structure ZnO/TiO_2 junction. Mater Res Bull 51:141–144. https://doi.org/10.1016/j.materresbull.2013.12.013
198. Davaslıoğlu İÇ, Volkan Özdokur K, Koçak S et al (2021) WO_3 decorated TiO_2 nanotube array electrode: Preparation, characterization and superior photoelectrochemical performance for rhodamine B dye degradation. J Mol Struct 1241. https://doi.org/10.1016/j.molstruc.2021.130673
199. Dai G, Yu J, Liu G (2011) Synthesis and Enhanced Visible-Light Photoelectrocatalytic Activity of p − n Junction BiOI/TiO_2 Nanotube Arrays. J Phys Chem C 115:7339–7346. https://doi.org/10.1021/jp200788n
200. Wang M, Sun L, Lin Z et al (2013) P-n Heterojunction photoelectrodes composed of Cu_2O-loaded TiO_2 nanotube arrays with enhanced photoelectrochemical and photoelectrocatalytic activities. Energy Environ Sci 6:1211–1220. https://doi.org/10.1039/c3ee24162a
201. Likodimos V (2018) Photonic crystal-assisted visible light activated TiO_2 photocatalysis. Appl Catal B Environ 230:269–303. https://doi.org/10.1016/j.apcatb.2018.02.039
202. Dasgupta N, Ranjan S, Lichtfouse E (2020) Environmental Nanotechnology, vol 4. Springer International Publishing, Cham
203. Athanasekou CP, Likodimos V, Falaras P (2018) Recent developments of TiO_2 photocatalysis involving advanced oxidation and reduction reactions in water. J Environ Chem Eng 6:7386–7394. https://doi.org/10.1016/j.jece.2018.07.026
204. Kment S, Riboni F, Pausova S et al (2017) Photoanodes based on TiO_2 and α-Fe_2O_3 for solar water splitting-superior role of 1D nanoarchitectures and of combined heterostructures. Chem Soc Rev 46:3716–3769
205. Fujishima AH (1972) Electrochemical Photolysis of Water at a Semiconductor Electrode. Nature 238:37–38. https://doi.org/10.1038/238037a0
206. Awitor KO, Rafqah S, Géranton G et al (2008) Photo-catalysis using titanium dioxide nanotube layers. J Photochem Photobiol A Chem 199:250–254. https://doi.org/10.1016/j.jphotochem.2008.05.023
207. Banerjee S, Pillai SC, Falaras P et al (2014) New insights into the mechanism of visible light photocatalysis. J Phys Chem Lett 5:2543–2554. https://doi.org/10.1021/jz501030x
208. Sorokina L, Savitskiy A, Shtyka O et al (2022) Formation of Cu-Rh alloy nanoislands on TiO_2 for photoreduction of carbon dioxide. J Alloys Compd 904:164012. https://doi.org/10.1016/j.jallcom.2022.164012

209. Shtyka O, Ciesielski R, Kedziora A et al (2022) Catalytic activity of semiconductors under the influence of electric fields. Appl Catal A Gen 635:118541. https://doi.org/10.1016/j.apcata.2022.118541
210. Savchuk TP, Kytina EV, Konstantinova EA et al (2022) Photocatalytic CO_2 Conversion Using Anodic TiO_2 Nanotube-Cu_xO Composites. Catalysts 12:1011. https://doi.org/10.3390/catal12091011
211. Park SM, Razzaq A, Park YH et al (2016) Hybrid Cu_xO-TiO_2 Heterostructured Composites for Photocatalytic CO_2 Reduction into Methane Using Solar Irradiation: Sunlight into Fuel. ACS Omega 1:868–875. https://doi.org/10.1021/acsomega.6b00164
212. Mirkhani V, Tangestaninejad S, Moghadam M et al (2009) Photocatalytic degradation of azo dyes catalyzed by Ag doped TiO_2 photocatalyst. J Iran Chem Soc 6:578–587. https://doi.org/10.1007/BF03246537
213. Tanaka K, Padermpole K, Hisanaga T (2000) Photocatalytic degradation of commercial azo dyes. Water Res 34:327–333. https://doi.org/10.1016/S0043-1354(99)00093-7
214. Houas A, Lachheb H, Ksibi M et al (2001) Photocatalytic degradation pathway of methylene blue in water. Appl Catal B Environ 31:145–157
215. Bianco Prevot A, Baiocchi C, Brussino MC et al (2001) Photocatalytic Degradation of Acid Blue 80 in Aqueous Solutions Containing TiO_2 Suspensions. Environ Sci Technol 35:971–976. https://doi.org/10.1021/es000162v
216. Nasikhudin, Diantoro M, Kusumaatmaja A, Triyana K (2018) Study on Photocatalytic Properties of TiO_2 Nanoparticle in various pH condition. J Phys Conf Ser 1011. https://doi.org/10.1088/1742-6596/1011/1/012069
217. Saravanan Rajendran Mu, Naushad LC, Ponce EL (2020) Green Methods for Wastewater Treatment. Springer International Publishing, Cham
218. Jafari T, Moharreri E, Amin AS et al (2016) Photocatalytic water splitting - The untamed dream: A review of recent advances. Molecules 21. https://doi.org/10.3390/molecules21070900
219. Zhang Q, Xu D, Zhou X, Zhang K (2014) Solar hydrogen generation from water splitting using ZnO/CuO hetero nanostructures. In: Energy Procedia. Elsevier Ltd, pp 345–348
220. Sığırcık G, Aydın EB (2020) Electrochemical synthesize and characterization of ZnO/ZnS nanostructures for hydrogen production. Int J Energy Res 44:11756–11771. https://doi.org/10.1002/er.5814
221. Online VA, Allam NK, Deyab NM, Ghany NA (2013) photoanode materials for efficient solar hydrogen production. 12274–12282. https://doi.org/10.1039/c3cp52076e
222. Li Y, Lu G, Li S (2003) Photocatalytic production of hydrogen in single component and mixture systems of electron donors and monitoring adsorption of donors by in situ infrared spectroscopy. Chemosphere 52:843–850. https://doi.org/10.1016/S0045-6535(03)00297-2
223. Radecka M, Rekas M, Trenczek-Zajac A, Zakrzewska K (2008) Importance of the band gap energy and flat band potential for application of modified TiO_2 photoanodes in water photolysis. J Power Sources 181:46–55. https://doi.org/10.1016/j.jpowsour.2007.10.082
224. Carabin A, Drogui P, Robert D (2015) Photo-degradation of carbamazepine using TiO_2 suspended photocatalysts. J Taiwan Inst Chem Eng 54:109–117. https://doi.org/10.1016/j.jtice.2015.03.006
225. Ashokkumar M (1998) An overview on semiconductor particulate systems for photoproduction of hydrogen. Int J Hydrogen Energy 23:427–438. https://doi.org/10.1016/s0360-3199(97)00103-1
226. Hattori M, Noda K, Kobayashi K, Matsushige K (2011) Gas phase photocatalytic decomposition of alcohols with titanium dioxide nanotube arrays in high vacuum. Phys Status Solidi Curr Top Solid State Phys 8:549–551. https://doi.org/10.1002/pssc.201000455
227. Mor GK, Shankar K, Paulose M et al (2005) Enhanced Photocleavage of Water Using Titania Nanotube Arrays. Nano Lett 5:191–195. https://doi.org/10.1021/nl048301k
228. Li H, Wu S, Hood ZD et al (2020) Atomic defects in ultra-thin mesoporous TiO_2 enhance photocatalytic hydrogen evolution from water splitting. Appl Surf Sci 513:145723. https://doi.org/10.1016/j.apsusc.2020.145723
229. Zhu K, Neale NR, Miedaner A, Frank AJ (2007) Enhanced charge-collection efficiencies and light scattering in dye-sensitized solar cells using oriented TiO_2 nanotubes arrays. Nano Lett 7:69–74. https://doi.org/10.1021/nl062000o
230. Hsiao PT, Liou YJ, Teng H (2011) Electron transport patterns in TiO_2 nanotube arrays based dye-sensitized solar cells under frontside and backside illuminations. J Phys Chem C 115:15018–15024. https://doi.org/10.1021/jp202681c
231. Roy P, Kim D, Lee K et al (2010) TiO_2 nanotubes and their application in dye-sensitized solar cells. Nanoscale 2:45–59. https://doi.org/10.1039/b9nr00131j
232. Paulose M, Shankar K, Varghese OK et al (2006) Application of highly-ordered TiO_2 nanotube-arrays in heterojunction dye-sensitized solar cells. J Phys D Appl Phys 39:2498–2503. https://doi.org/10.1088/0022-3727/39/12/005
233. Babar F, Mehmood U, Asghar H et al (2020) Nanostructured photoanode materials and their deposition methods for efficient and economical third generation dye-sensitized solar cells : A comprehensive review. Renew Sustain Energy Rev 129:109919. https://doi.org/10.1016/j.rser.2020.109919
234. Paulose M, Shankar K, Varghese OK et al (2006) Backside illuminated dye-sensitized solar cells based on titania nanotube array electrodes. Nanotechnology 17:1446–1448. https://doi.org/10.1088/0957-4484/17/5/046
235. Wang J, Lin Z (2012) Dye-sensitized TiO_2 nanotube solar cells: Rational structural and surface engineering on TiO_2 nanotubes. Chem An Asian J 7:2754–2762. https://doi.org/10.1002/asia.201200349
236. Qi L, Yin Z, Zhang S et al (2014) The increased interface charge transfer in dye-sensitized solar cells based on well-ordered TiO_2 nanotube arrays with different lengths. J Mater Res 29:745–752. https://doi.org/10.1557/jmr.2014.50
237. Zhu W, Liu Y, Yi A et al (2019) Facile fabrication of open-ended TiO_2 nanotube arrays with large area for efficient dye-sensitized solar cells. Electrochim Acta 299:339–345. https://doi.org/10.1016/j.electacta.2019.01.021
238. Peighambardoust NS, Asl SK, Mohammadpour R, Asl SK (2019) Improved efficiency in front-side illuminated dye sensitized solar cells based on free-standing one-dimensional TiO_2 nanotube array electrodes. Sol Energy 184:115–126. https://doi.org/10.1016/j.solener.2019.03.073
239. Liu M, Zhao G, Tang Y et al (2010) A simple, stable and picomole level lead sensor fabricated on DNA-based carbon hybridized TiO_2 nanotube arrays. Environ Sci Technol 44:4241–4246. https://doi.org/10.1021/es1003507
240. Yang L, Luo S, Su F et al (2010) Carbon-nanotube-guiding oriented growth of gold shrubs on TiO_2 nanotube arrays. J Phys Chem C 114:7694–7699. https://doi.org/10.1021/jp912007g
241. Tran.t T, Li J, Feng H et al (2014) Molecularly imprinted polymer modified TiO_2 nanotube arrays for photoelectrochemical determination of perfluorooctane sulfonate (PFOS). Sens Actuat B Chem 190:745–751. https://doi.org/10.1016/j.snb.2013.09.048