

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

5,400

Open access books available

132,000

International authors and editors

160M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



# TiO<sub>2</sub>: A Semiconductor Photocatalyst

*Azrina Abd Aziz, Fatema Khatun, Minhaj Uddin Monir,  
Sim Lan Ching and Leong Kah Hon*

## Abstract

Titanium dioxide (TiO<sub>2</sub>) is considered as an inert and safe material and has been used in many applications for decades. TiO<sub>2</sub> have been widely studied, due to its interesting general properties in a wide range of fields including catalysis, antibacterial agents, in civil as nano-paint (self-cleaning) and especially photocatalysis, and that affect the quality of life. Thus, the development of nanotechnologies TiO<sub>2</sub> nanoparticles, with numerous novel and useful properties, are increasingly manufactured and used. TiO<sub>2</sub> doped with noble metal are good candidates in the performance these applications. The fascinating physical and chemical features of TiO<sub>2</sub> depend on the crystal phase, size and shape of particles. For example, varying phases of crystalline TiO<sub>2</sub> have different band gaps that rutile TiO<sub>2</sub> of 3.0 eV and anatase TiO<sub>2</sub> of 3.2 eV, determine the photocatalytic performance of TiO<sub>2</sub>. This chapter explains basic information on TiO<sub>2</sub> and theoretical concepts of nanostructure of TiO<sub>2</sub> nanoparticles as a semiconductor photocatalyst.

**Keywords:** TiO<sub>2</sub>, nanoparticles, semiconductor, photocatalyst

## 1. Introduction

An ideal photocatalyst should possess following nature: biologically and chemically inert, inexpensive, nontoxic, stable towards photocorrosion and certainly highly active and suitable towards the visible/UV light photoreaction. An additional criterion for such ideal photocatalyst is better redox potential of the H<sub>2</sub>O/<sup>•</sup>OH couple (EOP = 2.80 V) [1]. Among the available semiconductors, TiO<sub>2</sub>, ZnO, ZnS and WO<sub>3</sub> have gap energies sufficient for catalyzing a wide range of chemical reactions [2].

Binary metal sulphide semiconductors such as CdS, CdSe or PbS are regarded as unstable photocatalyst due to easy photoanodic corrosion property and their toxic nature [2, 3]. Furthermore, the iron oxide semiconductors are not suitable as they readily perform the photocathodic reaction and finally produced corrosive materials [1]. ZnO on the other hand is known to have the similar quality of band gap energy like TiO<sub>2</sub> (3.0 eV) but it is highly unstable towards pH condition, where precipitate of Zn (OH)<sub>2</sub> is formed on the particle surface and resulted in photocatalyst deactivation [2].

Of these, titanium dioxide (TiO<sub>2</sub>) is the most ideal semiconductor for photocatalytic destruction of organic compounds [2, 4]. It also provides an excellent conciliation between catalytic performance and stabilization in aqueous media [5].

## 2. Titanium dioxide (TiO<sub>2</sub>)

The strong oxidation and reduction power of photoexcited TiO<sub>2</sub> was successfully discovered by Honda-Fujishima [6, 7]. Since its innovation, extensive efforts have been made in the development of TiO<sub>2</sub> photocatalyst owing to its potential application in the removal of various types of organics and in both aqueous and air phase [8, 9]. It resulted in flexible applicability either in the form of a suspension, or immobilization [10–13].

Regardless the high superior photocatalytic efficiency of TiO<sub>2</sub>, it is popular for its unique wider applications as electroceramic, antifogging agent and as therapy for cancer [14, 15]. Moreover, it also acts as an antibacterial agent due to its strong oxidation activity and superhydrophilicity and was employed for electrolysis of water (H<sub>2</sub>O) to produce H<sub>2</sub> and for harvesting solar energy as dye-sensitized solar cells [16]. Additionally, it possesses superior pigmentary property, UV light absorption capability and durability [17]. The high refractive indices of rutile and anatase phase of TiO<sub>2</sub> laid a pathway for its versatility nature.

In general, the crystallinity, impurities, specific surface area and density of the surface hydroxy groups are the physical parameters that have influence over the photocatalytic activity of TiO<sub>2</sub>. Apart from that the band gap energy, charge-carrier and recombination as well play a crucial role for photoactivation [18, 19]. Among the available phases the anatase is the most stable form with 8–12 kJ/mol. This describes the quantity of energy transferred during phase transformation. The rest phases such as brookite is very uncommon [14, 20–21].

In the terms of density, rutile is greater than anatase, i.e., 4.26 and 3.90 g/mL respectively. However, in terms of utilization and ability, anatase phase is more efficient due to its open structure [14]. The anatase phase remains as most active photocatalyst with greater stability after repeated catalytic cycles illuminated under a photon energy between 300 nm <  $\lambda$  < 390 nm [22]. In addition, it is also chemically stable in aqueous media and in broad range of pH (0 < pH < 14) [23]. Hence TiO<sub>2</sub> with its major anatase phase had more applicability as photocatalyst [24]. Furthermore, it also exhibits relatively high reactivity and chemical stability only under UV light ( $\lambda$  < 387 nm) [7]. Thus, its limited utilization of the activation energy becomes a major drawback. Therefore, to overcome this limitation of TiO<sub>2</sub>, an extensive research needs to be emphasized to develop a titania based photocatalyst that can exhibit high reactivity under visible light spectrum ( $\lambda$  > 400 nm) and can persuades the utilization of solar spectrum, even under poor luminance of interior lighting [7].

The reduction in energy gap between the CB and VB further leads to the easy recombination of the formed electrons and holes. This recombination further decreases the interfacial charge-carrier transfer. The size of the TiO<sub>2</sub> further causes difficulties in separating them from the waste's stream. All these issues stress the reseachers to find a suitable composition/dopant for its modification [25].

## 3. Modification of TiO<sub>2</sub> photocatalyst

The photoactivity of TiO<sub>2</sub> is hindered by the narrow UV wavelength spectrum for photoactivation under ambient conditions. The generation of this UV requires additional power source, which shoots the activation cost of the photocatalyst. Therefore, the utilization of renewable energy source could be a better sustainable choice for the photoactivation [26].

Type	Remark	Reference
Chromium (Cr)	This is a study on the effect of the photoreduction of dinitrogen in a gas–solid regime using Cr as a dopant for phenol degradation. The prepared Cr-TiO <sub>2</sub> showed an enhanced activity and displacement of the Fermi level at the TiO <sub>2</sub> interface. But the presence of Cr as donor ion did not favor the charge separation with respect to pure TiO <sub>2</sub> .	[34]
Iron (Fe)	Fe <sup>3+</sup> ion has a unique half-filled electronic structure which resulted in enhanced activity compared to Fe <sup>4+</sup> and Fe <sup>2+</sup> . The stable Fe <sup>3+</sup> ion detrapped the electron and hole to adsorbed oxygen and surface hydroxyl group, thereby suppressed the electron–hole recombinations.	[35]
	This study is about the effect of Fe doping into TiO <sub>2</sub> for the degradation of chloroform (CHCl <sub>3</sub> ). It observed that Fe provided shallow trapping sites for the charge-carriers and increase the photocatalytic efficiency. It also found that Fe can act as trap for both electron and hole, at high dopant concentration.	[36]
	This study is about the Fe-doped with TiO <sub>2</sub> for the degradation of 1, 2-dichloroethane. The study proved that Fe <sup>3+</sup> alleviates the surface phenomenon and act as both electron–hole traps.	[37]
Molybdenum (Mo)	The effect of Fe doping for the inactivation of <i>E. coli</i> was studied. The Fe-doped TiO <sub>2</sub> proved the enhancement in the inactivation of <i>E. coli</i> . Fe played as a source for the inhibition of the anatase crystal growth.	[38]
	The Mo as a cationic dopant was studied in 2009. The dopant increased the surface acidity of TiO <sub>2</sub> and accelerated the interfacial charge transfer process. Thus, prepared doped photocatalyst degraded the cationic dyes, rhodamine B (RhB) and methylene blue (MB) and anionic dyes, methyl orange (MO) and congo red (CR) at both alkaline and acidic pH.	[39]
Zinc (Zn)	Similarly, the same group studied the effect of Zn as a dopant in 2010 and applied the prepared photocatalyst for the degradation of CR. They produced a small crystallite size and stable filled electronic configuration of Zn <sup>2+</sup> -TiO <sub>2</sub> . Moreover, this photocatalyst provided a shallow trap for the charge-carriers contributing to the overall activity.	[40]
Manganese (Mn)	They further extended their study with Mn as a potential cationic dopant in 2011. From the study, it showed that Mn <sup>2+</sup> intimate contact between the mixed anatase and rutile phase of TiO <sub>2</sub> . Moreover, this dopant has synergistic effects in the bicrystalline framework of anatase and rutile. The unique half-filled electronic structure of Mn <sup>2+</sup> served as a shallow trap for the charge-carrier contributed for the appreciable degradation of both Indigo carmine dye and 4-chlorophenol.	[41]
Cobalt (Co)	Amadelli et al., 2008 studied the effect of Co-doping. They prepared the photocatalyst by incipient impregnation method and cobalt acetate as a precursor. Co addition brings about conspicuous changes in the point of zero charge and in surface polarity. They found that Co-doped TiO <sub>2</sub> is more active compared to TiO <sub>2</sub> . The best photocatalytic result of the prepared photocatalyst is obtained for heat treatment at 400°C for 30 min.	[42]
Thorium (Th)	Thorium a naturally occurring radioactive element was studied as a dopant in 2009. It observed that Th can contributed well for the BET surface area of photocatalyst. Moreover, the presence of two absorption edges at 460 and 482 nm in visible region enabled the photocatalyst to utilize more visible light. They reported that the strong adsorption of the pollutant was due to the complex formation between the vacant f orbital of Th <sup>4+</sup> . Besides, they observed that Th induced the oxygen vacancies which served as shallow traps. But thorium could further contribute for radioactive pollution.	[39]

**Table 1.**  
 Literature review of selected metal dopant/hybrid on TiO<sub>2</sub>.

Type	Remark	Reference
Nitrogen (N)	In 2001, researchers prepared $\text{TiO}_{2-x}\text{N}_x$ by sputtering the $\text{TiO}_2$ selectively on $\text{N}_2$ (40%)/Ar gas mixture for degradation of MB and acetaldehyde ( $\text{CH}_3\text{CHO}$ ) under UV/visible light.	[43]
	Researchers prepared a narrow band gap N-TiO <sub>2</sub> with oxygen vacancies. Thus, prepared N-TiO <sub>2</sub> failed to oxidize formate and $\text{NH}_3\text{-OH}^+$ under visible light illumination. Their preparation method resulted the N as a weak anion donor.	[44]
	This is the study about the preparation of N-TiO <sub>2</sub> by thermal decomposition of the $\text{Ti}^{4+}$ -bipyridine complex and had moderately better removal of $\text{NO}_x$ under artificial visible light.	[45]
	The researchers prepared $\text{TiO}_{2-x}\text{N}_x$ by solvothermal route, produced violet color of particles and further calcination between 200 and 800°C produced weak violet, bright yellow, weak yellow and gray; no white color of particles. Their findings proved the thermal stability of Ti-N bonding with $\text{TiO}_{2-x}\text{N}_x$ .	[46]
	N-TiO <sub>2</sub> was prepared using Ti-melamine and Ti-salen complex as precursors and reported a higher photoactivity was obtained for the Ti-melamine by degrading MB degradation. The reasoned for the low photoactivity of the Ti-salen complex was due to the low amount of N doping and smaller Ti-N bonds.	[47]
	N-doped layered titanates ( $\text{Cs}_{0.68}\text{Ti}_{1.83}\text{O}_{4-x}\text{N}_x$ and $\text{H}_{0.68}\text{Ti}_{1.83}\text{O}_{4-x}\text{N}_x$ ) with leciprocate structure was prepared and achieved better photoactivity by degrading RhB under visible light illumination. The unique layered structure of titanates and homogeneous distribution of N dopant contributed for the mobility of the charge-carrier further contributed for the faster and better photoactivity.	[48]
Multitype N-TiO <sub>2</sub> containing both substitutional (N-Ti-O and Ti-N-O) and interstitial NO characteristics was prepared. The substitutional and interstitial technique resulted in intraband states at 0.14 and 0.73 eV above the VB resulting in faster visible light driven photodegradation of gas phase toluene.	[49]	
Carbon (C)	A carbonaceous coke-like species embedded in the $\text{TiO}_2$ matrix was obtained by pyrolysis of alcohol in the sol-gel titania processing and calcined at 250 and 400°C. The resulted C-TiO <sub>2</sub> calcined at 250°C exhibited a maximum photoactivity for degradation of 4-chlorophenol (4-CP) under visible light than that the later. Further calcination to the higher temperature caused the elimination of carbon from the titania matrix. Thus, showed significance of the calcination temperature.	[50]
	A rutile $\text{TiO}_2$ doped with carbon was prepared by a pyrolysis method using combustion products namely $\text{CO}_2$ and $\text{H}_2\text{O}$ and used for water splitting reaction. Their doping method resulted in a band gap of 2.32 eV against 3.0 eV and showed the supremacy of the preparation method.	[51]
	$\text{TiO}_2\text{-G}$ (titania-glycine) was successfully prepared through solution combustion route by glycine (G), hexemethylene (H) and oxalyldihydrazide (O) as fuel. The precursors employed contributed for the carbide ion and thus reduced band gap energy and resulted in a superior photoactivity, crystallinity and surface area. The photoactivity was successfully experimented by degrading aqueous phase MB under solar irradiation.	[52]
	$\text{TiO}_2\text{-C}$ was prepared through a simple carbon sources, which is tetrabutylammonium hydroxide ( $\text{C}_{16}\text{H}_{37}\text{NO}$ ) and glucose ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) as precursors. The adopted precursors contributed in two visible absorption edges in their band gap namely 2.78 and 1.45 eV, respectively.	[53]
	Park et al., 2009 showed the importance of optimum calcination temperature like Lettmann and coworkers in 2001.	[54]

Type	Remark	Reference
Fluorine (F)	The researchers chose F as an anionic dopant and obtained F-TiO <sub>2</sub> via spray hydrolysis from fluorotitanic acid (H <sub>2</sub> TiF <sub>6</sub> ) precursor. Their work showed that F can excited under visible light but does not contributed for the intrinsic absorption properties rather that the extrinsic properties of TiO <sub>2</sub> absorption.	[55]
Boron (B)	Boron was selected as a potential anion dopant and obtained B-TiO <sub>2</sub> which resulted in wider band gap energy, larger thermodynamic and faster charge-carrier transfer.	[56]
Phosphorus (P)	Phosphorus as dopant was experimented via phosphoric acid (H <sub>3</sub> PO <sub>4</sub> ) and had higher photooxidation of <i>n</i> -pentane in air. It was due to the formation of Ti ions in tetrahedral coordination of TiO <sub>2</sub> .	[57]

**Table 2.**  
 Literature review of selected non-metal dopant/hybrid on TiO<sub>2</sub>.

Attempt to shift the optical response of TiO<sub>2</sub> from the UV to the visible spectrum will have a profound positive effect on the photocatalytic efficiency [27]. The visible light reception potential of these photocatalysts is either highly unstable under their illumination (e.g. CdS and CdSe) or have limited photoactivity (e.g. WO<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>) [26]. Therefore, doping/hybridizing TiO<sub>2</sub> with transition metals like Fe, Co, Ni, etc. [28], non-metals like N, O, C, B, etc. [29], noble metals like Ag, Pt, Au or its metal ions incorporation [30], incorporating carbon nanotubes [31] and dyed sensitizers [32] have been proposed to improve its photocatalytic efficiency under solar light.

These modifications either by doping or hybridization are based on the concept of balancing both the half-reaction rates of the photocatalytic reaction by adding electron acceptor, or modifying the photocatalyst structure and composition [26]. The enhancement shown by doped ions is by providing charge trapping sites which leads to the reduction of electron-hole recombination [33]. In addition, the excited electron is expelled by the electron acceptors and hence hinders the recombination of electron-hole pairs [26].

In general, parameters such as types of doping/hybrid, its concentration, synthesizing technique and physico-chemical characteristics of the photocatalyst will have control over the photocatalytic activity. It was observed that the formation of both free <sup>•</sup>OH and active O<sub>2</sub> species is improved with the increase in charge separation efficiency [26]. The detailed literature reviews of these metals and non-metals dopant/hybrid are tabulated in **Tables 1** and **2** respectively.

#### 4. Modification of TiO<sub>2</sub> with graphene oxide

The incorporation of highly conductive carbon materials can also enhance the electron-hole pair separation of the photocatalyst. Graphene oxide commonly known as GO, is one such high conductive carbon materials that can be employed as a dopant/hybrid. Graphene can be regarded as the origin of all graphitic forms and can be curled, rolled or stacked to shape buckyball fullerenes, carbon nanotubes or graphite [58–60]. With free-standing 2-dimensional (2D) crystal and one-atom thickness properties, it has emerged with wide applications in several fields but employed mostly in nanotechnology for the improvisation of materials chemistry [61]. The unique single atom-thick planar sheet of sp<sup>2</sup> hybridized carbon atoms contribute to efficient storing and shuttling of electrons [61]. Moreover, it attracted the scientific community tremendously because of its distinctive electronic properties, superior chemical stability and soaring specific surface area [61].

The exfoliated graphene sheets employ a theoretical surface area of around 2600 m<sup>2</sup>/g, and as a result graphene appears as an attractive high-surface area 2D photocatalyst support [62]. Besides it has potential ideal electron sinks or electron transfer bridges [63]. This was attributed to its exceptional structure that allow ballistic transport, in which electrons can travel without scattering at mobilities exceedingly approximately 15,000 m<sup>2</sup>/V/s at room temperature [63]. They are also foremost responsive for chemical doping, adsorbed or bound species and structure distortion [64]. Further incorporation of inorganic materials with modified graphene enormously improves their electronic, electrocatalytic and photocatalytic characteristics [32]. Thus, it proves the potential to enhance the fast electron transfer that highly benefits photocatalysis [32].

Recently modifying TiO<sub>2</sub> surface with carbonaceous materials propounded to induce visible-light responsive property. Few types of carbonaceous materials such as graphitic or coke-like carbon [50, 65], or carbonate structural fragments bonding with titanium were employed for this purpose. Graphene oxide supported TiO<sub>2</sub> is expected to create synergistic effect that enhances the solar photocatalytic activity. The synergistic effect attributes to its unique separation efficiency of electrons and holes between TiO<sub>2</sub> and graphene oxide [32, 66]. The photo-reductions initiated in the transformation of graphene oxide to graphene lays a platform for continuous electron conducting network through cross-surface charge percolation and permitted graphene to act as an efficient exciton sink [66].

Nguyen-Phan et al., [32] adopted a simple one-step colloidal blending method as an environmentally friendly that preserves the TiO<sub>2</sub> properties and combines the advantages of graphene oxide. The prepared composites showed superior adsorptivity and photocatalytic activity under both UV and visible light [32]. This was proved through a photocatalytic degradation study by adopting MB as model pollutant excited under artificial solar energy. The study indicated that graphene oxide acted as an adsorbent, electron acceptor and photosensitizer in the process of accelerating photodecomposition [32].

Recently Hu et al., 2012 also reported that graphene oxide/TiO<sub>2</sub> hybrid (GOT) demonstrated an excellent adsorption and photocatalysis performance under visible radiation by degrading MB dye under solar irradiation. The phenomenon was due to the electron sink in GOT that contributed for the photoactivity [67].

## 5. Noble metal deposited TiO<sub>2</sub> photocatalyst

Apart from these metals, non-metals and graphene oxide as dopant/hybrid, few reseachers have also utilized the noble metals like platinum (Pt), gold (Au) and silver (Ag) as a potential source of dopant. The expensive Pt deposition on both rutile and anatase TiO<sub>2</sub> was performed by Scalfani et al., 1998, Kim et al., 2002, Sun et al., 2003, Bosc and coworkers, 2006 and Hidalgo and coworkers, 2007. All their study showed that Pt had beneficial effects for the photocatalytic oxidation. The Pt as a dopant/hybrid has increased the electron mobility rate of TiO<sub>2</sub>. This mobility has contributed for the electron transfer to the adsorbed oxygen (O<sup>-</sup><sub>ads</sub>) especially in rutile TiO<sub>2</sub>. A negligible such effect was observed in the anatase phase [68–72].

Owing to the versatile potential of the Au, it was also chosen as a dopant by the reseachers [73, 74]. The study by reseachers showed that Au can behaves like a semiconductor rather than metallic. The size of Au plays a major role in the interfacial electron transfer to adsorbed oxygen (O<sup>-</sup><sub>ads</sub>). The Fermi level of the Au particle will be lowered than that of adsorbed oxygen (O<sup>-</sup><sub>ads</sub>) in TiO<sub>2</sub> and this depends on the

particle size of Au. The Au also contributed for the hindering effect of the surface recombination. Thus, they exhibited an improvised visible light photoactivity.

Finally, the influence of Ag as a dopant/hybrid was studied by Szabo et al., 2003 and Christopher et al., 2010. Their study showed that Ag as a dopant contributed for the uniform morphology of the TiO<sub>2</sub> and increased the probability function of excited oxygen atoms via electron transfer from adsorbed oxygen (O<sup>-</sup><sub>ads</sub>) produced from O<sub>2</sub><sup>2-</sup> to the hole. The Ag also further exhibited a unique Surface Plasmon Resonance (SPR) property. Thus, exhibited SPR lowered the electron-hole recombination rate. All these potentially improvised the photoactivity of TiO<sub>2</sub> with a better degradation of the pollutants either under natural or artificial visible light illumination [30, 75].

## 6. Magnetic particles deposited TiO<sub>2</sub> photocatalyst

Though these noble metals dopant/hybrid had a significant contribution on the photocatalytic mechanism of TiO<sub>2</sub>, they are highly expensive and further increasing the cost of the prepared photocatalyst. Most of the modification techniques solve the issues of photocatalytic efficiency however, leaving behind the separation difficulty. Such separation could make them reuse and contribute for economy of the treatment cost. Most commonly these photocatalysts are nanoparticles and requires high speed centrifugation or membrane filtration. However, adopting these techniques further burdens the economy of the treatment. Hence doping/hybridizing the photocatalyst with a ferromagnetic material could be a best alternative.

Hence coating the photocatalyst with magnetic particles emerges to be a promising method to separate the photocatalyst from treated stream [76]. Nanoparticles combine with magnetic core and photoactive shell using magnetic granules and semiconductor photocatalyst is reported to possess magnetic property and separation could be achieved easily by applying simple magnetic field [77]. For these purpose magnetic cores such as magnetite (Fe<sub>3</sub>O<sub>4</sub>), maghemite (Fe<sub>2</sub>O<sub>3</sub>), nickel ferrite (NiFe<sub>2</sub>O<sub>4</sub>), etc. were chosen. Though separation of photocatalysts was achieved their photocatalytic activity was found to decrease than that of pure TiO<sub>2</sub> [8, 78, 79].

Beydoun et al. prepared the magnetic photocatalyst by coating TiO<sub>2</sub> particles onto Fe<sub>3</sub>O<sub>4</sub> particles. They observed that the magnetic core was easily oxidized and suppressed the photoactivity of the TiO<sub>2</sub> [76, 80, 81]. Alternatively, Chen et al., 2001 prepared the magnetically separable photocatalyst by coating TiO<sub>2</sub> particles onto  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> particles. Their preparation method transformed ferromagnetic  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> to  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> paramagnetic material and resulted in poor separation efficiency [79]. Such phase transformation from  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> to  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> was triggered by annealing temperature. Therefore, difficulties arise to synthesize TiO<sub>2</sub> coated particles with high photoactivity without loss of magnetic property by an iron oxide phase transition, as well as of high crystallinity without agglomeration, or formation of impurities by solid diffusion [9].

Chung et al., 2004 reported a TiO<sub>2</sub>-coated NiFe<sub>2</sub>O<sub>4</sub> photocatalyst by multi-step ultrasonic spray pyrolysis method. Their complicated synthesize method resulted the photocatalyst in micron size. Owing to the micron size of the photocatalyst the activity and the separation efficiency declined drastically [4]. Similarly, Xu et al., 2007 prepared a magnetically separable nitrogen-doped photocatalyst, TiO<sub>2</sub><sub>x</sub>N<sub>x</sub>/SiO<sub>2</sub>/NiFe<sub>2</sub>O<sub>4</sub> (TSN) by a simple method, which consists of a NiFe<sub>2</sub>O<sub>4</sub> as magnetic core, a SiO<sub>2</sub> as magnetic barrier and nitrogen as visible-light-active dopant. Their prepared TSN was found to possess a great photocatalytic activity by removing MO in the presence of artificial UV and visible light illumination [9].



In recent years the M type hexaferrites,  $MFe_{12}O_{19}$  ( $M = Ba, Sr, Pb, \text{etc}$ ) gained interest over the spinel ferrite ( $NiFe_2O_4$ ), since the magnetic properties of M type hexaferrites allow them to serve as highly stable permanent magnet. One such M type hexaferrites, strontium ferrite ( $SrFe_{12}O_{19}$ ), is regarded as an excellent magnetic material [82]. There was so far no report discussed about nanoscale hexaferrites as carriers for magnetic photocatalyst before Fu et al., 2006 synthesized  $TiO_2/SrFe_{12}O_{19}$  composite nanoparticles with core-shell structure. Despite the fact that the photocatalytic activity of the composite is slightly lower than that of Degussa P25, the separation of composite particles was well achieved with an external magnetic field, thus proved the separation incapability of commercial photocatalyst Degussa P25 [82].

Researches on protective layer-coated permanent magnets nanoparticles have been studied for both fundamental magnetic investigations and practical engineering applications. In such investigations, coated nanoparticles attracted the attention as the coating hinders the nanocomposites from coarsening and agglomeration. In practical engineering applications, coating works well in magnetic applications as an insulate phase to achieve high electric resistivity and behaves as a binder to ease the consolidation of the nanoparticles [18, 19].

Coating magnetic nanoparticles with silica ( $SiO_2$ ) is becoming a significant topic in the research of magnetic nanocomposites. The formation of  $SiO_2$  interlayer on the surface of magnetic nanoparticles helps to screen the magnetic dipolar attraction between magnetic nanoparticles. It also protects from leaching of the core magnetic materials during the dispersion in the aqueous phase. Moreover,  $SiO_2$  coating could be easily activated to provide its surface with various functional groups due to the presence of abundant silanol groups in it. Finally,  $SiO_2$  interlayer plays a very significant role in providing a chemically inert surface for magnetic layer. Hence inclusion of a protective  $SiO_2$  coating will suppress the electron-hole recombination rate that occurs in the photocatalyst and benefits both the photo and magnetic activity.

## 7. Doped/hybrid $TiO_2$ photocatalytic mechanism

The basic mechanism of  $TiO_2$  photocatalyst is described based on **Figure 1**, which initiated by the absorption of the photon  $h\nu_1$  with energy equal to the band gap of anatase  $TiO_2$  (3.20 eV). Electron-hole pair is produced on the surface of titania as schematized. As known, the electron from the CB is promoted and produced positive hole in VB. The excited state electrons and holes get trap in the metastable states as well as dissipate energy as heat. Besides, they also can react with the electron donor or acceptor adsorbed on its surface. Therefore, the  $\cdot OH$  is produced with high oxidation potential which plays an important role in photocatalysis [1, 17].

The interstitial metal doped  $TiO_2$  on the other hand beneficially produced the new energy level in the band gap of  $TiO_2$  by the dispersion of metal nanoparticles in titania matrix. As shown in **Figure 1**, electron from the CB can be excited from the defect state by photon energy equals to  $h\nu_2$ . The improvement of the electrons trapping to inhibit the electron-hole recombination during its photoactivation as well described the additional advantageous of the metal ion doping. Thus, decreasing in the charge-carrier recombination resulted in enhanced photoactivity of the photocatalyst.

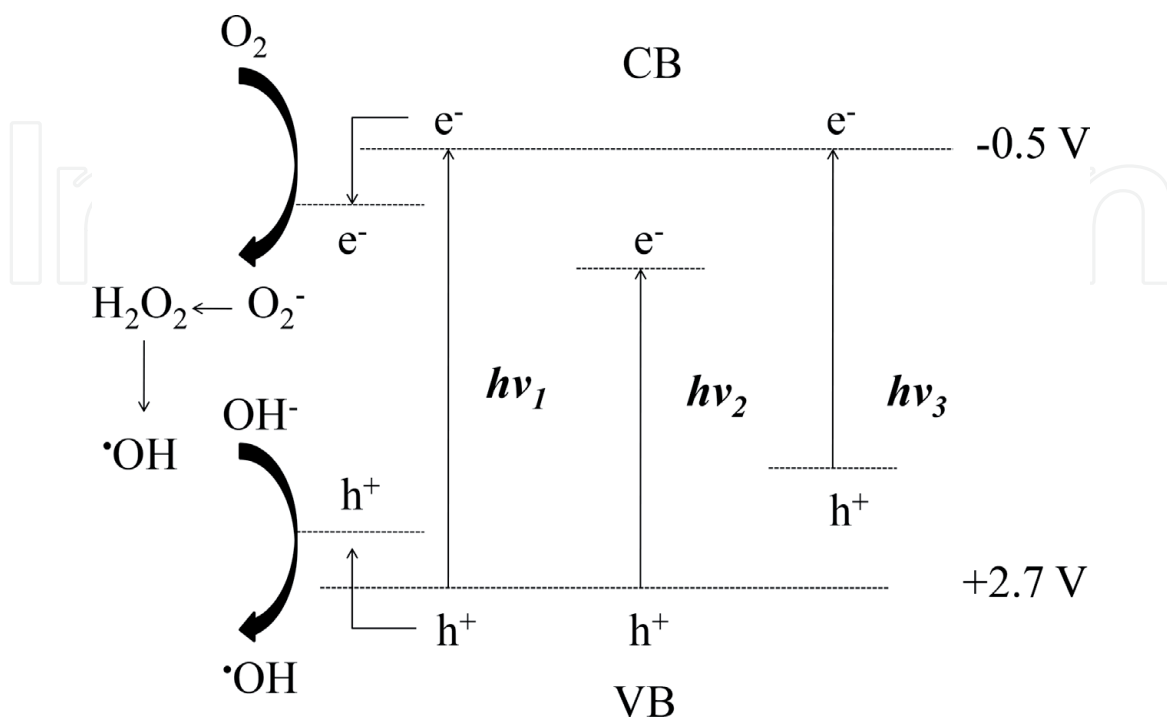
The modification of  $TiO_2$  with the non-metal ion doping provides four main opinions regarding the changes in the nature mechanism of photocatalyst as described below [7]:

1. Band gap narrowing: Asahi et al., 2001 found that the energies of the CB and VB are very narrow during the absorption of visible light. The N 2p state hybrids with the O 2p state in anatase TiO<sub>2</sub> doped with nitrogen, narrowed the band gap of N-TiO<sub>2</sub> [43].
2. Impurity energy level: Irie et al., 2003 reported that substitutional doping of nitrogen ion into TiO<sub>2</sub> forms an isolated impurity energy level above the VB. Thus, obtained impurity energy level benefits the visible light driven photocatalysis as the visible light only excites electrons in the impurity energy level [83].
3. Oxygen vacancies: Ihara et al., 2003 showed the importance of oxygen deficient sites which act as a blocker for reoxidation. These sites are produced in the grain boundaries in order to emerge visible light activity.
4. Shallowing the acceptor states: Zhao & Liu, 2008 studied the shallowing effect by substitutional doping of nitrogen into TiO<sub>2</sub> [84].

All these obtained modification in the mechanism will contribute for the better and sustainable treatment of the organic pollutants.

## 8. Conclusions

Though various studies have been carried out to find an ideal semiconductor photocatalyst, TiO<sub>2</sub> however remains as a benchmark and active photocatalyst among them and was proved in both laboratory and pilot studies. Other oxides such as ZrO<sub>2</sub>, SnO<sub>2</sub>, WO<sub>2</sub> and MoO<sub>3</sub> do not have the similar application prospects as TiO<sub>2</sub> due to the fact that these oxides are much less active, chemically and biologically instable. Several commercial TiO<sub>2</sub> photocatalysts are produced worldwide. Among



**Figure 1.** Mechanism of TiO<sub>2</sub> photocatalysts:  $h\nu_1$ : Pure TiO<sub>2</sub>;  $h\nu_2$ : Metal doped TiO<sub>2</sub> and  $h\nu_3$ : Non-metal doped TiO<sub>2</sub> [7].

them Degussa P25®, an amorphous TiO<sub>2</sub>, emerged as the best photocatalyst due to its better utilization of the UV light. It has a phase ratio of 25:75 (rutile:anatase). It is also considered as standard photocatalyst for environmental applications. The wider band gap, greater recombination of electron–hole pair and low interfacial charger carrier transfer, limit the visible light or sustainable solar energy utilization of TiO<sub>2</sub> photocatalyst. The limitations were successfully achieved by synthesizing a new and modified TiO<sub>2</sub>-based composite nanophotocatalysts through a series of simple preparation processes. The nano-size morphology of the composite photocatalysts well created the quantum effect that improved the photocatalytic properties.

## Acknowledgements

The authors express gratitude to the Ministry of Higher Education, Malaysia (MOHE) for the Fundamental Research Grant Scheme FRGS (FRGS/1/2017/TK02/UMP/02/20) for the financial support of this book chapter.

## Author details

Azrina Abd Aziz<sup>1\*</sup>, Fatema Khatun<sup>1</sup>, Minhaj Uddin Monir<sup>2</sup>, Sim Lan Ching<sup>3</sup> and Leong Kah Hon<sup>4</sup>

<sup>1</sup> Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Kuantan, Pahang, Malaysia

<sup>2</sup> Faculty of Engineering and Technology, Jashore University of Science and Technology, Department of Petroleum and Mining Engineering, Jashore, Bangladesh

<sup>3</sup> Chemical Engineering Department, Lee Kong Chian Faculty of Engineering and Science (LKC FES), UTAR Sungai Long Campus, Selangor, Malaysia

<sup>4</sup> Environmental Engineering Department, Faculty of Engineering and Green Technology, UTAR Kampar, Perak, Malaysia

\*Address all correspondence to: azrinaaziz@ump.edu.my

## IntechOpen

© 2021 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

## References

- [1] Hoffmann MR, Martin ST, Choi W, Bahnemann DW. Environmental applications of semiconductor photocatalysis. *Chemical Reviews*. 1995;95(1): 69-96.
- [2] Howe RF, Gratzel M. EPR observation of trapped electrons in colloidal TiO<sub>2</sub>. *The Journal of Physical Chemistry*. 1985; 89(21): 4495-4499.
- [3] Fischer CH, Lillie J, Weller H, Katsikas L, Henglein A. Photochemistry of colloidal semiconductors. 29. Fractionation of CdS sols of small particles by exclusion chromatography. *Berichte der Bunsengesellschaft für physikalische Chemie*. 1989;93(1): 61-64.
- [4] Beydoun D, Amal R, Low G, McEvoy S. Role of nanoparticles in photocatalysis. *Journal of Nanoparticle Research*. 1999;1(4): 439-458.
- [5] Aruna ST. Synthesis and properties of nanosized titania. *Journal of Materials Synthesis and Processing*. 1996; 4(3): 175-179.
- [6] Fujishima A, Honda K. Electrochemical photolysis of water at a semiconductor electrode. *Nature*. 1972;238(5358): 37-38.
- [7] Zaleska A. Doped-TiO<sub>2</sub>: A review. *Recent Patents on Engineering*. 2008; 2(3): 157-164.
- [8] Chung YS, Park SB, Kang DW. Magnetically separable titania-coated nickel ferrite photocatalyst. *Materials Chemistry and Physics*. 2004;86(2-3): 375-381.
- [9] Xu S, Shangguan W, Yuan J, Chen M, Shi J. Preparations and photocatalytic properties of magnetically separable nitrogen-doped TiO<sub>2</sub> supported on nickel ferrite. *Applied Catalysis B: Environmental*. 2007; 71(3-4): 177.
- [10] Chang H, Wu NM, Zhu FA. Kinetic model for photocatalytic degradation of organic contaminants in a thin-film TiO<sub>2</sub> catalyst. *Water Research*. 2000; 34(2):407-416.
- [11] Huang A, Cao L, Chen J, Spiess FJ, Suib SL, Obee TN, Freihaut JD. Photocatalytic degradation of triethylamine on titanium oxide thin films. *Journal of Catalysis*. 1999; 188(1): 40-47.
- [12] Huan AC, Spiess FJ, Suib S, Obee T, Hay S, J.D. F. Photocatalytic degradation of triethylamine on titanium dioxide thin films. *Journal of Catalysis*. 1999;188(1): 40-47.
- [13] Matthews R. Photooxidation of organic impurities in water using thin films of titanium dioxide. *The Journal of Physical Chemistry*. 1987; 91(12): 3328-3333.
- [14] Al-Rasheed R. Water treatment by heterogeneous photocatalysis an overview. Paper presented at the 4th SWCC Acquired Experience Symposium 2005, Jeddah, Saudi Arabia.
- [15] Znad H, Kawase Y. Synthesis and characterization of S-doped Degussa P25 with application in decolorization of Orange II dye as a model substrate. *Journal of Molecular Catalysis A: Chemical*. 2009; 314(1-2): 55-62.
- [16] Hanaor DAH, Sorrell CC. Review of anatase to rutile phase transformation. *Journal of Materials Science*. 2011; 46(4): 855-874.
- [17] Fujishima A, Rao TN, Tryk DA. Titanium dioxide photocatalysis. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*. 2000;1(1): 1-21.
- [18] Fu W, Yang H, Li M, Chang L, Yu Q, Xu J, Zou G. Preparation and

- photocatalytic characteristics of core-shell structure  $\text{TiO}_2/\text{BaFe}_{12}\text{O}_{19}$  nanoparticles. *Materials Letters*. 2006; 60(21-22): 2723-2727.
- [19] Fu W, Yang H, Li M, Li M, Yang N, Zou G. Anatase  $\text{TiO}_2$  nanolayer coating on cobalt ferrite nanoparticles for magnetic photocatalyst. *Materials Letters*. 2005; 59(27): 3530-3534.
- [20] Bickley R, Gonzalez-Carreno T, Lees J, Palmisano L, Tilley R. A structural investigation of titanium dioxide photocatalysts. *Journal of Solid State Chemistry*. 1991; 92(1): 178-190.
- [21] Cotton F, Wilkinson G, Murillo C, Bochmann M. *Advance Inorganic Chemistry*. New York, NY: Wiley, 1999.
- [22] Malato S, Fernández-Ibáñez P, Maldonado MI, Blanco J, Gernjak W. Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends. *Catalysis Today*. 2009; 147(1): 1-59.
- [23] Herrmann JM. Heterogeneous photocatalysis: Fundamentals and applications to the removal of various types of aqueous pollutants. *Catalysis Today*. 1999; 53(1):115-129.
- [24] Rajeshwar K, Chenthamarakshan CR, Goeringer S, Djukic M. Titania based heterogenous photocatalysis. *Materials, mechanistic issues, and implications for environmental remediation*. *Pure Applied Chemistry*. 2001; 73(12): 1849-1860.
- [25] Yu J, Zhang L, Cheng B, Su Y. Hydrothermal preparation and photocatalytic activity of hierarchically sponge-like macro-/mesoporous titania. *The Journal of Physical Chemistry C*. 2007; 111(28): 10582-10589.
- [26] Chong MN, Jin B, Chow CWK, Saint C. Recent developments in photocatalytic water treatment technology: A review. *Water Research*. 2010; 44(10): 2997-3027.
- [27] Liu SX, Chen XY, Chen X, Sun CL. A novel high active  $\text{TiO}_2/\text{AC}$  composite photocatalyst prepared by acid catalyzed hydrothermal method. *Chinese Chemical Letters*. 2006; 17(4): 529-532.
- [28] Litter MI. Heterogeneous photocatalysis transition metal ions in photocatalytic systems. *Applied Catalysis B: Environmental*. 1999; 23(2-3): 89-114.
- [29] Fujishima A, Zhang X, Tryk D.  $\text{TiO}_2$  photocatalysis and related surface phenomena. *Surface Science Reports*. 2008; 63(12): 515-582.
- [30] Christopher P, Ingram DB, Linic S. Enhancing photochemical activity of semiconductor nanoparticles with optically active Ag nanostructures: Photochemistry mediated by Ag surface plasmons. *The Journal of Physical Chemistry C*. 2010; 114(19):9173-9177.
- [31] Woan K, Pyrgiotakis G, Sigmund W. Photocatalytic carbon-nanotube- $\text{TiO}_2$  composites. *Advanced Materials*. 2009; 21(21): 2233-2239.
- [32] Nguyen-Phan TD, Pham VH, Shin EW, Pham HD, Kim S, Chung JS, Hur SH. The role of graphene oxide content on the adsorption-enhanced photocatalysis of titanium dioxide/graphene oxide composites. *Chemical Engineering Journal*. 2011; 170(1): 226-232.
- [33] Ahmed S, Rasul MG, Martens WN, Brown R, Hashib MA. Heterogeneous photocatalytic degradation of phenols in wastewater: A review on current status and developments. *Desalination*. 2010; 261(1-2):3-18.
- [34] Palmisano L, Augugliaro V, Sclafani A, Schiavello M. Activity of chromium-ion-doped titania for the

dinitrogen photoreduction to ammonia and for the phenol photodegradation. *The Journal of Physical Chemistry*. 1988; 92(23): 6710-6713.

[35] Choi W, Termin A, Hoffmann MR. Effects of metal-ion dopants on the photocatalytic reactivity of quantum-sized TiO<sub>2</sub> particles. *Angewandte Chemie*. 1994; 33(10): 1091-1092.

[36] Zhang Z, Wang CC, Zakaria R, Ying JY. Role of particle size in nanocrystalline TiO<sub>2</sub>-based photocatalysts. *The Journal of Physical Chemistry B*. 1998; 102(52): 10871-10878.

[37] Hung WC, Chen YC, Chu H, Tseng TK. Synthesis and characterization of TiO<sub>2</sub> and Fe/TiO<sub>2</sub> nanoparticles and their performance for photocatalytic degradation of 1, 2-dichloroethane. *Applied Surface Science*. 2008;255(5): 2205-2213.

[38] Sikong L, Kongreong B, Kantachote D, Sutthisripok W. Photocatalytic activity and antibacterial behavior of Fe<sup>3+</sup>-doped TiO<sub>2</sub>/SnO<sub>2</sub> nanoparticles. *Energy Research Journal*. 2010; 1(2): 120-125.

[39] Devi LG, Murthy BN, Girish K. Photocatalytic activity of V<sup>5+</sup>, Mo<sup>6+</sup> and Th<sup>4+</sup> doped polycrystalline TiO<sub>2</sub> for the degradation of chlorpyrifos under UV/solar light. *Journal of Molecular Catalysis A: Chemical*. 2009; 308(1-2): 174-181.

[40] Devi LG, Murthy BN, Girish K. Photocatalytic activity of TiO<sub>2</sub> doped with Zn<sup>2+</sup> and V<sup>5+</sup> transition metal ions: Influence of crystallite size and dopant electronic configuration on photocatalytic activity. *Materials Science and Engineering: B*. 2010; 166(1): 1-6.

[41] Devi LG, Kottam N, Murthy BN, Girish K. Enhanced photocatalytic activity of transition metal ions Mn<sup>2+</sup>, Ni<sup>2+</sup> and Zn<sup>2+</sup> doped polycrystalline

titanium for the degradation of Aniline Blue under UV/solar light. *Journal of Molecular Catalysis A: Chemical*. 2010; 328(1-2): 44-52.

[42] Amadelli R, Samiolo L, Maldotti A, Molinari A, Valigi M, Gazzoli D. Preparation, characterisation, and photocatalytic behaviour of Co-TiO<sub>2</sub> with visible light response. *International Journal of Photoenergy*. 2008; 2008:1-9.

[43] Asahi R, Morikawa T, Ohwaki T, Aoki K, Taga Y. Visible-light photocatalysis in nitrogen-doped titanium oxides. *Science*. 2001;293(5528):269-271.

[44] Mrowetz M, Balcerski W, Colussi AJ, Hoffmann MR. Oxidative power of nitrogen-doped TiO<sub>2</sub> photocatalysts under visible illumination. *The Journal of Physical Chemistry B*. 2004; 108(45): 17269-17273.

[45] Sano T, Negishi N, Koike K, Takeuchi K, Matsuzawa S. Preparation of a visible light-responsive photocatalyst from a complex of Ti<sup>4+</sup> with a nitrogen-containing ligand. *Journal of Materials Chemistry*. 2004; 14(3): 380-384.

[46] Yin S, Aita Y, Komatsu M, Sato, T. Visible-light-induced photocatalytic activity of TiO<sub>2-x</sub>N<sub>y</sub> prepared by solvothermal process in urea-alcohol system. *Journal of the European Ceramic Society*. 2006; 26(13): 2735-2742.

[47] Sathish M, Viswanathan B, Viswanath RP. Characterization and photocatalytic activity of N-doped TiO<sub>2</sub> prepared by thermal decomposition of Ti-melamine complex. *Applied Catalysis B: Environmental*. 2007; 74(3-4): 307-312.

[48] Liu G, Wang L, Sun C, Yan X, Wang X, Chen Z, Lu GQ. Band-to-band visible-light photon excitation and

- photoactivity induced by homogeneous nitrogen doping in layered titanates. *Chemistry of Materials*. 2009; 21(7): 1266-1274.
- [49] Dong F, Zhao W, Wu Z, Guo S. Band structure and visible light photocatalytic activity of multi-type nitrogen doped TiO<sub>2</sub> nanoparticles prepared by thermal decomposition. *Journal of Hazardous Materials*. 2009;162(2-3): 763-770.
- [50] Lettmann C, Hildenbrand K, Kisch H, Macyk W, Maier W. F. Visible light photodegradation of 4-chlorophenol with a coke-containing titanium dioxide photocatalyst. *Applied Catalysis B: Environmental*. 2001; 32(4): 215-227.
- [51] Khan SUM. Efficient photochemical water splitting by a chemically modified n-TiO<sub>2</sub>. *Science*. 2002; 297(5590): 2243-2245.
- [52] Nagaveni K, Hegde MS, Ravishankar N, Subbanna GN, Madras G. Synthesis and structure of nanocrystalline TiO<sub>2</sub> with lower band gap showing high photocatalytic activity. *Langmuir*. 2004; 20(7): 2900-2907.
- [53] Xu C, Killmeyer R, Gray ML, Khan SUM. Photocatalytic effect of carbon-modified n-TiO<sub>2</sub> nanoparticles under visible light illumination. *Applied Catalysis B: Environmental*. 2006; 64(3-4): 312-317.
- [54] Park Y, Kim W, Park H, Tachikawa T, Majima T, Choi W. Carbon-doped TiO<sub>2</sub> photocatalyst synthesized without using an external carbon precursor and the visible light activity. *Applied Catalysis B: Environmental*. 2009; 91(1-2): 355-361.
- [55] Li D, Haneda H, Labhsetwar NK, Hishita S, Ohashi N. Visible-light-driven photocatalysis on fluorine-doped TiO<sub>2</sub> powders by the creation of surface oxygen vacancies. *Chemical Physics Letters*. 2005; 401(4-6): 579-584.
- [56] Chen D, Yang D, Wang Q, Jiang Z. Effects of boron doping on photocatalytic activity and microstructure of titanium dioxide nanoparticles. *Industrial & Engineering Chemistry Research*. 2006;45(12): 4110-4116.
- [57] Yu JC., Zhang L, Zheng Z, Zhao J. Synthesis and characterization of phosphated mesoporous titanium dioxide with high photocatalytic activity. *Chemistry of Materials*. 2003; 15(11): 2280-2286.
- [58] Akhavan O. Graphene nanomesh by ZnO nanorod photocatalysts. *ACS Nano*. 2010; 4(7): 4174-4180.
- [59] Akhavan O, Abdolahad M, Esfandiar A, Mohatashamifar M. Photodegradation of graphene oxide sheets by TiO<sub>2</sub> nanoparticles after a photocatalytic reduction. *The Journal of Physical Chemistry C*. 2010; 114(30):12955-12959.
- [60] An X, Yu J. C. Graphene-based photocatalytic composites. *RSC Advances*. 2011; 1(8):1426-1434.
- [61] Dreyer DR, Park S, Bielawski CW, Ruoff RS. The chemistry of graphene oxide. *Chemical Society Reviews*. 2010;39(1): 228-240.
- [62] Lee JS, You KH, Park CB. Highly photoactive, low bandgap TiO<sub>2</sub> nanoparticles wrapped by graphene. *Advanced Materials*. 2012; 24(8): 1084-1088.
- [63] Huang X, Yin Z, Wu S, Qi X, He Q, Zhang Q, Zhang H. Graphene-based materials: Synthesis, characterization, properties, and applications. *Small*. 2011; 7(14): 1876-1902.
- [64] Kim F, Cote LJ, Huang J. Graphene oxide: Surface activity and two-dimensional assembly. *Advanced Materials*. 2010; 22(17): 1954-1958.
- [65] Zhang J, Xiong Z, Zhao XS. Graphene-metal-oxide composites for

the degradation of dyes under visible light irradiation. *Journal of Materials Chemistry*. 2011; 21(11): 3634-3640.

[66] Manga KK, Wang S, Jaiswal M, Bao Q, Loh KP. High-gain graphene-titanium oxide photoconductor made from inkjet printable ionic solution. *Advanced Materials*. 2010; 22(46): 5265-5270.

[67] Hu Z, Huang Y, Sun S, Guan W, Yao Y, Tang P, Li C. Visible light driven photodynamic anticancer activity of graphene oxide/TiO<sub>2</sub> hybrid. *Carbon*. 2012; 50(3): 994-1004

[68] Bosc F, Ayrál A, Keller N, Keller, V. Room temperature visible light oxidation of CO by high surface area rutile TiO<sub>2</sub>-supported metal photocatalyst. *Applied Catalysis B: Environmental*. 2007;69(3-4): 133-137.

[69] Hidalgo MC, Maicu M, Navío JA, Colón G. Photocatalytic properties of surface modified platinumised TiO<sub>2</sub>: Effects of particle size and structural composition. *Catalysis Today*. 2007; 129(1-2): 43-49.

[70] Kim S, Choi W. Dual photocatalytic pathways of trichloroacetate degradation on TiO<sub>2</sub>: Effects of nanosized platinum deposits on kinetics and mechanism. *The Journal of Physical Chemistry B*. 2002; 106(51): 13311-13317.

[71] Sclafani A, Herrmann JM. Influence of metallic silver and of platinum-silver bimetallic deposits on the photocatalytic activity of titania (anatase and rutile) in organic and aqueous media. *Journal of Photochemistry and Photobiology A: Chemistry*. 1998; 113(2): 181-188.

[72] Sun B, Vorontsov AV, Smirniotis PG. Role of platinum deposited on TiO<sub>2</sub> in phenol photocatalytic oxidation. *Langmuir*. 2003; 19(8): 3151-3156.

[73] Orlov A, Jefferson DA, Tikhov M, Lambert RM. Enhancement of MTBE

photocatalytic degradation by modification of TiO<sub>2</sub> with gold nanoparticles. *Catalysis Communications*. 2007; 8(5): 821-824.

[74] Tian B, Zhang J, Tong T, Chen F. Preparation of Au/TiO<sub>2</sub> catalysts from Au(I)-thiosulfate complex and study of their photocatalytic activity for the degradation of methyl orange. *Applied Catalysis B: Environmental*. 2008; 79(4): 394-401.

[75] Szabó-Bárdos E, Czili H, Horváth A. Photocatalytic oxidation of oxalic acid enhanced by silver deposition on a TiO<sub>2</sub> surface. *Journal of Photochemistry and Photobiology A: Chemistry*. 2003; 154(2-3): 195-201.

[76] Beydoun D, Amal R, Low G, McEvoy S. Occurrence and prevention of photodissolution at the phase junction of magnetite and titanium dioxide. *Journal of Molecular Catalysis A: Chemical*. 2002;180(1-2): 193-200.

[77] Ao Y, Xu J, Zhang S, Fu D. Synthesis of a magnetically separable composite photocatalyst with high photocatalytic activity under sunlight. *Journal of Physics and Chemistry of Solids*. 2009; 70(6):1042-1047.

[78] Beydoun D, Amal R. Novel photocatalyst: Titania-coated magnetite. Activity and photodissolution. *The Journal of Physical Chemistry B*. 2000;104(18): 4387-4396.

[79] Chen F, Xie Y, Zhao J, Lu G. Photocatalytic degradation of dyes on a magnetically separated photocatalyst under visible and UV irradiation. *Chemosphere*. 2001; 44(5):1159-1168.

[80] Beydoun D, Amal R, Low G, McEvoy S. Novel photocatalyst: titania-coated magnetite. Activity and photodissolution. *The Journal of Physical Chemistry B*. 2000;104(18): 4387-4396.



[81] Beydoun D, Amal R, Scott J, Low G, McEvoy S. Studies on the mineralization and separation efficiencies of a magnetic photocatalyst. *Chemical Engineering & Technology*. 2001;24(7): 745-748.

[82] Fu W, Yang H, Chang L, Hari B, Li M, Zou G. Anatase TiO<sub>2</sub> nanolayer coating on strontium ferrite nanoparticles for magnetic photocatalyst. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2006; 289(1-3): 47-52.

[83] Iri H., Watanabe Y, Hashimoto K. Nitrogen-concentration dependance on photocatalytic activity of TiO<sub>2-x</sub>N<sub>x</sub> powders. *The Journal of Physical Chemistry B*. 2003; 107(23): 5483-5486.

[84] Zhao Z, Liu Q. Mechanism of higher photocatalytic activity of anatase TiO<sub>2</sub> doped with nitrogen under visible-light irradiation from density functional theory calculation. *Journal of Physics D: Applied Physics*. 2008; 41: 1-10.

IntechOpen