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Maryline Nsar

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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE L'UNIVERSITÉ DE MONTPELLIER

En Chimie et Physico Chimie des matériaux

École doctorale Sciences chimiques Balard (ED459)

Unité de recherche Institut Européen des Membranes (IEM)

Elaboration of oxides membranes by electrospinning
for photocatalytic applications

Présentée par Maryline NASR

Le 16 octobre 2017

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UNIVERSITÉ
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To My Wonderful Parents
To My Precious “Sister and Brother”

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Table of Contents

Abstract	7
Résumé	8
List of Figures	9
List of Tables	12
General Introduction	15
Chapter 1: Literature Review	19
Chapter 2: Enhanced visible-light photocatalytic performance of electrospun GO/TiO₂ composite nanofibers	63
Chapter 3: Enhanced Photocatalytic performance of novel electrospun BN/TiO₂ composite nanofibers	87
Chapter 4: High photocatalytic and antibacterial activity of BN-Ag/TiO₂ composite nanofibers under visible light	113
Chapter 5: Optical and structural properties of Al₂O₃ doped ZnO nanotubes by ALD and their photocatalytic application	141
Chapter 6: Synthesis of Novel ZnO/ZnAl₂O₄ Multi Co-Centric Nanotubes and their Photocatalytic Application	161
General Conclusion	185
Scientific Contributions	189
Annex	193

Abstract

Nowadays, industrial toxic chemicals are still not properly treated and these contaminants may directly impact the safety of drinking water. Photocatalysis “a green technology” is an effective and economical approach and plays an important role in solar energy conversion and degradation of organic pollutants. This thesis manuscript reports on developing advanced materials (based on TiO_2 and ZnO) being capable of exploiting renewable solar energy for solving the environmental pollution problems. A part of this work was dedicated to improve the UV and visible light TiO_2 photoresponse. Therefore, rGO/TiO_2 , BN/TiO_2 and BN-Ag/TiO_2 composites nanofibers were successfully elaborated using the electrospinning technique. The second part focused on ZnO . Novel structures of $\text{ZnO/ZnAl}_2\text{O}_4$ multi co-centric nanotubes and Al_2O_3 doped ZnO nanotubes were designed by combining the two techniques of atomic layer deposition (ALD) and electrospinning. The morphological, structural and optical properties of all synthesized nanostructures were investigated by several characterization techniques. The results show that the chemical and physical properties have a high impact on the photocatalytic properties of the synthesized materials. Moreover, it was found that the doping effect lead to a more efficient charge separation in the photocatalyst, which is an advantage for photocatalytic activities. In addition, methyl orange and methylene blue were used as model reference. A significant enhancement and a long-term stability in the photocatalytic activity were observed with the doped materials compared to the non-doped ones under both UV and visible light. Antibacterial tests against *Escherichia coli* have also been performed; the results indicate that BN-Ag/TiO_2 present interesting photocatalytic properties for both organic compound degradation and bacterial removal.

Résumé

De nos jours, les produits chimiques toxiques industriels ne sont pas toujours traités proprement, et leurs contaminants peuvent directement affecter la sécurité de l'eau potable. La photocatalyse, «une technologie verte» est une approche efficace et économique qui joue un rôle important dans la conversion de l'énergie solaire et la dégradation des polluants organiques. Ce manuscrit de thèse rapporte sur le développement des matériaux avancés (basés sur TiO_2 et ZnO) susceptibles d'exploiter l'énergie solaire renouvelable pour résoudre les problèmes de pollution environnementale. Une partie de ce travail a été consacrée pour l'amélioration de l'activité photocatalytique du TiO_2 sous lumière UV et visible. Par conséquent, les nanofibres composites de rGO/TiO_2 , BN/TiO_2 et BN-Ag/TiO_2 ont été élaborées en utilisant la technique d'électrofilage (electrospinning). La deuxième partie porte sur le ZnO , ainsi que les nanotubes multi concentriques de $\text{ZnO/ZnAl}_2\text{O}_4$ et les nanotubes de ZnO dopés Al_2O_3 qui ont été synthétisés en combinant les deux techniques : dépôt de couche atomique (ALD) et electrospinning. Les propriétés morphologiques, structurelles et optiques de toutes les nanostructures synthétisées ont été étudiées par différentes techniques de caractérisations. Les résultats ont montré que les propriétés chimiques et physiques ont un effet très important sur les propriétés photocatalytiques des matériaux synthétisés. En outre, il a été constaté que l'effet de dopage conduit à une séparation de charge efficace dans le photocatalyseur, ce qui rend l'activité photocatalytique plus efficace. De plus, le méthyle orange et le bleu de méthylène ont été utilisés comme modèle de référence. Une amélioration significative et une stabilité à long terme de l'activité photocatalytique ont été observées avec les matériaux dopés comparés aux matériaux non-dopés sous lumière UV et visible. Des tests antibactériens contre *Escherichia coli* ont été également effectués; les résultats indiquent que BN-Ag/TiO_2 présente à la fois des propriétés photocatalytiques intéressantes pour la dégradation des composés organiques et pour l'élimination des bactéries.

List of Figures

Figure 1.1. Schematic of a semiconductor photocatalysis.....	22
Figure 1.2. Crystalline phases of TiO ₂	23
Figure 1.3. Schematic of the electrospinning process.....	25
Figure 1.4. Different morphology types of 1D TiO ₂ nanostructures synthesized through hydrothermal methods: (a, b) TiO ₂ nanotubes, (c, d) TiO ₂ nanorods, (e, f) TiO ₂ nanobelts, (g, h) TiO ₂ nanowires.....	28
Figure 1.5. Schematics showing the growth process of ALD.....	30
Figure 1.6. Ti–O–C bonding formed through interaction between unpaired π electrons on GO with Ti atoms surface of TiO ₂ . This bonding narrows the band gap of TiO ₂ and extends the light absorption range of TiO ₂	36
Figure 1.7. A possible mechanism of photocatalytic reactions of \dot{O}^- radical and the schematic band structure of N-doped TiO ₂ under visible light irradiation.....	38
Figure 1.8. Vectorial transfer of electrons–holes in coupled semiconductor system:(a) when the conduction band of TiO ₂ is more anodic than the corresponding band of the sensitizer and (b) when the valence band of the sensitizer is more cathodic than that of TiO ₂ one.....	40
Figure 1.9. Proposed photogenerated charge separation and migration process in Ag AgBr/TiO ₂ heterostructured nanofibers under visible light irradiation.	41
Figure 1.10. Mechanism of TiO ₂ photocatalytic water-splitting for hydrogen production	47
Figure 2.1. Scanning Electron Microscope images of TiO ₂ and rGO/TiO ₂ annealed composite nanofibers under N ₂ atmosphere for 6h at 500°C.....	69
Figure 2.2. Transmission electron microscopy images of TiO ₂ GO (2 wt. %) /TiO ₂ annealed nanofibers under N ₂ atmosphere for 6h at 500°C.....	71
Figure 2.3. XRD patterns of photocatalysts: (a) TiO ₂ , (b) GO (2 wt. %) /TiO ₂ , (c) GO (5wt. %) /TiO ₂ , and (d) GO (7wt. %) /TiO ₂ annealed nanofibers under N ₂ atmosphere for 6h at 500°C	72
Figure 2.4. (A-B) Raman Shift of (a) TiO ₂ , (b) GO (2 wt. %) /TiO ₂ , (c) GO (5wt. %) /TiO ₂ , (d) GO (7wt. %) /TiO ₂ annealed nanofibers under N ₂ atmosphere for 6h at 500°C.	74
Figure 2.5. FTIR spectra of (a) TiO ₂ , (b) GO (2 wt. %) /TiO ₂ , (c) GO (5wt. %) /TiO ₂ , (d) GO (7wt. %) /TiO ₂ GO annealed nanofibers under N ₂ atmosphere and (e) GO.	76
Figure 2.6. UV-Vis absorption spectra of (a) TiO ₂ , (b) GO (2 wt. %) /TiO ₂ , (c) GO (5wt. %) /TiO ₂ , (e) GO (7wt. %) /TiO ₂ nanofibers.	77
Figure 2.7. UV-Vis spectra of the photocatalytic degradation of MO under visible light: (a) MO without catalyst, (b) TiO ₂ -P25, (c) TiO ₂ NFs, (d) GO (2 wt. %) /TiO ₂ , (e) GO (5wt. %) /TiO ₂ and (f) GO (7wt. %) /TiO ₂	79
Figure 2.8. Photodegradation of MO by TiO ₂ -P25, TiO ₂ NFs and rGO/TiO ₂ composite nanofibers.	80
Figure 2.9. Kinetics of Methyl orange degradation by TiO ₂ -P25, TiO ₂ NFs and rGO/TiO ₂ composite nanofibers.	82
Figure 3.1. Scanning Electron Microscope images of TiO ₂ and BN/TiO ₂ annealed composite nanofibers in air for 4h at 500°C.....	93

Figure 3.2. Element mapping images of the BN (5 wt.%)/TiO ₂ composite nanofibers.	94
Figure 3.3. (A-B) XRD patterns of (a) TiO ₂ , (b) BN (3 wt. %) /TiO ₂ , (c) BN (5wt. %) /TiO ₂ , (d) BN (7wt. %) /TiO ₂ and (e) BN (10wt. %) /TiO ₂ annealed nanofibers in air for 4h at 500°C.	96
Figure 3.4. (A-B) Raman shift of (a) TiO ₂ , (b) BN (3 wt. %)/TiO ₂ , (c) BN (5wt. %)/TiO ₂ , (d) BN (7wt. %)/TiO ₂ and (e) BN (10wt. %)/TiO ₂ annealed nanofibers in air for 4h at 500°C.	98
Figure 3.5. FTIR spectra of (a) TiO ₂ , (b) BN (3 wt. %)/TiO ₂ , (c) BN (5wt. %)/TiO ₂ , (d) BN (7wt. %)/TiO ₂ and (e) BN (10wt. %)/TiO ₂ annealed nanofibers in air for 4h at 500°C.....	99
Figure 3.6. UV-VIS absorption spectra of (a) TiO ₂ , (b) BN (3 wt. %)/TiO ₂ , (c) BN (5wt. %)/TiO ₂ , (d) BN (7wt. %)/TiO ₂ and (e) BN (10wt. %)/TiO ₂ annealed nanofibers in air for 4h at 500°C.	100
Figure 3.7. Photoluminescence of TiO ₂ and BN/TiO ₂ NFs annealed in air at 500°C.....	102
Figure 3.8. One example of a deconvoluted PL spectrum of BN/TiO ₂ NFs annealed in air at 500°C.....	103
Figure 3.9. UV-Vis spectra of the photocatalytic degradation of MO under UV light: (a) MO without catalyst, (b) P 25, (c) TiO ₂ nanofibers, (d) BN (3wt. %)/TiO ₂ , (e) BN (5wt. %)/TiO ₂ , (f) BN (7wt. %)/TiO ₂ and (g) BN (10wt. %)/TiO ₂ composite nanofibers.	106
Figure 3.10. Photodegradation of MO by P25, TiO ₂ nanofibers and BN/TiO ₂ composite nanofibers.	107
Figure 3.11. Kinetics of Methyl orange degradation by P25, TiO ₂ nanofibers and BN/TiO ₂ composite nanofibers.	109
Figure 4.1. Scanning electron microscope images of pure TiO ₂ nanofibers, Ag _{0.5} /TiO ₂ , Ag _{1.5} /TiO ₂ , Ag ₃ /TiO ₂ , BN ₃ -Ag ₃ /TiO ₂ and BN ₅ -Ag ₃ /TiO ₂ composite nanofibers after annealing under air at 500°C for 4h.....	122
Figure 4.2. Elemental mapping images of BN ₅ -Ag ₃ /TiO ₂ composite nanofibers with 5 wt% of BN and 3 wt% of Ag.	123
Figure 4.3. (A-B) XRD patterns of (a) TiO ₂ , (b) Ag _{0.5} /TiO ₂ , (c) Ag _{1.5} /TiO ₂ , (d) Ag ₃ /TiO ₂ , (e) BN ₃ -Ag ₃ /TiO ₂ and (f) BN ₅ -Ag ₃ /TiO ₂ nanofibers annealed in air at 500°C for 4h.	126
Figure 4.4. (A-B) Raman shifts of a) TiO ₂ , (b) Ag _{0.5} /TiO ₂ , (c) Ag _{1.5} /TiO ₂ , (d) Ag ₃ /TiO ₂ , (e) BN ₃ -Ag ₃ /TiO ₂ and (f) BN ₅ -Ag ₃ /TiO ₂ nanofibers annealed in air at 500°C for 4h.	127
Figure 4.5. (A) Reflectance spectra and (B) Band gap calculation from the reflectance spectra of TiO ₂ , Ag/TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.	129
Figure 4.6. Photoluminescence spectra of pure TiO ₂ nanofibers, and Ag/TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.	131
Figure 4.7. (A) Absorbance spectra of MB degradation in the presence of BN ₅ -Ag ₃ /TiO ₂ composite nanofibers. (B) MB photodegradation by the TiO ₂ , Ag/TiO ₂ and BN-Ag/TiO ₂ photocatalysts under visible light. (C) Kinetics of MB degradation. (D) Long-term catalytic stability of BN ₅ -Ag ₃ /TiO ₂ nanofibers in four repeated cycles of MB degradation under visible light.	133
Figure 5.1. Scanning Electron Microscope images of ZnO and Al ₂ O ₃ doped ZnO annealed nanotubes in air for 8h at 500°C.....	148

Figure 5.2. XRD spectra of (a) ZnO, (b) Al ₂ O ₃ /ZnO (5 wt%), (c) Al ₂ O ₃ /ZnO (10 wt%) and (d) Al ₂ O ₃ /ZnO (20 wt%) annealed nanotubes.....	150
Figure 5.3. Reflectance spectra of ZnO, Al ₂ O ₃ /ZnO (5 wt%), Al ₂ O ₃ /ZnO (10 wt%) and Al ₂ O ₃ /ZnO (20 wt%) nanotubes.	152
Figure 5.4. Evaluation of Urbach tail and free electron concentration with Al ₂ O ₃ doping amounts.	153
Figure 5.5. Photoluminescence spectra of (a) ZnO, (b) Al ₂ O ₃ /ZnO (5 wt %), (c) Al ₂ O ₃ /ZnO (10 wt%) and (d) Al ₂ O ₃ /ZnO (20 wt%) nanotubes.....	154
Figure 5.6. FTIR spectra of ZnO, Al ₂ O ₃ /ZnO (5 wt%), Al ₂ O ₃ /ZnO (10 wt%) and Al ₂ O ₃ /ZnO (20 wt%) nanotubes.	155
Figure 5.7. Photodegradation of MO by ZnO, Al ₂ O ₃ /ZnO (5 wt%), Al ₂ O ₃ /ZnO (10 wt%) and Al ₂ O ₃ /ZnO (20 wt%) photocatalysts under UV light.....	157
Figure 5.8. Kinetics of methyl orange degradation by the prepared samples.	157
Figure 6.1. Scanning Electron Microscope images of ZnO/ZnAl ₂ O ₄ double, triple and quadruple co-centric nanotubes annealed in air at 900°C.....	168
Figure 6.2. Transmission Electron Microscope images of ZnO/ZnAl ₂ O ₄ double, triple and quadruple co-centric nanotubes.....	169
Figure 6.3. (A-B) XRD patterns of (a) Double, (b) Triple and (c) Quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄	170
Figure 6.4. Raman Shift of (a) Double, (b) Triple and (c) Quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄	172
Figure 6.5. (A) Reflectance spectra and (B) band gap calculation from reflectance spectra of ZnO nanotubes and double, triple, quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄	173
Figure 6.6. Photoluminescence spectra of ZnO and double, triple, quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄	174
Figure 6.7. (A) Different steps of ZnO/ZnAl ₂ O ₄ nanotubes formation. (B) Kirkendall effect and surface diffusion process, where J _A , J _B , and J _V are diffuse flux of metal A, B, and void, respectively.	175
Figure 6.8. UV-Vis spectra of the photocatalytic degradation of MO under UV light: (a) MO without catalyst, (b) Double, (c) Triple and (d) Quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄	176
Figure 6.9. Photodegradation of MO by Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄	178
Figure 6.10. Long-term catalytic stability of Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄ in four repeated cycles of MO degradation under UV irradiation.	181

List of Tables

Table 1.1. Different multiple functional/TiO ₂ based materials, their preparation methods, their band gap, their photocatalysis application and their photocatalytic efficiency under visible light.	42
Table 2.1. EDX data showing the composition of TiO ₂ , GO (2 wt. %) /TiO ₂ , GO (5wt. %) /TiO ₂ and GO (7wt. %) /TiO ₂ annealed nanofibers under N ₂ atmosphere.	70
Table 2.2. Kinetic parameters for photocatalytic activities of TiO ₂ -P25, TiO ₂ NFs and rGO/TiO ₂ composite nanofibers.	82
Table 3.1. EDX data showing the composition of TiO ₂ , BN (3 wt. %)/TiO ₂ , BN (5wt. %)/TiO ₂ , BN (7wt. %)/TiO ₂ and BN (10 wt. %)/TiO ₂ annealed nanofibers under air.....	93
Table 3.2. BET surface area of TiO ₂ nanofibers and BN/TiO ₂ composite nanofibers.....	95
Table 3.3 Grain size of TiO ₂ NFs and BN/TiO ₂ composite nanofibers.	97
Table 3.4. Normalized integrated intensity of the TiO ₂ PL peaks.....	104
Table 3.5. Quantum yield of the pure TiO ₂ and BN/TiO ₂ composite nanofibers.	104
Table 3.6. Kinetic parameters for photocatalytic activities of the pure TiO ₂ nanofibers and BN/TiO ₂ composite nanofibers.	108
Table 4.1. TiO ₂ , Ag/TiO ₂ and BN-Ag/TiO ₂ samples prepared with different weight amounts of BN nanosheets and AgNO ₃	117
Table 4.2. Average diameter of annealed TiO ₂ , Ag/TiO ₂ and BN-Ag/TiO ₂ nanofibers.	122
Table 4.3. EDX data showing the composition of annealed TiO ₂ , Ag/TiO ₂ and BN-Ag/TiO ₂ nanofibers.	123
Table 4.4. Surface area of TiO ₂ nanofibers, and Ag/TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.	124
Table 4.5. Grain size of annealed TiO ₂ , Ag/TiO ₂ and BN-Ag/TiO ₂ nanofibers.....	126
Table 4.6. Photo-absorption edge and band gap values of pure TiO ₂ nanofibers, Ag/TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.	128
Table 4.7. Kinetic parameters of the photocatalytic activities of pure TiO ₂ nanofibers, and Ag/TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.	134
Table 4.8. Comparison of the photocatalytic activity of different Ag/TiO ₂ nanocomposites.	135
Table 4.9. <i>E. coli</i> log-removal values after incubation with pure TiO ₂ nanofibers or BN5-Ag3/TiO ₂ composite nanofibers at 20°C for 3 hours ($C_0 = 2.3 \pm 0.3 \times 10^8$ CFU.mL ⁻¹).	136
Table 5.1. Step time investigation of Al ₂ O ₃ and ZnO deposition on PAN nanofibers.	145
Table 5.2. Deposition sequences of Al ₂ O ₃ and ZnO cycles on the PAN nanofibers.	145
Table 5.3. EDX data showing the atomic percentage composition of ZnO and Al ₂ O ₃ /ZnO prepared samples.	148
Table 5.4. Lattice constants and interplane distances of the prepared nanotubes.	150
Table 5.5. Band gap energies of ZnO and Al ₂ O ₃ /ZnO nanotubes.....	152
Table 5.6. Peak positions of ZnO and Al ₂ O ₃ /ZnO nanotubes with different Al ₂ O ₃ amounts.	154

Table 5.7. Kinetic parameters of ZnO and Al ₂ O ₃ /ZnO nanotubes.	158
Table 6.1. Step time investigation of Al ₂ O ₃ and ZnO deposition on PAN nanofibers.	165
Table 6.2. Deposition sequences of Al ₂ O ₃ and ZnO cycles on the PAN nanofibers.	165
Table 6.3. EDX data showing the composition of multi co-centric nanotubes of ZnO/ZnAl ₂ O ₄ annealed under air.....	168
Table 6.4. Grain size of ZnO and ZnAl ₂ O ₄ multi co-centric nanotubes.....	170
Table 6.5. Ratio of intensities of visible and UV emissions.	173
Table 6.6. Kinetic parameters for photocatalytic activities of ZnO/ZnAl ₂ O ₄ double, triple and quadruple co-centric nanotubes.....	178
Table 6.7. MO photodegradation percentages by Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl ₂ O ₄ in four repeated cycles.....	181

General Introduction

General Introduction

A combination of a growing population and a rapid development of industry have resulted in a steady increase of water pollution in many parts of the world due to the accelerated release of harmful agents especially organic pollutants, toxic heavy metal ions, and pathogenic microorganisms. Therefore the need for clean water increases the demand for new purification technologies. Photocatalysis is a promising process in the field of green technology because it can use solar energy to degrade organics and inactivate pathogens. This technique requires the absorption of a photon by a semiconductor with an energy equal to or higher than the band gap of the semiconductor, leading to the creation of charge carriers with an oxidizing or reducing power that will accelerate a chemical reaction for the degradation of pollutants. Among many candidates for photocatalysts, TiO_2 is almost the only material suitable for industrial use in the present and probably also in the future. This is because TiO_2 has the most efficient photoactivity, the highest stability, the lowest cost and its safety to humans and the environment has been guaranteed overtime. Titanium dioxide has been used in a wide variety of applications in many fields: glass, ceramics, paper industries, cosmetics, painting, medicine, electronic components and chemical catalysis. Even though, TiO_2 still possesses undesirable disadvantages such as a wide optical band gap (3.2 eV) that leads to limited applications using solar light, and fast recombination of photo-reduced carriers. In order to overcome the above drawbacks, many strategies have been used via further modifying the TiO_2 . Recently, combining TiO_2 with metals and/or non-metals has been testified to be effective in strengthening the visible light activity as well as facilitating the charge separation. Zinc oxide, a naturally n-type semiconductor with a wide bandgap ($E_g = 3.37$ eV), has been a very attractive material for several applications including solar cells, UV-absorbing material in sunscreen, UV light emitters, spin functional devices, gas sensors, transparent electronics and photocatalysis. ZnO nanostructures have been recognized as excellent materials for photocatalytic processes due to their high photosensitivity, high catalytic activity, suitable band gap, low cost, and environmental friendliness. However, enhancing the photocatalytic activity and stability of ZnO nanomaterial to meet the practical application requirements is still a challenge because of the bottleneck of poor quantum yield caused by the fast recombination rate of photogenerated electron-hole pairs and low stability due to photochemical corrosion.

Photo-corrosion leads to a fast decrease in activity, or deactivation, and difficult recycling of the catalyst. It was found that the design and fabrication of high quality ZnO nanocrystals with desired nanostructure or morphology are of great fundamental and technological interest in the enhancement of their photocatalytic activity and stability.

The purpose of this research is to find a way of reducing the recombination rate of TiO₂ and ZnO photogenerated charge carriers and to shift the absorption edge of TiO₂ toward visible range in order to improve their photocatalytic activity and stability under UV and visible light. During this work, electrospinning and atomic layer deposition were the two synthesis techniques used for the elaboration of the materials. Methyl orange and methylene blue were used as model pollutant to evaluate the photocatalytic performance of the prepared nanomaterials. The antibacterial properties were evaluated against Escherichia coli bacterium. The morphological, structural and optical properties of the synthesized nanostructures were investigated using different characterization techniques such as scanning electron microscopy, transmission electron microscopy, energy-dispersive X-ray spectroscopy, BET measurements, X-ray diffraction, Raman spectroscopy, Fourier-transform infrared spectrometer, UV–VIS spectrophotometer and photoluminescence.

To achieve the above objectives, the following topics were investigated:

- Chapter 1: a literature review about the recent progress in enhancing the visible light photocatalysis of titanium dioxide, the current synthesis techniques and the different photocatalysis applications.
- Chapter 2: Synthesis of electrospun reduced graphene oxide/TiO₂ composite nanofibers and their photocatalytic performance in the degradation of methyl orange under visible light.
- Chapter 3: Enhanced photocatalytic activity under UV light of Novel Boron Nitride nanosheets/TiO₂ composite nanofibers using electrospinning technique.
- Chapter 4: Elaboration of BN-Ag/TiO₂ composite nanofibers and their photocatalytic performance for bactericidal effect and degradation of pollutants under visible light.
- Chapter 5: Synthesis of Al₂O₃ doped ZnO nanotubes and the effect of their optical and structural properties on their photocatalytic application.

- Chapter 6: Elaboration of novel ZnO/ZnAl₂O₄ multi co-centric nanotubes by combining the two techniques: atomic layer deposition and electrospinning and their photocatalytic stability.

Chapter 1: Literature Review

Table of Contents

1. Abstract.....	21
2. Introduction.....	21
3. Synthesis methods.....	24
3.1. Electrospinning technique.....	24
3.2. Spin coating.....	25
3.3. Dip coating.....	26
3.4. Hydrothermal methods.....	27
3.5. Chemical vapor deposition (CVD).....	28
3.6. Atomic Layer deposition.....	29
4. Photocatalysis parameters.....	31
4.1. Operating parameters.....	31
4.2. Modification of TiO ₂ properties.....	32
4.2.1. Metal-doping.....	33
4.2.2. Non-metal doping.....	34
4.2.3. Coupling with other semiconductors.....	38
4.2.4. Multiple functional components.....	40
5. Photocatalysis applications.....	42
5.1. Pollutant degradation.....	43
5.1.1. Organic compounds.....	43
5.1.2. Heavy metals.....	44
5.2. Bacterial removal for water disinfection.....	44
5.3. Hydrogen generation.....	45
6. Conclusion and Perspectives.....	47
7. Research Aim.....	48

1. Abstract

Recently, many efforts have been devoted to improve the visible-light photocatalytic activity using titanium dioxide as photocatalyst due to its wide range of applications in energy and environment fields. However, the fast charge recombination and the absorption edge in the UV range limits the photocatalytic efficiency of TiO₂ under visible-light irradiation. Many investigations have been carried out in order to overcome the limitations of TiO₂ and therefore enhance its photocatalytic activity under visible light. The present literature review focuses on different strategies used to promote the separation efficiency of the electron-hole pairs and shift the absorption edge of TiO₂ to the visible region. Current synthesis techniques of TiO₂ based material, recent progresses in enhancing visible photocatalytic activity and the different photocatalysis applications will be discussed. Based on the studies reported in the literature, we believe that this review will help in the development of new strategies to further improve the visible photocatalytic performance of TiO₂ based materials.

2. Introduction

In recent years, there has been great concern over many serious environmental problems that we are facing on a global scale [1]. One of them concerns water safety, our most important natural resource [2]. The need for clean water put more stresses on the removal of organic pollutants, and toxic heavy metal ions from water sources [3, 4], therefore new effective and low cost purification technologies are required [5]. Several techniques are already used for the treatment of water such as absorption with or without chemical reaction [6], adsorption [7], condensation [8], biological degradation and photocatalysis [9]. The adsorption techniques on highly porous materials have the disadvantage of transferring the pollutants to another phase without destroying them. Thus, their destruction requires the subsequent use of filters [10], while the ideal solution should be applicable to all types of pollutants and should not consume energy or emit environmentally harmful by-products [11]. Photocatalysis has appeared as an innovative and promising technology for water disinfection [12]. Figure 1.1 describes the principle of a semiconductor photocatalysis. The absorption of a photon by the semiconductor ($h\nu \geq E_g$) will cause an excitation of an electron from its valence band to its conduction band creating a

positively charged hole (h^+) in the valence band. The electron-hole pairs can migrate separately to the surface of the semiconductor and participate in the redox reactions in order to degrade the pollutants (Equation 1 to 4) [12, 13].

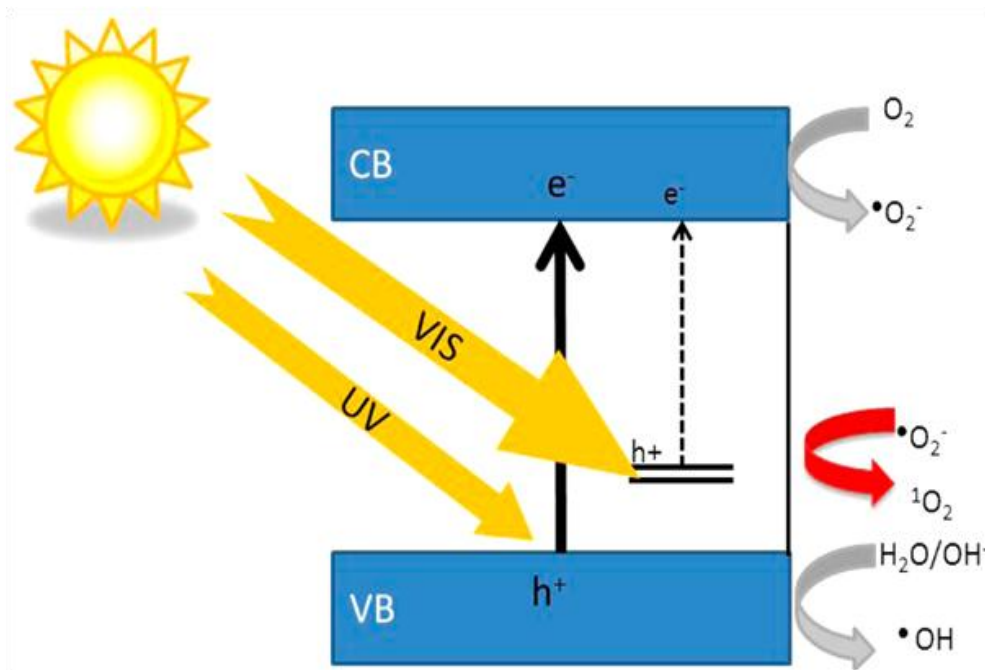
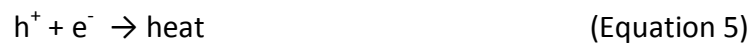
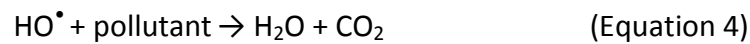
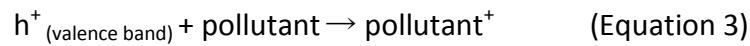
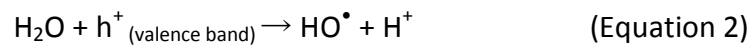


Figure 1.1. Schematic of a semiconductor photocatalysis. [14]

In 1972, Fujishima and Honda [15] observed that under UV irradiation, the use of a TiO_2 electrode in an electrochemical cell lead to water dissociation, even without imposing an external voltage. This experiment demonstrates another property of TiO_2 : its photocatalytic activity, thereby opening up a new field of application [16]. Till now, titanium oxide is the most photoactive material [17] due to its oxidizing ability, chemical stability and

low cost [18, 19]. Anatase, rutile and brookite are the main crystalline phases of TiO_2 . The three crystalline phases are all made up of oxygen's octahedral around a titanium atom (TiO_6 octahedral) but with a different organization from one phase to another (Figure 2). The rutile is the most abundant form and crystallizes in the quadratic Bravais network. The rutile is formed of oxygen's octahedral connected regularly in the direction [001]. The atoms are well organized in each face and thus contribute to the stability of the rutile phase. The anatase as well has a tetrahedral structure (also called quadratic) in the Bravais network. On the other hand, the anatase consists of irregular oxygens' octahedral giving it an elongated structure. The brookite has an orthorhombic structure which their oxygens' octahedral are organized regularly (Figure 1.2) [20, 21]. According to previous studies, anatase TiO_2 has demonstrated a greater photocatalytic activity compared to other crystalline phases of TiO_2 [22]. However, till now TiO_2 has not yet reached the expected photocatalytic activity due to several limitations including the fast electron-hole pair recombination [23]. In addition, TiO_2 has a large band gap ($E_g > 3.2$ eV), and it can only be excited by ultraviolet light with a wavelength less than 388 nm (less than 7% of solar light) [24]. To overcome these limitations, several strategies have been adopted to improve the visible-light absorbance and increase the charge carrier's life time of TiO_2 -based photocatalyst [25, 26]. The present literature review will focus on tuning the photocatalyst properties to overcome the limitations of TiO_2 and enhance the visible-light photocatalytic activity. Also, the current synthesis techniques of TiO_2 based materials and the recent progresses in this field will be discussed.

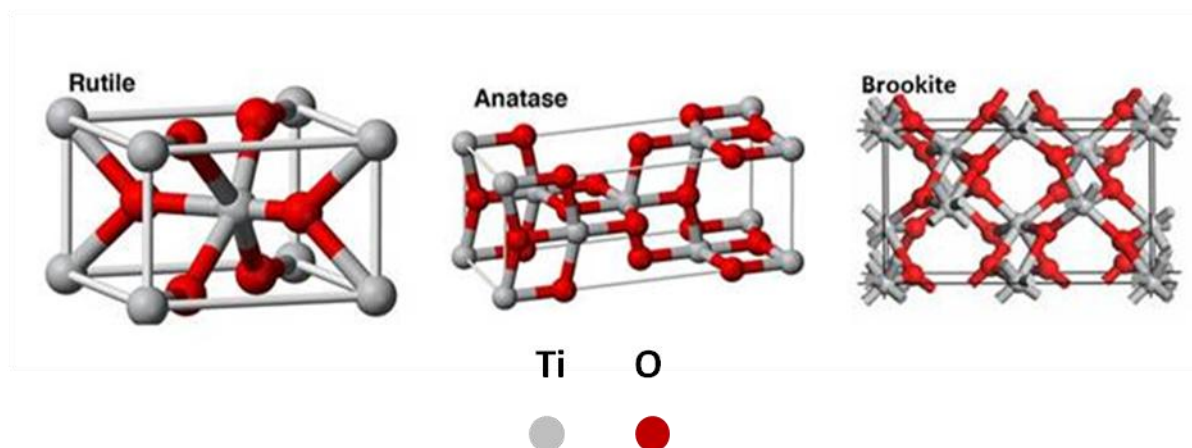


Figure 1.2. Crystalline phases of TiO_2 . [27]

1.3. Synthesis methods

Previous studies showed that different morphologies of a photocatalyst may result in different photocatalytic properties [28], those diversities can be achieved by a wide variety of titanium dioxide synthesizing methods [29]. The size, the morphology and the composition of titanium dioxide can be controlled by different parameters, such as titanium precursor concentration, pH, temperature, duration of treatment and the used chemical species [30, 31]. This following section will focus on the most common synthesis techniques used to elaborate different structures of TiO₂ based materials including electrospinning, spin coating, dip coating, hydrothermal, chemical vapor deposition and atomic layer deposition.

1.3.1. Electrospinning technique

Electrospinning is a versatile and cost-effective technique for the production of multi-functional nanofibers from various polymers, composites, sol-gels, ceramics etc. [32, 33] The basic principle of this technique is based on generating the direct movement of charged molecules by applying a high voltage to supply the ejection of a viscous liquid jet through a spinneret [34]. Electrospinning setup consists of three main components; (1) high voltage power supply, (2) syringe pump and (3) collector. Figure 1.3 shows the schematic view of electrospinning. When the electric field is created between the droplet of solution and the grounded collector, it overcomes the surface tension and the polymer jet is then created to begin the fiber formation [35]. The Taylor cone shape starts to be observed at the tip of the needle during the injection [36]. In electrospinning process, the morphology and the uniformity of nanofibers are determined by considering a number of parameters which are investigated under two main parts: (a) polymer/solution properties such as molecular weight, viscosity, conductivity and surface tension; and (b) set-up parameters such as the electric field, the flow rate of solution and the tip-to-collector distance. Moreover, the ambient conditions (temperature, humidity) may affect the formation of nanofibers [37, 38]. In general, the elaboration of TiO₂ nanofibers using electrospinning involves the following three steps: (1) preparation of the electrospun solution with titania precursor and a polymer template; (2) electrospinning of the solution to obtain the composite nanofibers, and (3) calcination of the as-prepared nanofibers to remove the polymer and to obtain the crystalline phase of TiO₂ nanofibers [39]. In order to increase the active surface area of TiO₂ nanofibers, different TiO₂-based composites and co-doped nanofibers were elaborated by

electrospinning such as graphene-TiO₂[40], BN-TiO₂[41], ZnO/TiO₂[42], CuO/TiO₂[43], and Ag/TiO₂ [44]. The performances of these composites and co-doped materials for photocatalytic application have shown a significant enhancement compared to pure TiO₂ nanofibers [44]. Even though electrospinning has a potential for industrial production, though it may not be suitable for mass production, due to the large standard deviations on nanofibers' diameter, and the restricts fiber mat purity by the presence of polymer beads.

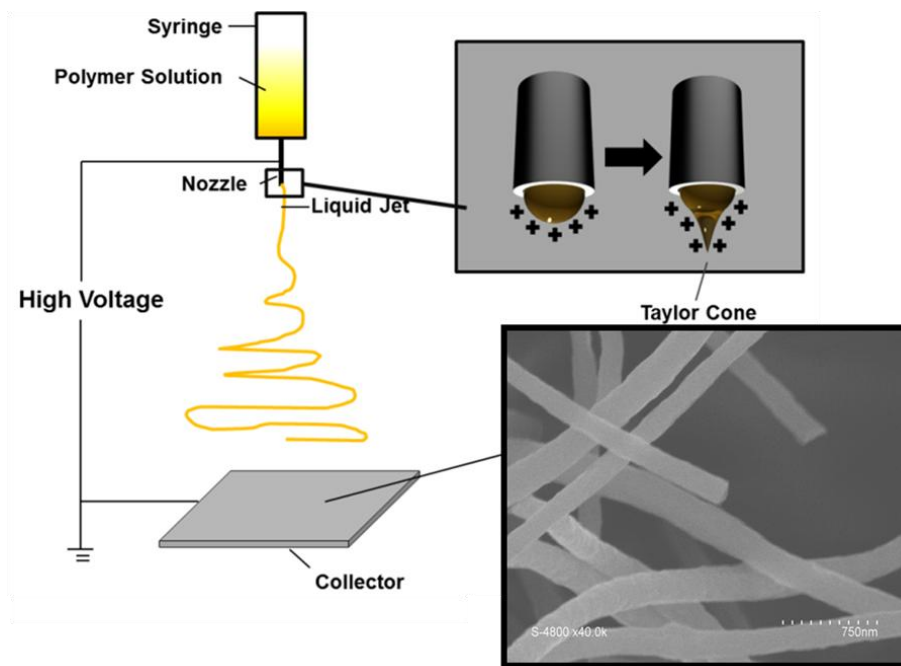


Figure 1.3. Schematic of the electrospinning process.

1.3.2. Spin coating

Spin coating is one of the most common techniques for applying thin films to substrates. It is used in a wide variety of industries and technology sectors [45]. The advantage of spin coating is the ability to quickly and easily produce uniform films with a thickness ranging from a few nanometres to a few microns. A droplet of the coating liquid is applied on the center of the substrate. The substrate is then rotated at high speed in order to spread the coating material by centrifugal force. Alternatively, the liquid solution may be applied while the substrate is spinning [46]. The thickness, morphology and surface topography of the final film obtained from a particular material in a given solvent at a given concentration are highly reproducible. Due to the ability to have high spin speeds, the high airflow leads to fast drying. Different parameters affect the spin-coating deposition process

such as rotational speed, viscosity, spinning time, molecular weight and concentration of the solutes [47]. Pan *et al.* [48] have grown highly ordered cubic mesoporous WO_3/TiO_2 thin films using spin coating method. The optimized doping amount was found at 4 mol % of WO_3 concentration and they showed that the long-range ordering of the mesostructure was appreciably organized. The enhancement of WO_3/TiO_2 photocatalytic activity in the decomposition of 2-propanol was ascribed to the surface acidity of the resultant mesoporous structures. Spin coating insure an easy film thickness control by changing spin speed, or switching to a different viscosity photoresist, while a large substrate cannot be spun at a sufficiently high rate in order to allow the film to thin. Another disadvantage of spin coating is its lack of material efficiency. Spin coating processes use only 2-5% of the material dispensed onto the substrate, while the remaining 95–98% is flung off in to the coating bowl and disposed.

1.3.3. Dip coating

Dip coating is particularly well suited to the production of thin films because it allows the deposition of very homogeneous films on substrates of different sizes [49]. Moreover, this technique is perfectly controlled and it allows to properly adjust the microstructure (porosity, crystalline structure) of the deposition and to control their thickness [50]. This technique is based on immersing a substrate in the coating solution, fixing it for a while inside the solution then pulling it up at a constant speed. The thin layer deposits itself on the substrate while it is pulled up [51]. The assembly must be devoid of any vibration so that the surface of the solution remains immobile during the deposition in order to obtain a good quality of deposition. The slightest disturbance during this step (immersion-pulling up) will cause horizontal streaks on the deposited film [52]. Different parameters should be controlled during the dip-coating process such as the immersion speed and the solution concentration and viscosity [53]. Several studies reported on the synthesis of TiO_2 and TiO_2 based materials via dip coating technique. For example, Janczarek *et al.* [54] elaborated transparent thin films of Cu-TiO_2 on glass surface with different amounts of copper using the simple dip coating method. They concluded that the Cu-TiO_2 photocatalytic activity under visible light is correlated to the optimal content of copper (Cu/Ti ratio = 0.017). Despite the low cost and the easy process of dip coating, this sol gel technique is not able to elaborate completely densified and uniform coatings.

1.3.4. Hydrothermal methods

Hydrothermal technique is usually performed in a stainless steel vessel [55], this technique is the most commonly used for elaboration of powdery nanostructures [56]. It involves the growth of materials from aqueous solutions at high temperature (above the boiling point of water) which produces high pressure [57]. Hydrothermal method is based on mixing the reagent with the precursor to be injected in the solvent which plays a double role: it accelerates the dissolution of the precursor as well as the reaction rate between the precursor and the reagent with the pressure and temperature increasing [58]. Tian *et al.* [59] report on the different 1D nanostructures elaborated by hydrothermal methods such as nanotubes [60], nanorods [61], nanowires [62] and nanobelts [63] as shown in Figure 1.4. It was found that the morphology and the length of the nanotubes affect the photocatalytic performance of TiO₂. Therefore, increasing the length of the TiO₂ nanotubes improves the photocatalytic performance due to the increased specific surface area. In addition, this structure promotes the decomposition of organic pollutants due to the facile diffusion of pollutants into the TiO₂ nanotubes [64]. Different TiO₂ based materials were synthesized by hydrothermal methods and they showed an enhancement in the visible light photocatalytic activity compared with pure TiO₂ such as Fe-TiO₂ [65], N-TiO₂ [66], Co/Cu-TiO₂ [67] and S-TiO₂ [68]. Despite the advantages of hydrothermal technique such as cost-effective, low energy consumption, simple equipment, chemical homogeneity and high dispersibility, the hydrothermal method has some disadvantages such as having long reaction time duration and producing non-uniform particle sizes of samples

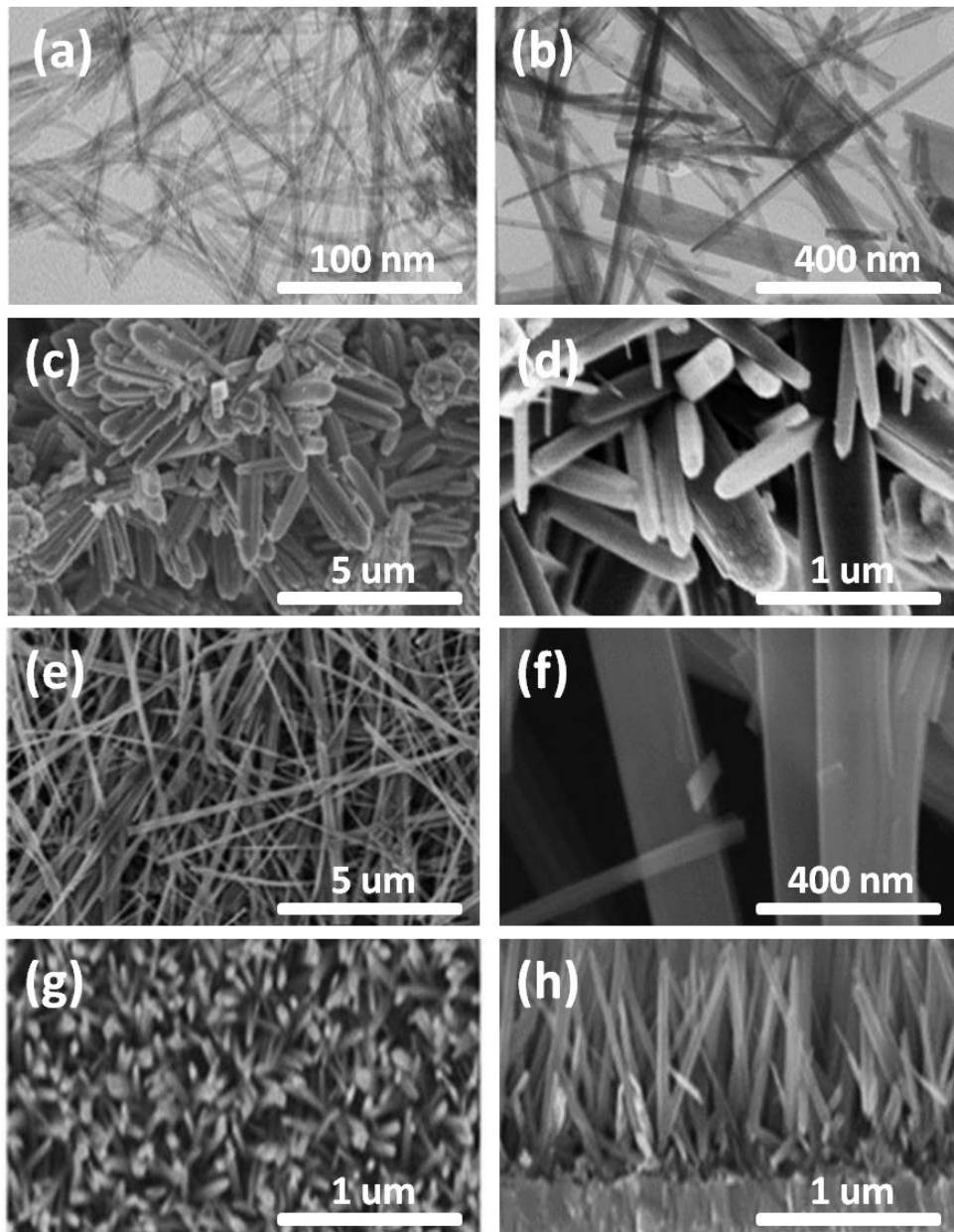


Figure 1.4. Different morphology types of 1D TiO₂ nanostructures synthesized through hydrothermal methods: (a, b) TiO₂ nanotubes, (c, d) TiO₂ nanorods, (e, f) TiO₂ nanobelts, (g, h) TiO₂ nanowires. [59]

1.3.5. Chemical vapor deposition (CVD)

Chemical Vapor Deposition (CVD) is a low cost technique that consists of growing a solid phase material from a gas phase material [69]. In a typical CVD process, the substrate is exposed to one or more precursors which react and/or decompose in gas phase to produce the final film [70, 71]. The CVD technique can be coupled with a plasma system as activation energy instead of thermal activation and it is called PECVD [72]. Yoshitake *et al.*

[73] elaborated mesoporous titanium dioxide using chemical vapor deposition (CVD) of titanium isopropoxide followed by its decomposition with water vapor. They reported that CVD treatment improved the thermal stability of template-extracted titania in air without changing the chemical composition. Recently, Youssef et al. [74] prepared single-oriented pure and N-doped anatase films via PECVD technique using titanium isopropoxide as a precursor and NH_3 as a doping agent. They concluded that N-doped TiO_2 film is an efficient photocatalyst for the photodegradation of stearic acid under visible light. Chemical vapor deposition is widely used for laboratory and industrial applications due to the conformal coating ability in the micrometric range. Despite those advantages of CVD, the nanoscience and nanotechnology need a deposition technique with a conformal coating ability in the nanometer scale.

1.3.6. Atomic Layer deposition

Many deposition techniques are available to deposit TiO_2 thin films on surfaces as explained above. First, these methods cannot deposit conformal films in the nano scale range. In addition, the thick films created using these processes require significant precursor usage relative to alternate thin film solutions [75]. Atomic layer deposition (ALD) is gaining an increased attention in energy and environmental fields as promising method of surface modification and protection [76]. ALD is a vapor deposition method of ultrathin layers. The originality of ALD is given to Professor Aleskovskii and his team in 1960 when they realized the deposition of TiO_2 from TiCl_4 and H_2O [77]. Atomic layer deposition is a deposition technique that derives from the CVD (Chemical Vapor Deposition) technique, it is based on 2 self-limiting reactions absolutely separated in gas phases. Two precursors A and B react on gas phases during the CVD deposition to produce a thin film on the surface of the substrate; the same precursors react separately in ALD with the substrate surface to produce a uniform coating. ALD is a multi-step gas phase adsorption technique that is an analogue of a one-step CVD reaction. No other thin film technique can approach the conformity achieved by the ALD on high aspect ratio structures [78-80]. One cycle including four steps is needed to be able to perform the 2 self-limiting reactions as presented in Figure 1.5: (1) Pulse precursor 1 (introducing the first precursor to the deposition chamber to react with the substrate surface and form a chemisorbed and physisorbed layer), (2) Purge to eliminate both of the physisorbed layer and the by-products of the reaction, (3)

Pulse precursor 2 (introducing the second precursor to react with the chemisorbed layer resulting by the reaction of the first precursor with the substrate). As for the step 1, the chemisorbed and physisorbed layers were formed and (4) Purge to eliminate both of the physisorbed layer and the by-products of the reaction [81]. For photocatalysis application, various nanostructures of TiO_2 based materials have been obtained using ALD methods including Zn_2TiO_4 nanowires [82], ZnO-TiO_2 core-shell [83], Ag-TiO_2 nanocomposites [84] and Pt-TiO_2 , nanoparticles [85]. The potential area of research is increasing in this field due to the accomplishment of ALD in deposition of conformal thin films over complex nanostructures in a precise manner. However, the long deposition time limits the use of ALD in laboratory scale. Therefore, the fabrication in industrial scale is a crucial challenge posed on ALD which could be overcome either by scaling-up or quickening the processes.

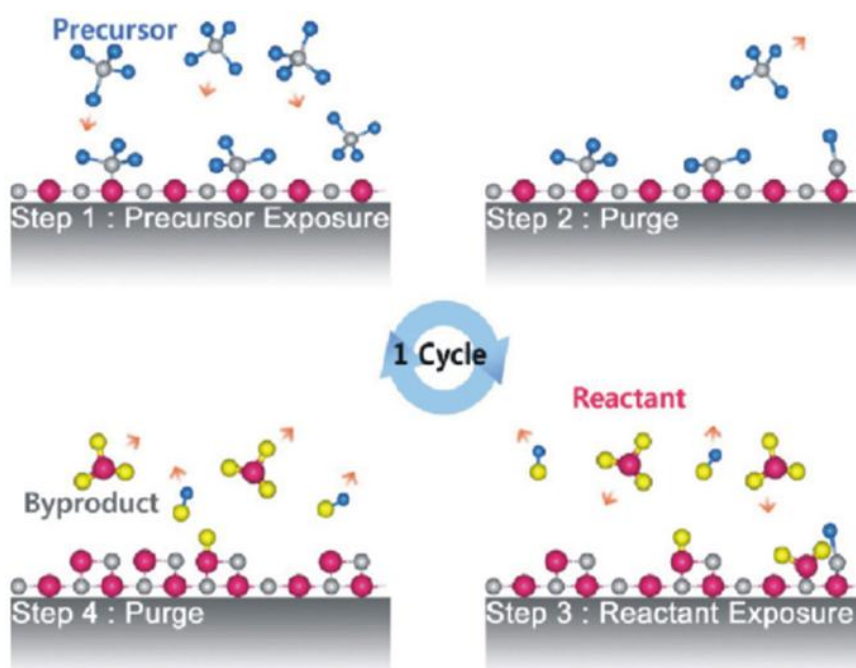


Figure 1.5. Schematics showing the growth process of ALD. [86]

Since the nanostructure's morphology has a high impact on the photocatalytic activity, the most current synthesis techniques used to elaborate different morphologies of TiO_2 nanostructures have been presented. In the next section we will present and discuss the different photocatalysis parameters and how it could be controlled and/or modified in order to improve the photocatalytic performance of TiO_2 .

1.4. Photocatalysis parameters

Many factors affect the rate of a photocatalytic reaction; a distinction can be made between the operating parameters and those relating to the characteristics of the photocatalyst. The operating or extrinsic parameters are external factors such as the pH of the solution, the initial concentration of the organic compound, the catalyst concentration, the oxygen content and the temperature. The parameters related to the photocatalyst or intrinsic properties are those related to the properties of the photocatalyst itself such as structure, band gap, crystallite size ...) [16, 87, 88].

1.4.1. Operating parameters

In photocatalytic process, the followings are operating parameters which affect the process: the pH of the solution, the initial concentration of the organic compound, the catalyst concentration, the oxygen content and the temperature. These parameters will be considered one after the other as they influenced the photocatalytic processes.

- (1) The concentration of the catalyst: previous studies showed that the catalyst concentration is proportional to the concentration of the electron-hole pairs (generated during the process). Actually, an increase in the amount of catalyst increases the number of active sites on the photocatalyst surface and thus improves the photoreaction rate [89, 90]. It was also found that the reaction rate increases with the concentration of catalyst until a maximum constant value (limit concentration) corresponding to the total absorption. Above this limit concentration, the photoreaction rate could even decrease [91, 92].
- (2) The initial concentration of the pollutant: as in any chemical reaction, the reaction is limited by the concentration of one or more reagents in a heterogeneous medium as follow:

$$r = \frac{dC}{dt} = \frac{kKC}{(1+KC)} \quad (\text{Equation 6})$$

In general, the behavior of Langmuir-Hinshelwood type is observed, where r is the degradation rate of the reagent, k represents the kinetic reaction constant, K the adsorption equilibrium constant and C the concentration of the reagent in the aqueous medium. For low value of C ($KC \ll 1$), the reaction follows a first order apparent behavior whereas for high value of C ($KC \gg 1$) the reaction follows a zero order behavior with the reaction rate [16, 93]. Several researches affirmed that the photodegradation efficiency decreased when

the initial concentration of the pollutant increased. In fact, more pollutant molecules were adsorbed on the surface of the catalyst, thus the generation of OH radicals at the catalyst surface was reduced because the active sites were occupied by pollutant cations [94, 95].

- (3) The oxygen content in the medium: The oxygen (from air flow) reacts with the electrons on the surface of the semiconductor and allows the balance of charges to be maintained [90]. Huang *et al.* [96] studied the effect of adding H₂O₂ on the decolorization of methyl orange. They found that the decolorization rate was increased with the increase in H₂O₂ concentration. They reported an optimum concentration of 1.2 mM/L H₂O₂ for photocatalytic decolorization of methyl orange solution by Pt modified TiO₂.

- (4) The pH value plays an important role on the charge surface of both semiconductor and pollutant. On the one hand, it can modify the size of the particles in the aqueous medium; on the other hand, it can modify the adsorption of the pollutant on the surface of the semiconductor. The effects of pH on the photocatalytic degradation of the pollutant have been studied by many researchers and they found that the degradation rate of pollutants is increasing with the decrease in pH [97-99].

- (5) Temperature: previous studies showed that the photocatalytic system does not require heat input because it is a photonic activation process. The majority of photoreactions are not sensitive to small variations of temperature. The decrease in temperature promotes the adsorption which is a spontaneously exothermic phenomenon. When the temperature rises above 80°C, the exothermic adsorption of the pollutants is disadvantaged. Actually, the photocatalysis experiments using high power lamps are equipped with cooling system in order to maintain the temperature of the whole system at 25°C [100, 101].

1.4.2. Modification of TiO₂ properties

One of the limitations of the photocatalytic process in the presence of TiO₂ is the fast recombination of charge carriers [102]. This recombination reduces the quantum efficiency of the photocatalytic process of TiO₂. On the other hand, the non-absorption of visible light limits its applications in sunlight [103, 104]. In order to improve the photocatalytic activity of TiO₂, researches have been carried out on the modification of TiO₂.

1.4.2.1. Metal-doping

Hoffman *et al.* [105] have shown that the substitution of Ti atoms with metallic atoms modify the absorption of TiO₂ by introducing localized energy levels between the valence band and the conduction band of TiO₂. The energy of these levels as well the distribution and the concentration of dopants in the semiconductors play an important role in the photocatalytic process. They introduce extrinsic band gap with lower energy, facilitates the electron-hole separation (formation of Schottky barrier between the semiconductor and the metal) and the hosting of active sites on the surface of TiO₂ [106]. To overcome the limitations of TiO₂ photocatalyst, it was doped with different metals such as silver, iron, palladium, platinum, copper and gold. Among all the noble metals, Ag is promising for extensive applications because of its low cost, facile preparation and antibacterial properties [107]. Until now, many strategies including chemical reduction, UV irradiation, hydrothermal method and electrospinning have been investigated to synthesize different Ag/TiO₂ nanostructures for photocatalytic application [44, 108-111]. These studies show that the presence of Ag nanoparticles can largely prevent the recombination of photo-induced electron-hole pairs in TiO₂. On the other hand, they demonstrated that the fact of introducing Ag leads to a red shift of TiO₂ absorption edge wavelength, thus to an enhancement of the photocatalytic activity of TiO₂ under visible light irradiation [44, 107]. Iron doping was also used to improve the photocatalytic properties of TiO₂. The substitution of Ti atoms by Fe atoms in the TiO₂ network is possible thanks to the similarity of their ionic radii. DFT simulation studies were carried out by Asai *et al.* [112] and more recently by Yalçın *et al.* [113]. In both studies, a slight shift in the energy levels of VB and CB and the creation of intermediate levels are predicted: these results are based on the interaction of the iron 3d orbits with the TiO₂ conduction band. Therefore, Fe-TiO₂ nanoparticles are able to absorb visible radiation. Wang *et al.* [114] have shown that the deposition of Pd on the surface of TiO₂ significantly decreases the rate of depolarization of the particles to such an extent that the accumulation of negative charges in the particles becomes zero. This phenomenon is attributed to the improvement of the mechanism of capture and transport of photo-electrons by Pd to adsorbed O₂. With the decrease of electrons in the particles, the probability of charges recombination decreases and the photocatalytic process is more efficient [114, 115]. The enhancement of the photocatalytic activity with Pt-TiO₂ as photocatalyst was also studied and explained as follow: the electrons are transferred to the

Pt while the deficiency accumulates at the Pt/TiO₂ interface leading to the charges separation and thus reducing the recombination of the electron/hole pairs [116, 117]. The deposition of metals such as Cu [118], Au [119] etc. on the TiO₂ surface enhances its photocatalytic activity, the metal nanoparticles act as electron sensors and improve the separation of charges [120]. Copper-doped nanoparticles, Cu-TiO₂ have been frequently applied in antibacterial treatments, and in CO₂ reduction reactions. The nanoparticles doped with gold (Au-TiO₂) have interesting applications for the production of H₂. As results, the metal-doping has shown both positive and negative effects: some studies confirm that in this case, metal-doping can act as electron-hole recombination centers which are detrimental to the photocatalytic activity [121]. Others also report that metal-doping reduces the band gap energy of TiO₂ and increases its visible-light photoresponse [122]. Although metal-TiO₂ catalysts have been an efficient photocatalyst under visible light they still suffer from multiple competitive disadvantages, including their high cost, susceptibility to gas poisoning, and detrimental effects on the environment. The cost-effectiveness needed by industrial application usually causes their replacement by more economical transition or non-metals doping.

1.4.2.2. Non-metal doping

Due to problems associated with metal doping, non-metal doping was studied comprehensively in the hope of achieving visible light active stable titanium dioxide [123, 124]. The fact of introducing these elements in the TiO₂ network reduced the excitation energy of TiO₂ either by reducing the band gap energy or by creating intermediate energy levels between the valence band and the conduction band [125, 126].

Carbon doping (CNT, graphene, graphene oxide)

Previous studies showed that non-metal doping are able to shift the optical absorbance of TiO₂ to the visible region [127, 128]. Recently, many attentions were devoted toward TiO₂ doped with carbon materials. Etacheri *et al.* [129] have reported that the observed visible light activity is due to the substitution of carbon atoms in the TiO₂ photocatalyst which introduces a new state (C 2p) close to the valence band of TiO₂ (O 2p). C-doped TiO₂ offers high active surface area which is one of the important parameters leading to the increase of the photocatalytic activity. Several studies were focused on

Carbon nanotubes (CNT)/TiO₂ nanocomposites [130, 131]. CNT is considered as a remarkable material due to its unique hollow structure, high electrochemical stability, strong adsorption and high surface-to-volume ratio. It also has an excellent charge transfer ability that contributes to restrain the combination of electron–holes in TiO₂ [130, 132]. Single-walled carbon nanotubes (SWCNTs) have shown a synergy effect on enhancing photoactivity over a mixture of SWCNTs and TiO₂ [133]. On the other hand, previous studies have also demonstrated that multi-walled carbon nanotubes (MWCNTs) could enhance the visible-light-driven photoactivity of TiO₂ by acting as a photosensitizer and promoting the charge transfer in the MWCNT-TiO₂:Ni composites [134].

In 2004, the synthesis of graphene was reported for the first time [135]. Graphene is a one-atom-thick sheet of sp² bonded carbon atoms packed into a 2D honeycomb structure [136, 137]. Graphene has excellent thermal conductivity, large specific area, high electron mobility and good mechanical strength. These properties of graphene make it an ultimate candidate material for enhancement of TiO₂ photoreactivity [138]. Previous studies concluded that graphene enhances the transport of the electron and recombination of the electron and hole gets suppressed. They demonstrated that with the use of graphene-TiO₂ composite (with small amount of graphene) agglomeration of TiO₂ can be avoided so that higher surface area can be maintained and there will be more active sites for the degradation of pollutants. Graphene-TiO₂ composite was doped with different metal and non-metal ions in order to improve the visible-light photocatalysis activity of TiO₂ [139, 140].

Due to the high cost of graphene production, most of researchers choose to work with reduce graphene oxide which can be produced at low cost [141, 142]. Graphene oxide (GO) is usually obtained by the oxidation of graphite using the famous Hummers' method and followed with an exfoliation step (high power ultrasound) [143]. Reduced graphene oxide (removal of some oxygen functionalities) can be obtained by thermal or chemical reduction of graphene oxide [144]. Several advantages motivated the researchers to use rGO or GO/TiO₂ composites to enhance the visible light photocatalytic activity of TiO₂. For example, GO has an excellent carrier mobility, thus the photoelectrons will be rapidly transferred to the GO layers, which reduce the probability of electron-hole recombination. The large surface area of graphene oxide will offer more active adsorption sites of pollutants. In addition, the band gap of graphene oxide can be tuned (from 2.7 to 1.15 eV) by varying the oxidation level (reduced graphene oxide) [145-147]. The key of an effective

visible light photocatalytic activity is to shift the absorbance of TiO_2 from UV range to the visible range by reducing the band gap energy of TiO_2 . Many researchers have proved that using graphene oxide as a dopant for TiO_2 will lead to the Ti-O-C bond formation and therefore introduces lower band gap energy which will improve the visible light photoactivity of TiO_2 , as shown in Figure 6 [148, 149].

Since the surface complexity, the crystalline phase, the porosity and the size of photocatalyst play an important role in the photocatalysis process enhancement, different morphologies of GO/ TiO_2 structures were successfully elaborated [150-152]. Lavanya *et al.* [144] fabricated reduced graphene oxide wrapped with mesoporous TiO_2 nanofibers using the simple electrospinning technique and easy chemical reduction. They demonstrated that the reaction area and the adsorption of dye were increased due to the high surface area of the rGO. As result, the photocatalytic activity of the composites is enhanced compared to TiO_2 nanofibers alone. Li *et al.* [153] showed that the porosity improves the utilization rate of the visible light because the light enters the porous TiO_2 nanotubes and is repeatedly reflected inside the nanotubes until it is completely absorbed.

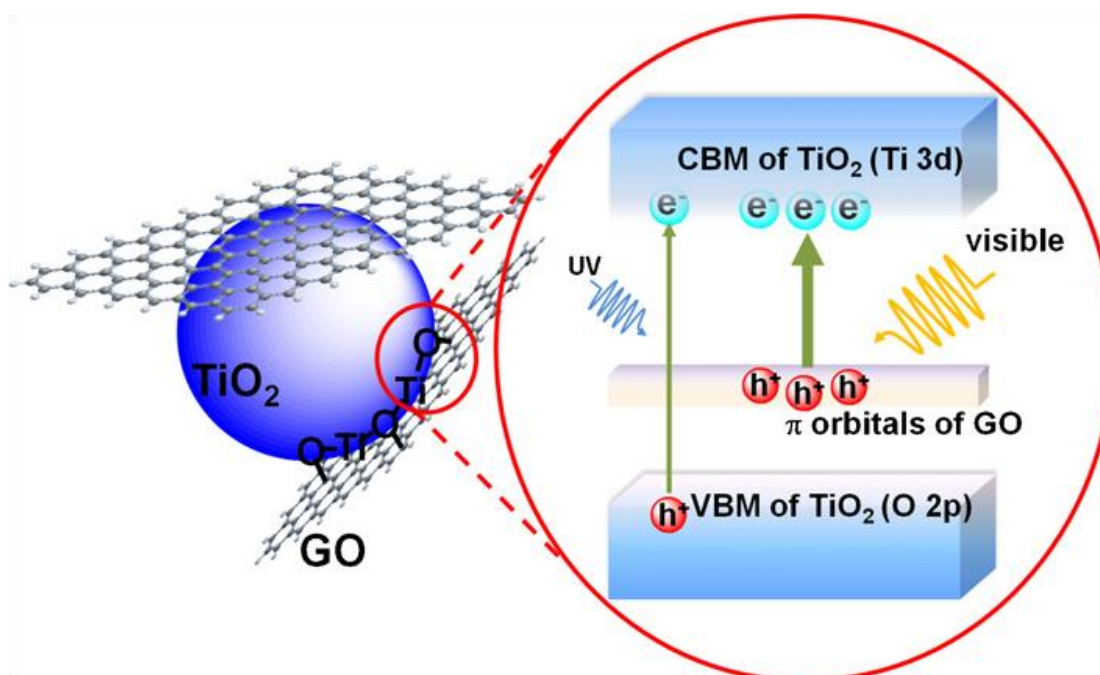


Figure 1.6. Ti–O–C bonding formed through interaction between unpaired π electrons on GO with Ti atoms surface of TiO_2 . This bonding narrows the band gap of TiO_2 and extends the light absorption range of TiO_2 . [154]

Nitrogen doping

Due to its high stability and small ionization energy, nitrogen was also an element of increased interest over the years with several publications focusing on the N doped TiO₂ for visible light photocatalysis [66, 155, 156]. There are three different explanations regarding modification mechanism of TiO₂ doped with nitrogen:

- (1) Impurity energy levels: Wang *et al.* [157] suggest that after nitrogen doping, N element substitutes the O element in the lattice of TiO₂ and forms isolated impurity energy levels above the valence band. They suggest that Irradiation with UV light excites electrons in both the VB and the impurity energy levels, but illumination with visible light only excites electrons in the impurity energy level.
- (2) Band gap decreasing: Cao *et al.* [158] found that due to their close energies, N 2p state hybrids with O 2p states, leading to the band gap narrowing which made N-TiO₂ active under visible light.
- (3) Oxygen vacancies: Ihara *et al.* [159] affirmed that oxygen vacancies, formed in the grain boundaries, are stabilized by the presence of nitrogen. As a result of charge compensation they improve the visible light response. Till now, no study has demonstrated completely the exact chemical states of N species that are responsible for achieving visible light photocatalytic activity of TiO₂.

Figure 1.7 shows a possible mechanism of photocatalytic reactions of \dot{O}^- radical and the schematic band structure of N-doped TiO₂ under visible light irradiation. The electron transfers directly into the conduction band of TiO₂, reducing O₂ to form superoxide ions (O₂⁻). The hole (h⁺) then reacts with OH⁻ group to produce $\dot{O}H$ radical, which are responsible for the degradation of the pollutants under visible light irradiation [160, 161].

As reported for metal-doping, non-metal doped TiO₂ has also its own problems. For example, the doping of nonmetals into the lattice of TiO₂ usually results in the formation of oxygen vacancies in the bulk which can act as massive recombination centers of photo-induced electron-hole pairs and therefore limits the visible light photocatalysis efficiency of doped TiO₂. The stability of non-metal doped TiO₂ is also a concern in regard to the long-term photocatalytic stability. Therefore, other research focuses on the coupling of two semiconductors as it will be discussed in the following section.

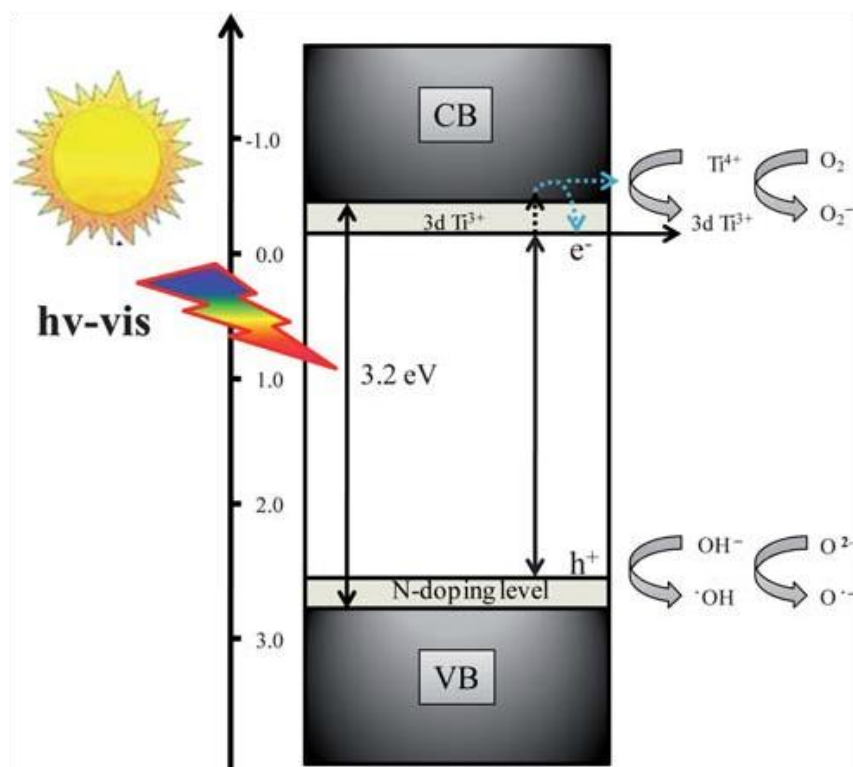


Figure 1.7. A possible mechanism of photocatalytic reactions of $\text{O}^{\cdot -}$ radical and the schematic band structure of N-doped TiO_2 under visible light irradiation. [155]

1.4.2.3. Coupling with other semiconductors

During the formation of an interface between two different semiconductor's phases, the difference in energy between the conduction and valence bands of the two phases may allow the irreversible spatial separation of the charge carriers as long as this difference in energy is sufficiently large [162]. In addition to the importance of these interfaces between crystalline phases for the efficient separation of charge carriers, the interfaces' structure plays an important role for the interfacial transfer process efficiency [163]. For visible light photocatalysis, the nanoscale coupling is between TiO_2 and another small band gap semiconductor such as WO_3 , SnO_2 , FeO_3 and CdS [164-167]. The small band gap semiconductor allows the absorption band of TiO_2 to be shifted toward visible wavelengths. These semiconductors with a smaller band gap absorb a part of the visible light and can serve as sensitizers for TiO_2 . Thus, many coupled photocatalysts have been used in the field of pollutant degradation [168]. The coupling between TiO_2 and another semiconductor at the nanometric scale leads to the formation of an interface between the two semiconductors, called heterojunction. The existence of this interface under optimum

conditions will make it possible to increase the efficiency of the photocatalytic process by reducing the probability of the photogenerated charges recombination through their spatial separation on the two semiconductors. Therefore, we must consider the relative positions of the energy levels of the valence and conduction bands of the two semiconductors [169]. Figure 8 presents the semiconductors configuration in which a vectorial transfer of photogenerated electron-hole, between corresponding band levels, ensures a spatial separation between them. Previous study shows that it is necessary that the conduction band of TiO_2 be more anodic than the corresponding band of the sensitizer. Thus, under visible irradiation, only the sensitizer is excited and the generated electrons will flow into the conduction band of the adjacent TiO_2 (Figure 1.8. a). Besides, if the valence band of the sensitizer is more cathodic than that of TiO_2 , the holes will be lower in the valence band of the sensitizer (Figure 1.8. b) [163]. Subsequently, this phenomenon has been widely studied and discussed. Moreover, for an effective vectorial phenomenon under visible light, the following steps are required: (1) the sensitizer should have a strong absorption threshold in the visible region; (2) the conduction band edge potential of the sensitizer should be higher than the TiO_2 conduction band to facilitate the smooth electron transfer; (3) simultaneous irradiation and excitation of the two semiconductors; and (4) intimate contact between the two types of semiconductor particles. Thus, this physical separation of the photogenerated charges will make it possible to increase their lifetime and improve the efficiency of the visible light photocatalytic phenomenon [170]. Li *et al.* [171] prepared CdS (2.4 eV) sensitized mesoporous TiO_2 photocatalysts. Both the conduction band and the valence band of CdS are higher than their counterparts in TiO_2 . The presence of CdS in the TiO_2 framework extended its photoresponse to the visible light region by accelerating the photogenerated electron transfer from the inorganic sensitizer to TiO_2 . High photocatalytic activity has been recorded toward the degradation of organic compounds under visible light. Despite all these advantages for using coupled semiconductors, the presence of a large number of unpassivated or partially passivated surface states act as trap centers for holes and electrons, leading to a decrease in the photocatalytic activity.

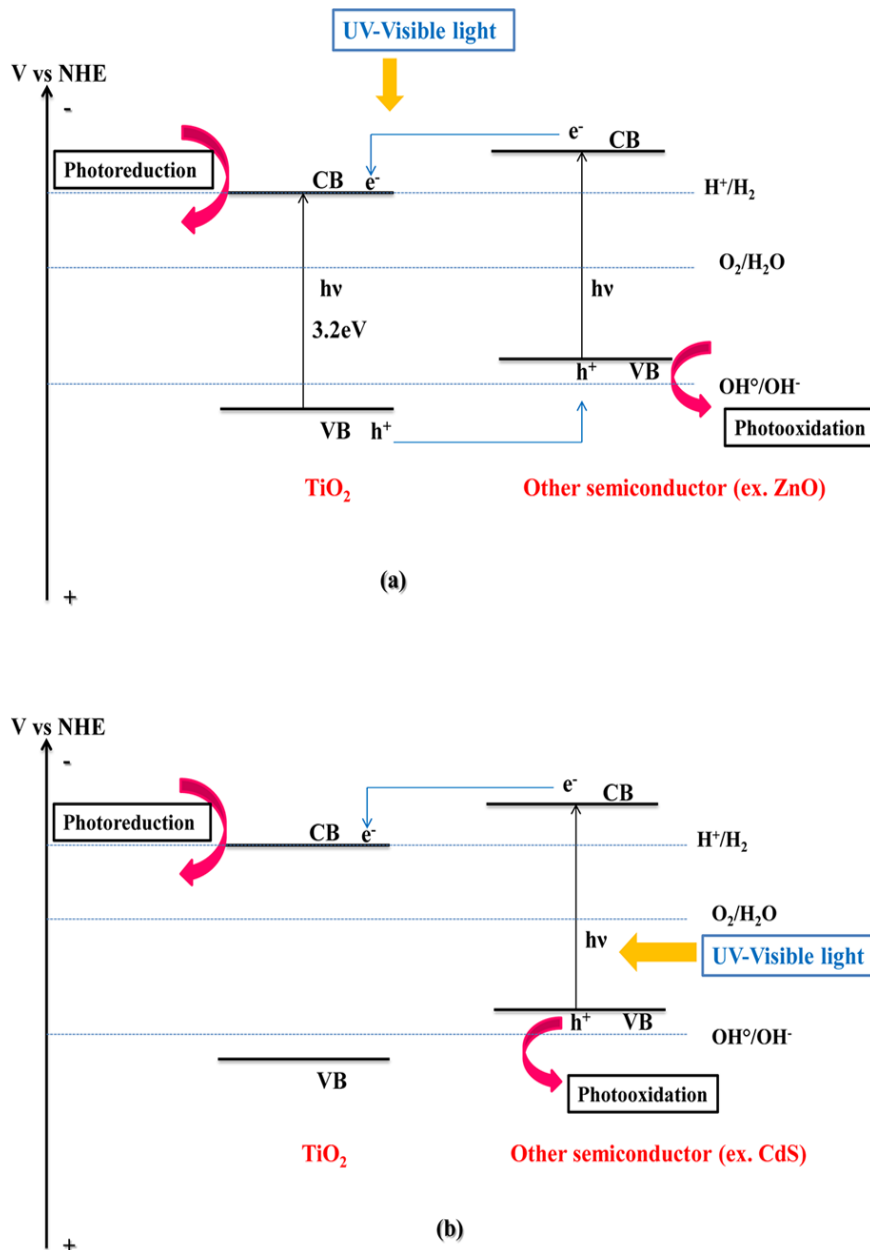


Figure 1.8. Vectorial transfer of electrons–holes in coupled semiconductor system:(a) when the conduction band of TiO_2 is more anodic than the corresponding band of the sensitizer and (b) when the valence band of the sensitizer is more cathodic than that of TiO_2 one. [172]

1.4.2.4. Multiple functional components

The heterostructure junctions with built-in potential effectively drive the separation and transportation of photogenerated electron-hole pairs [173, 174]. Different rational design and nanoscale integration of multiple functional components were elaborated in order to promote the photogenerated charge carriers and therefore improve the

photocatalytic activity and stability [175, 176]. A list of different multiple functional/ TiO_2 based materials; their preparation methods and their photocatalysis application are shown in Table 1.1. The reported studies show that the multiple functional components exhibit a higher photocatalytic performance compared to single - or two-component photocatalysts. For example, Sui *et al.* [24] fabricated Ag-AgBr/ TiO_2 heterostructured nanofibers by combining solvothermal technique with photoreduction method. Ag-AgBr/ TiO_2 heterostructured nanofibers showed an enhanced photocatalytic activity and good stability (reuse for up to five cycles) for the degradation of methylene blue under visible light compared with TiO_2 nanofibers and Ag-AgBr powder. These results were explained by the surface plasmon resonance effect of Ag nanoparticles and the synergetic effect between the three components of Ag, AgBr powder and TiO_2 nanofibers. Figure 1.9 shows the proposed photogenerated charge separation and migration process in Ag-AgBr/ TiO_2 heterostructure.

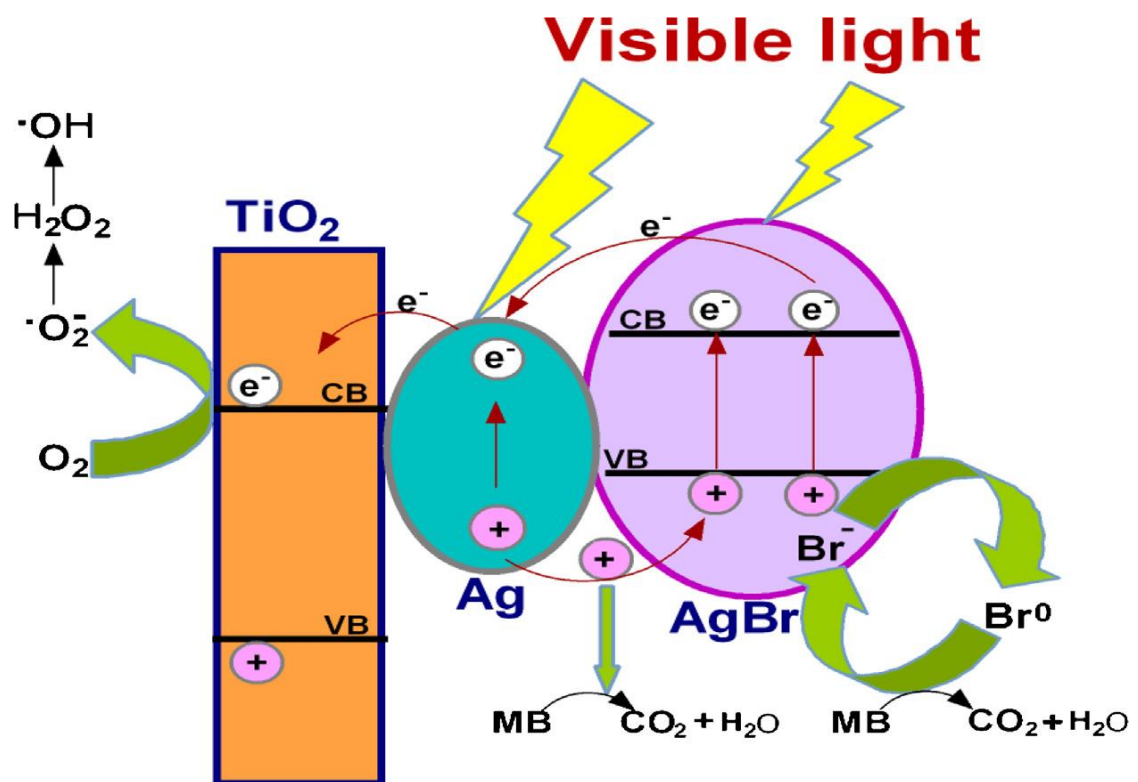


Figure 1.9. Proposed photogenerated charge separation and migration process in Ag AgBr/ TiO_2 heterostructured nanofibers under visible light irradiation. [24]

Table 1.1. Different multiple functional/TiO₂ based materials, their preparation methods, their band gap, their photocatalysis application and their photocatalytic efficiency under visible light.

TiO ₂ based heterostructures	Preparation method	Band gap (ev)	Photocatalysis application	Photocatalytic efficiency	References
Ag-AgBr/TiO ₂ nanofibers	Solvothermal technique and photoreduction method	2.59	Degradation of methylen blue under visible light	2.5 times higher than TiO ₂ -P25	[24]
3D ordered assembly of Thin-Shell Au/TiO ₂ hollow nanospheres	Layer-by-Layer technique	2.53	Decomposition of isopropanol	2.8 times higher than TiO ₂ -P25	[177]
Heterostructured g-C ₃ N ₄ (4%)/Ag/TiO ₂ microspheres	Photodeposition method	2.68	Photodegradation of methyl orange	40 times higher than TiO ₂ microspheres	[178]
Au-Pd/TiO ₂ nanobelts nanostructures	Deposition-precipitation method	2.83	Aerobic oxidation of benzyl alcohol	3 times higher than Au/TiO ₂ nanobelts	[179]
Au-Cu nanoparticles supported on SrTiO ₃ /TiO ₂ coaxial nanotube arrays	Hydrothermal and solvothermal methods	2.17	Photoreduction of CO ₂ into CO	16 times higher than TiO ₂ nanotube arrays	[180]
CdS/Pt-TiO ₂ hybrids	Chemical precipitation	2.25	Hydrogen production	10 times higher than CdS/TiO ₂	[181]
Ag ₃ PO ₄ /TiO ₂ /Fe ₃ O ₄ heterostructure nanospheres	In situ hydrolysis and precipitation method.	2.75	Photodegradation of acid orange 7	5.1 times higher than TiO ₂ nanoparticles	[182]

The most efficient strategies and the recent progress to enhance the visible light photocatalytic activity of TiO₂ were discussed in this section. As results, there is a critical necessity to further develop these strategies in the purpose to be used in the industrial field. The TiO₂ based photocatalyst could be used in different photocatalysis applications in energy conversion and environmental remediation purposes as it will be discussed in the following section.

1.5. Photocatalysis applications

Increasing the need of clean water sources due to the rapid development of industries, population growth, science and technology have become issues worldwide. Recently, much attention was devoted to the photocatalysis process in the water depollution process. In addition, the photocatalysis process also concerns the energy storage via the ability to produce hydrogen. In this section, we briefly discuss the implication of TiO₂ in the various photocatalysis applications for treatment of water sources (pollutant degradation and bacterial removal) and hydrogen production.

1.5.1. Pollutant degradation

Water pollution, by some industrial, pharmaceutical or agricultural chemicals constitutes a source of environmental degradation and is currently attracting a particular national and international attention [183]. Several types of organic and inorganic pollutants have been identified in industrial effluents such as dyes, heavy metals and pharmaceutical products [3, 184, 185]. The degradation of these pollutants by photocatalysis process will be discussed in this section.

1.5.1.1. Organic compounds

Because the textile industry uses large volume of water, a large number of organic compounds are released into the environment [186]. Organic pollutants are defined by the following properties: (1) Toxicity: they have one or more harmful impacts on human health as well as on the environment [187]; (2) Persistence in the environment: there are molecules that resist natural biological degradation; and (3) Bioaccumulation: the molecules accumulate in living tissues [188]. In addition to their properties of persistence and bioaccumulation, these molecules tend to move along very long distances and they deposit away from their emission sites, such as pesticides, hydrocarbons, dyes, drugs etc [189-192]. Removing organic contaminants via photocatalysis has been shown to be more efficient than conventional waste water treatment such as filtration [193]. Several studies reported on the photodegradation of dyes as model pollutants by TiO₂-based photocatalyst under visible light include methylene blue[194], methyl orange[195], rodamine B[196-198], brilliant green[199, 200], phenol[201, 202], acid red [203, 204]. Wand *et al.* [205] elaborated

carbon-sensitized and nitrogen-doped TiO₂ (C/N–TiO₂) using sol-gel method. They obtained a high efficient photodegradation of sulfanilamide (SNM) under visible light due to the incorporated carbon which serves as photosensitizer and the nitrogen doping which is responsible of the absorption edge red shift of C/N–TiO₂. Senthilnathan *et al.* [206] used lindane, an insecticide, as a target pollutant. They found that lindane was completely degraded under visible light by N-TiO₂ photocatalyst.

1.5.1.2. Heavy metals

Heavy metals are numerous and their toxicity depends on the context in which they are located and their concentration in aquatic environments [207]. In environmental science, heavy metals associated to the pollution and toxicity are generally cadmium (Cd), chromium (Cr), mercury (Hg), manganese (Mn), arsenic (As), nickel (Ni) and plumb (Pb) [208]. When we discuss the problem of heavy metals, it is worth noting that these elements are found in our everyday environment in different chemical forms which can confer a particular property (solubility, toxicity, etc.) on the studied metal [209]. Schrank *et al.* [210] evaluated the effect of pH and pollutants concentration on the kinetics of the reactions. They concluded that Cr(VI) reduction using TiO₂-P25 as photocatalyst was faster in acidic pH (pH = 2.5) compared to neutral pH. Recently, Sreekantan *et al.* [211] synthesized Cu-TiO₂ nanotubes using electrochemical anodization. The results showed that the removal of Pb(II) heavy metal by Cu-TiO₂ photocatalyst was up to 97% due to Cu²⁺ ions which play an important role in suppressing the recombination of charge carriers. In 2016, Zhang *et al.* [212] developed TiO₂-modified sewage sludge carbon (SS-carbon). They reported that the combination of the SS carbon with TiO₂ doubled the adsorption capacity of mercury on the SS carbon, and the photocatalytic removal rate was increased to 151 g/kg compared to 87 g/kg for SS carbon only. In addition, they concluded that Hg(II) removal increased with the increase of pH value.

1.5.2. Bacterial removal for water disinfection

Over the past 35 years, the use of TiO₂ photocatalysis for remediation of contaminated water has been extensively reported [213]. TiO₂-mediated disinfection has been studied for the first time by Matsunaga *et al.* [214] when they reported the destruction of three different bacterial species (*E. coli*, *Lactobacillus*, *Acidophilus*) using Pt-

TiO₂ as photocatalyst. Due to its strong oxidizing power, non-toxicity, and long-term photostability, photocatalytic disinfection is a promising process compared to the chlorination and UV disinfection methods [215]. Matsunaga *et al.* [216] studied the photocatalytic inactivation of E. Coli TiO₂. They found an E. coli inactivation of 99% in deionized water. The authors suggested that cell death was caused by the inhibition of its respiratory activity caused by the decrease in coenzyme A. They also reported that no cell wall destruction caused by the semiconductor was observed. Other studies demonstrated that the oxidative damage is initially due to oxidation of the cell wall, where the TiO₂ photocatalytic surface allows first contact with the intact cells. Then, the oxidative damage of the cytoplasmic membrane occurs. The photocatalytic action progressively increases the cell permeability and then allows the release of the intracellular content leading eventually to death. These authors also suggested that free particles of TiO₂ could also penetrate the membrane of damaged cells and attack intracellular components, which can accelerate the cell death [217]. Nadochenkoa *et al.* [218] showed that trapping holes in TiO₂ by the cell wall is more efficient than photogenerated electrons trapping, leading to a decrease in electron/hole recombination. Several authors have reported that cell wall modification by UV/TiO₂ is the main cause of bacterial inactivation [219-221].

1.5.3. Hydrogen generation

The production of hydrogen by photocatalysis is based on the decomposition of many organic species (alcohols, acids ...). The main objective of photocatalysis is to directly use water, or polluted effluents as a source of hydrogen [222]. The following three mechanisms are used for the hydrogen production:

- (1) Mechanism for the dehydrogenation of an alcohol: when the reagent used to produce hydrogen is a pure alcohol, the resulting photocatalytic reaction corresponds to the dehydrogenation of this alcohol [223]. Higashimoto *et al.* [224] reported on the synthesis of CdS/TiO₂ photocatalyst modified with a Pd co-catalyst for the selective dehydrogenation of benzyl alcohol to benzaldehyde with high selectivity (>99%) accompanied by the formation of H₂ in aqueous solution under visible-light irradiation.
- (2) Water splitting: this mechanism is one of the most attractive reactions for hydrogen production [225]. The objective is to use solar energy to obtain hydrogen from water, and then to use this hydrogen directly to produce electricity via a fuel cell. The chosen

photocatalyst should have a conduction band with an electrochemical potential lower than that of the H^+/H_2 redox couple to reduce the hydrogen. In addition, the electrochemical potential of the photocatalyst's valence band should be greater than that of the O_2/H_2O redox couple to oxidize the water [226]. The photocatalytic hydrogen production by TiO_2 is shown in Figure 1.10. Thus, all the photocatalysts that satisfy the above-mentioned requirements are capable to reduce hydrogen or to oxidize water. TiO_2 [227], $SrTiO_3$ [228], $KTaO_3$ [229, 230] and CdS [231, 232] are the most used candidates for water splitting.

- (3) Mechanism of an alcohol reforming: photocatalytic reforming of organic compounds such as alcohols is another method of hydrogen production. These reactions generally consist of several successive steps leading to the formation of CO_2 and H_2 . Various alcohols have been used in this type of photocatalytic reforming reaction such as methanol, and ethanol [233, 234]. The hydrogen produced by photocatalysis is not pure. The species present in the gas phase will be dependent on the organic compounds used for reforming. Thus, hydrogen is accompanied by different species such as CO_2 , alkanes and aldehydes [235]. Recently, Kennedy *et al.* [236] produced hydrogen by methanol reforming using $Au-Ag/TiO_2$ photocatalyst prepared via sol immobilization. They studied the effect of gold loading over Au/TiO_2 catalysts. They showed that the maximum rate of H_2 production was observed for Au loadings of 1–2 wt.%. In addition, they reported that the order of the metal addition is significant for the preparation of active $Au-Ag/TiO_2$ photocatalysts and in improving the hydrogen production.

Now, it is well-established that energy production and environmental challenges constitute issues worldwide. As conclusion we can assume that the photocatalysis applications with TiO_2 should have a future beneficial impact on the environment, energy production and public health. In addition, the results found from different photocatalytic applications employed in the laboratory scale encourage further research to use photocatalysis to advance in the large scale such as commercial and industrial processes.

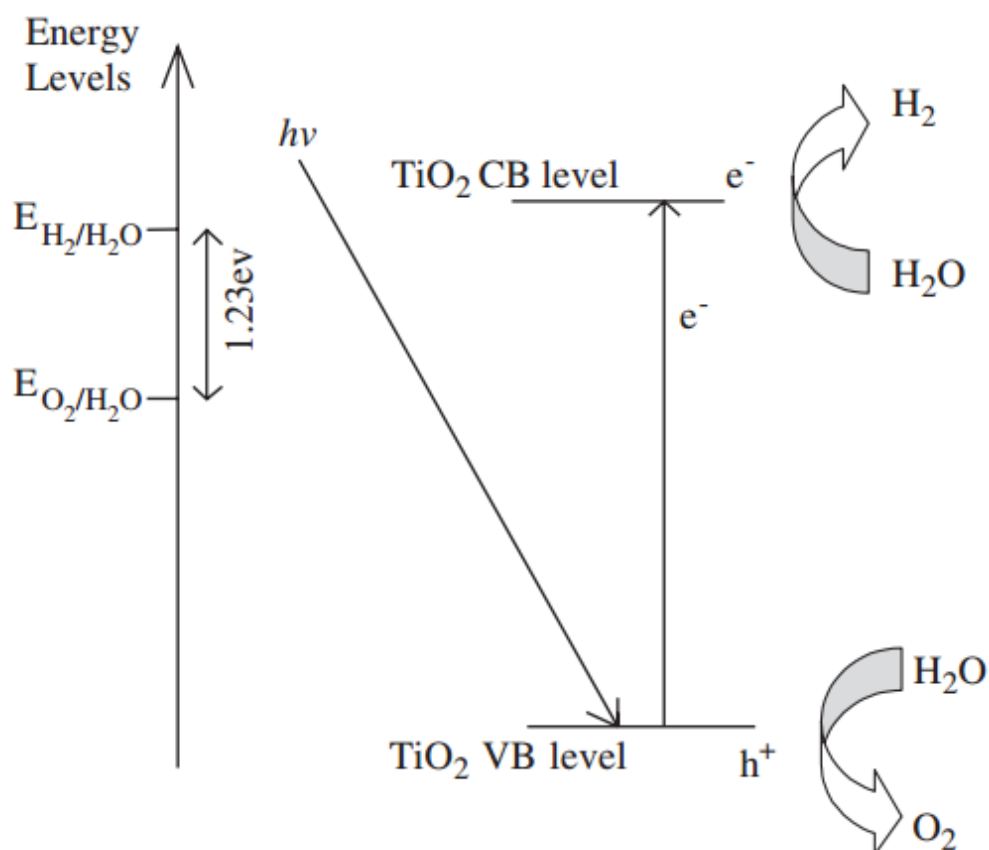


Figure 1.10. Mechanism of TiO₂ photocatalytic water-splitting for hydrogen production.

[225]

1.6. Conclusion and Perspectives

Since the two principle limitations of TiO₂ are the fast charge recombination and the UV absorption edge, many efforts have been devoted to develop a new TiO₂ photocatalyst with low charge recombination rate and able to absorb visible light which is the main part of solar spectrum. The present chapter has summarized the recent research development to enhance the photocatalytic activity of TiO₂ photocatalyst under visible light and solar irradiation. First, we defined current techniques used to synthesize different morphological structures of TiO₂ based materials. In order to promote the charge separation efficiency and improve the visible light photocatalytic activity of TiO₂, different strategies were discussed such as metal doping, non-metal doping, coupling of two semiconductors with different energy band gap, metal deposition on the surface of TiO₂ and the multiple functional components heterostructure. These strategies promote the charge separation of TiO₂ and extend the absorption to the visible region allowing the use of solar light to achieve the photocatalytic process. In addition, we showed the different photocatalysis applications.

Photocatalysis process can be used for the treatment of industrial wastewater for the removal of heavy metals and organic compounds. This technique can be used also for hydrogen production and water disinfection. As perspectives, future research should be focused on the development of new strategies to improve the photocatalytic efficiency of TiO_2 . Although the achieved great progress in the TiO_2 photocatalyst under visible light is still at a laboratory scale, the major challenge for the scientific research is to further improve the efficiency of these photocatalysts for industrial use.

1.7. Research Aim

The aim of the present work is to find a way of reducing the recombination of photogenerated charge carriers and to shift the absorption edge of TiO_2 . Our research will focus on elaborating titanium dioxide nanofibres, modified with metal doping and/or non-metal doping and to study the effect of structural and optical properties on the photocatalytic properties of the prepared samples. The photocatalytic activity of the prepared photocatalysts will be investigated for the degradation of organic dyes (methylene blue and methyl orange) as well as for the water disinfection against E.coli bacteria under UV and visible light.

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Chapter 2: Enhanced Visible-Light Photocatalytic Performance of Electrospun rGO/TiO₂ Composite Nanofibers

Table of Contents

1. Abstract.....	65
2. Introduction.....	65
3. Materials and methods.....	66
3.1. Materials	66
3.2. Synthesis of Graphene Oxide	66
3.3. Preparation of TiO ₂ and rGO composite nanofibers	66
3.4. Chemical and structural Characterization.....	67
3.5. Photocatalytic activity measurement	67
4. Results and discussion.....	69
4.1. Morphological properties of TiO ₂ /rGO nanofibers	69
4.2. Structural properties of TiO ₂ /rGO nanofibers.....	71
4.3. Optical properties of TiO ₂ /rGO nanofibers	75
4.4. Photocatalytic degradation of methyl orange by rGO/TiO ₂ composite nanofibers	77
5. Conclusion.....	82

1. Abstract

Reduced graphene oxide (rGO) / Titanium dioxide (TiO₂) composite nanofibers as photocatalytic materials were successfully elaborated by using electrospinning. The as-spun nanofibers with controlled ratio of rGO were annealed at 500°C under Nitrogen in a tubular furnace. Structural, morphological and optical characterizations demonstrate the success of rGO incorporation in the TiO₂ nanofibers. The performances of these nanocomposites for photocatalytic application have been evaluated. The presence of rGO sheets decreases the band gap energy of TiO₂ NFs from 3.2 eV to 2.9 eV. Hence, in the photodegradation of methyl orange (MO), a significant enhancement in the reaction rate was observed with rGO/TiO₂ (2wt. %) composite NFs compared to commercial TiO₂-P25. In addition, the kinetic of MO degradation by rGO/TiO₂ (2wt. %) composite NFs is 6 times higher than that by commercial TiO₂. Thus, the photocatalytic activity of the composites rGO/TiO₂ significantly increases the visible light photo-response and improves the separation of photo-induced electron-hole pairs of TiO₂.

2. Introduction

The aim of this chapter was the enhancement of the photocatalytic activity of TiO₂ under visible light by doping with reduced Graphene Oxide (rGO) nanosheets. The role of rGO is to shift the absorption edge of TiO₂ toward higher wavelengths and to decrease its band gap. As well, rGO plays an important role in the photodegradation process by improving the separation efficiency of the electron/hole pairs in the semiconductor. In this chapter, we will report on the synthesis of Graphene Oxide (GO) using modified Hummer's method and the elaboration of rGO/TiO₂ composite nanofibers by electrospinning technique. Different characterisations techniques were used to study the morphological, structural and optical properties of the prepared samples. The photocatalytic activity of TiO₂ and rGO/TiO₂ composite nanofibers was evaluated by the degradation of Methyl Orange (MO) under visible light irradiation.

3. Materials and methods

3.1. Materials

Commercial graphite powder (99.95%), titanium tetraisopropoxide (TTIP) Ti{OCH(CH₃)₂} (97%), polyvinylpyrrolidone (PVP) (M_w = 13,00,000), acetic acid (98%), phosphoric acid (H₃PO₄, 85%), sulfuric acid (H₂SO₄, 98%), hydrochloric acid (HCl, 30%), potassium permanganate (KMnO₄, 98%), hydrogen peroxide (H₂O₂, 30%), methyl orange (MO), and absolute ethanol were purchased from Sigma Aldrich, and used without any further purification.

3.2. Synthesis of Graphene Oxide

Graphene oxide was synthesized from natural graphite powder, following modified Hummer's method [1]. Briefly, 3g of graphite were dispersed in concentrated H₂SO₄:H₃PO₄ (9:1, 400 mL) solution. 18 g of KMnO₄ were added gradually to the mixture with stirring for 12 h. Later on, the mixture was cooled down to room temperature and then H₂O₂ (3 mL) was added. Brown precipitate was observed showing the exfoliation of graphene oxide from graphite. After one hour of stirring, GO was separated by centrifugation at 2697 G for 10 minutes and the supernatant was decanted away. The resultant precipitates were washed several times with 30% hydrochloric acid and absolute ethanol. Finally, the obtained powder was dried at 50°C for 24 hours to obtain the pure graphene oxide.

3.3. Preparation of TiO₂ and rGO composite nanofibers

The electrospinning process was used to prepare the rGO-incorporated TiO₂ nanofibers. Spun solution was prepared in three steps. In the first one, different amounts of graphene oxide (0, 2, 5, 7 wt. % of mass Ti) and 2 ml of absolute ethanol were sonicated for 12h to disperse the graphene oxide into ethanol solution. In the second step, titanium tetraisopropoxide was dissolved in a mixture of 2 ml of acetic acid and 3 ml of ethanol mixed with 0.3 g of polyvinylpyrrolidone (PVP). The precursor mixture was stirred for 1 h at room temperature to obtain sufficient viscosity required for electrospinning. Finally, the GO solution was added to the precursor solution with vigorous magnetic stirring (150 rpm) for 30 min. The homogeneous dark black solution was loaded into a plastic syringe having a stainless steel needle with a diameter of 0.7 mm at a constant flow rate of 1 ml/h. The feeding rate was controlled by the syringe pump. The temperature level inside the

electrospinning chamber was $38 \pm 5^\circ\text{C}$. Nanofibers were collected on a rotating coil covered with an aluminum foil with a rotation speed of 400 rpm. The distance between the tip of the needle and the aluminum foil was maintained at 20 cm, and a DC voltage of 25 kV was applied. During electrospinning process, the applied electric field overcomes the surface tension of the polymeric solution, thereby ejecting a continuous jet, which upon subsequent solvent evaporation and bending produces nanofibers on the collector surface [2]. The electrospun TiO₂-GO composite nanofibers were collected and then calcined at 500°C with a heating rate of $1^\circ\text{C}\cdot\text{min}^{-1}$ for 6 h in N₂ environment in a tubular furnace in order to reduce the GO sheets [3] to form rGO/TiO₂ NFs.

3.4. Chemical and structural Characterization

X-ray diffraction (XRD) measurements were carried out using a PANalytical Xpert-PRO diffractometer equipped with an X'celerator detector using Ni-filtered Cu-radiation ($\lambda = 1.54 \text{ \AA}$). Fourier-transform infrared (FTIR) spectra were recorded on a Nicolet 370 FTIR spectrometer using an ATR system. Transmission electron microscopy (TEM) images were taken with a PHILIPS-CM 20 (accelerating voltage: 200 KV). Scanning electron microscopy (SEM) images were taken with a Hitachi S4800, Japan (accelerating voltage: 1 KV). The UV-Vis absorbance spectra of methyl orange were recorded by a Jasco V-570 UV-VIS-NIR spectrophotometer. Raman spectra have been obtained from Horiba xplora, $\lambda = 659 \text{ nm}$. Energy-dispersive X-ray spectroscopy analysis (EDX) was taken with Zeiss EVO ED15 microscope coupled with an Oxford X-MaxN EDX detector.

3.5. Photocatalytic activity measurement

Methyl orange was used as a reference of organic pollutant to evaluate the photocatalytic activity of the rGO/TiO₂ composite NFs. The photocatalytic performance of the samples was evaluated by analyzing the decrease in concentration of the MO during exposure to visible light irradiation. The reaction temperature was kept constant at $25 \pm 0.2^\circ\text{C}$ by circulating water in a cylindrical tube surrounding the photo-reactor during the entire experiment. The decomposition was carried out in several beakers containing a suspension of 10 mg of each sample in 25 mL of MO solution (10 mg/L) under visible light irradiation (obtained from a 150 W light source, emission wavelength $> 400 \text{ nm}$). The distance between the lamp and the dye solution was maintained at 10 cm. First, the solution

mixture was magnetically stirred for 30 min without irradiation to reach the adsorption–desorption equilibrium of MO [4]. Then, the solution was irradiated with visible light for 2 hours. Each 30 minutes, 3 ml of the sample solution was taken out and centrifuged to remove the catalyst. The centrifuged solutions were analyzed by a UV/Vis spectrometer. The absorbance spectra of MO (major absorption band around 462 nm)[5] were recorded to measure the change in the concentration of MO[6]. After irradiation, the photocatalytic degradation efficiency has been calculated by equation 1:

$$\text{Degradation efficiency (\%)} = (C_0 - C) / C_0 \times 100 \quad (\text{Equation 1})$$

where C_0 and C are the initial concentration and the final concentration of dye before and after photo-irradiation respectively. This equation shows the dye photocatalyst degradation percentage [7].

4. Results and discussion

4.1. Morphological properties of TiO₂ /rGO nanofibers

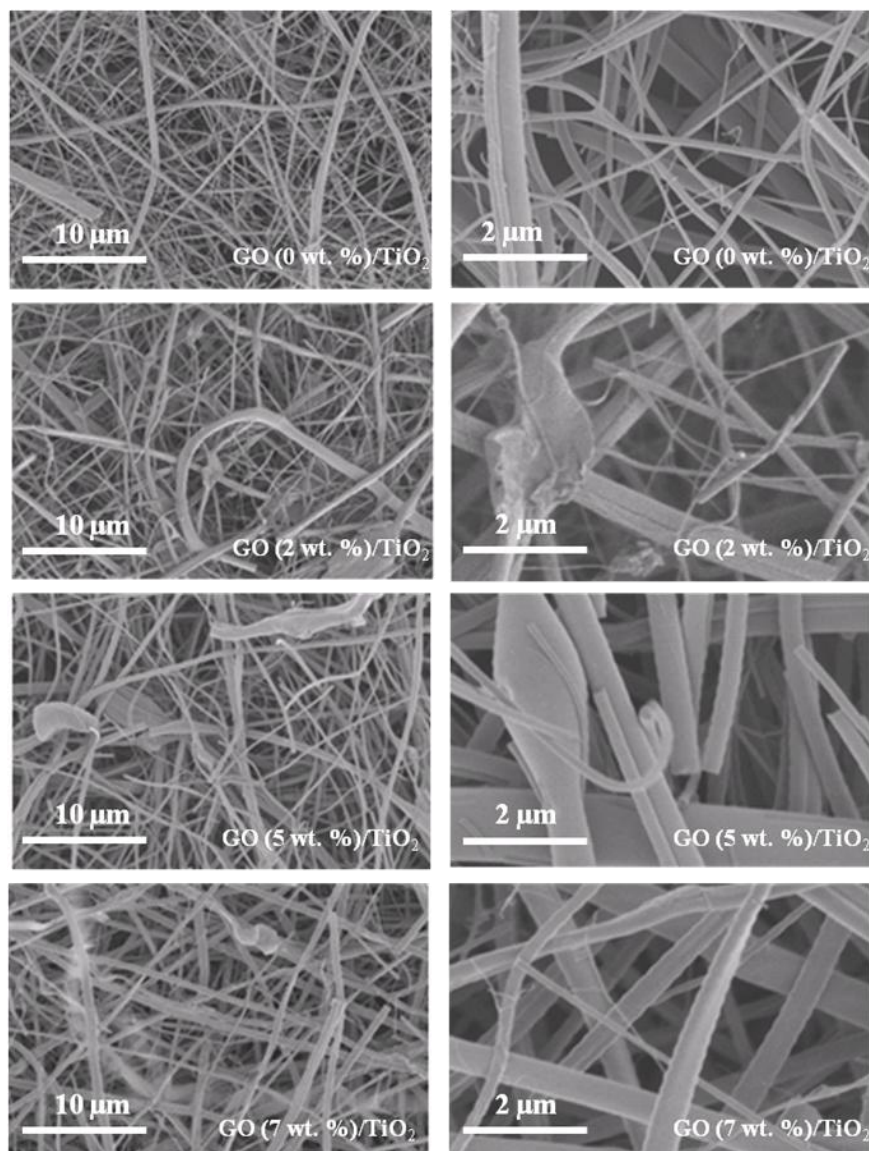


Figure 11. Scanning Electron Microscope images of TiO₂ and rGO/TiO₂ annealed composite nanofibers under N₂ atmosphere for 6h at 500°C.

The TiO₂ and TiO₂/GO NFs with different amounts of graphene oxide were fabricated by electrospinning of a polymeric solution with titanium tetraisopropoxide as precursor. The morphological and microstructural details of TiO₂ and TiO₂/GO nanofibers were examined by SEM. Figure 1.1 displays the SEM images of the obtained TiO₂ and GO-containing electrospun NFs after calcination at 500°C for 6h under N₂ atmosphere. The formation of highly interconnected networks of continuous, randomly oriented nanofibers can be clearly seen. It can also be observed that the incorporation of GO did not affect the nanofibrous

morphology of TiO₂. The diameters have been obtained using the ImageJ, Java-based image processing software. The average diameter was measured on 100 randomly chosen nanofibers of each sample (Figure 1). After calcination, we measured an average diameter of (141 ± 5 nm), (263 ± 7nm), (293 ± 10 nm) and (355 ± 13 nm) for samples with GO weight amount of 0, 2, 5 and 7 wt. % respectively. The average diameter of the nanofibers increases with the increase of the amount of graphene oxide. It can be attributed to the increase of the solution viscosity induced by inclusion of the GO in the electrospinning solution[8]. This increase reveals the successful incorporation of the graphene oxide in the TiO₂ nanofibers. An energy dispersive X-ray spectrum (EDX) of GO/TiO₂ NFs recorded along with elemental mapping is presented in Table 2.1. The EDX analysis revealed the molar ratio of Ti and O to be 1:2 for the above fibers, which is in good agreement with the stoichiometric ratio of TiO₂. Comparing the GO doped fibers to the pure one, we can notice the increase of the carbon content in GO (2 wt. %) /TiO₂, GO (5wt. %) /TiO₂ and GO (7wt. %) /TiO₂.

Table 2.1. EDX data showing the composition of TiO₂, GO (2 wt. %) /TiO₂, GO (5wt. %) /TiO₂ and GO (7wt. %) /TiO₂ annealed nanofibers under N₂ atmosphere.

Samples	Atomic percentages		
	Ti	O	C
TiO ₂	30.49	60.76	8.75
GO (2 wt. %)	30.89	58.31	10.8
GO (5 wt. %)	29.29	53.26	17.45
GO (7 wt. %)	24.98	52.07	22.95

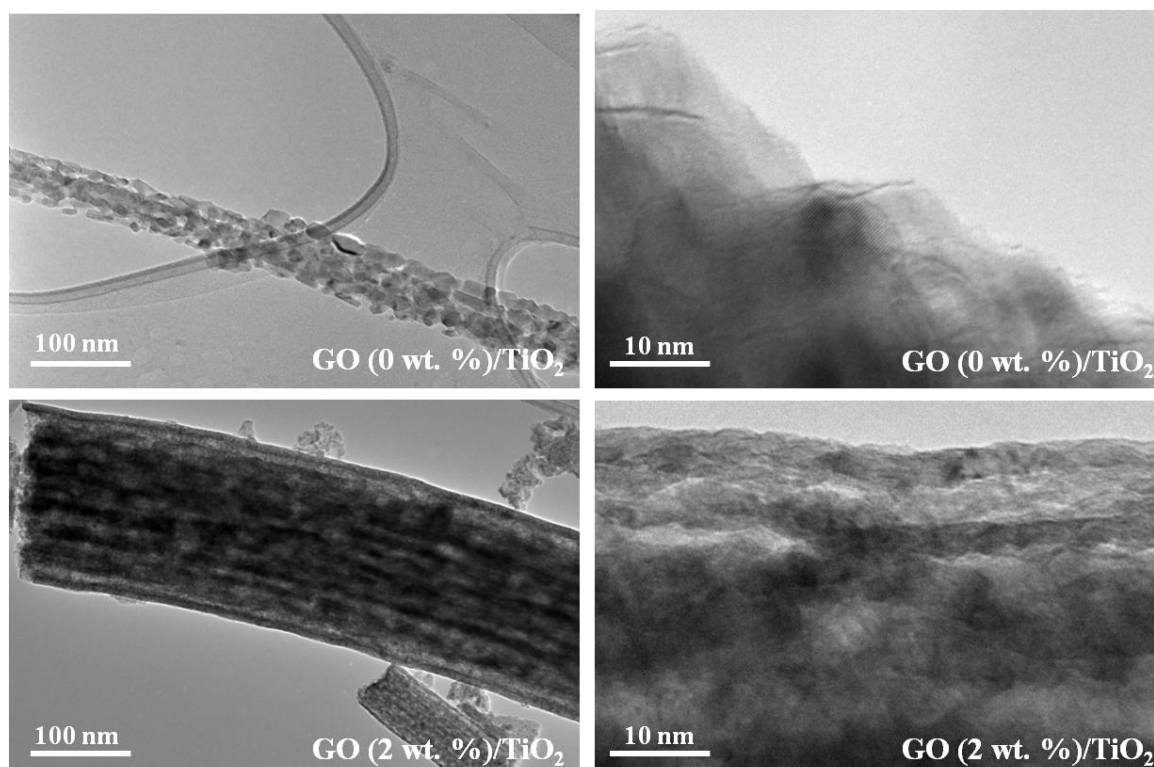


Figure 12. Transmission electron microscopy images of TiO₂ GO (2 wt. %) /TiO₂ annealed nanofibers under N₂ atmosphere for 6h at 500°C.

Figure 2.2 illustrates the TEM images of TiO₂ NFs and GO (2 wt. %) /TiO₂ composite NFs. Figure 2.2.a shows the granular aspect of the pure TiO₂, with an approximate grain diameter of 10 nm. When TiO₂ is mixed with graphene oxide, the close up morphology of the fibers appears to be more linear with the absence of apparent grains and the presence of small voids. This could be due to the dispersion of TiO₂ within the GO monosheets even though the flakes of GO do not appear in the image. We may suppose that the TiO₂ is intercalated between the layers of GO with a certain spacing that may provide a better alignment inside the fiber as shown in Figure 2.2.b. In addition, GO does not have any define structures because oxidation destroys the initial (002) peak of pristine graphite. Therefore the amorphous structure of GO (carbon based) could not be detected by selected area diffraction.

4.2. Structural properties of TiO₂ /rGO nanofibers

The crystalline phase of TiO₂, GO (2 wt. %) /TiO₂, GO (5wt. %) /TiO₂, and GO (7wt. %) /TiO₂ was analyzed by X-ray diffraction (XRD). The patterns in Figure 2.3 show the diffraction

peaks of anatase phase of TiO₂ (101), (200), (105), (211), (204) which correspond to $2\theta = 25.5^\circ, 48.2^\circ, 54.1^\circ, 55.3^\circ$ and 64.2° and three diffraction peaks of rutile phase of TiO₂ (110), (101), (111) which correspond to $2\theta = 27.7^\circ, 35.8^\circ$ and 41.6° [7][9]. The crystallite average sizes of TiO₂ and GO/TiO₂ with different amounts of GO were estimated using the Scherrer equation [10]. The calculated results show that the crystallite average sizes of GO/TiO₂ fibers increased as compared to pure TiO₂ fibers. The crystallite sizes were found to be 9.4, 18.4, 15.5 and 10.1 nm for the samples TiO₂, GO (2 wt. %) /TiO₂, GO (5wt. %) /TiO₂, and GO (7wt. %) /TiO₂ respectively. However, when the amount of GO exceeds 5 wt. % the crystallite size decreases which might be attributed to the agglomeration of GO sheets [11]. Evidence for stacks of graphene oxide sheets comes from the broad XRD peak of rGO (002) at around $2\theta = 25^\circ$ which corresponds to the d-spacing interlayer distance between the sheets [12]. It is worth noting that the diffraction peak of (rGO) cannot be distinguished in the composite, probably due to the presence of the diffraction peak of TiO₂ at the same position.

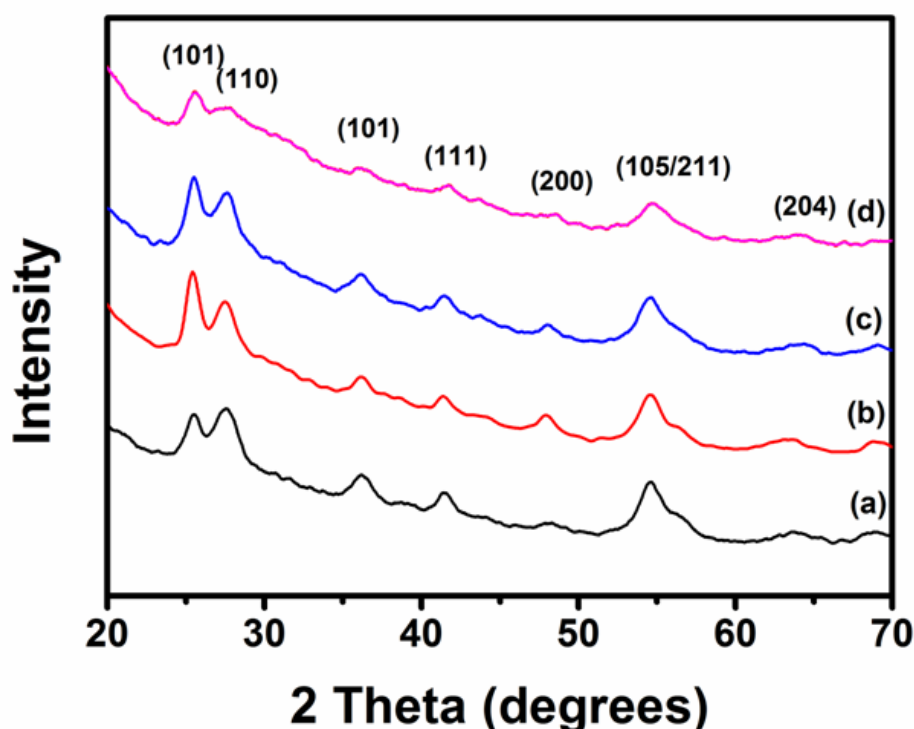


Figure 13. XRD patterns of photocatalysts: (a) TiO₂, (b) GO (2 wt. %) /TiO₂, (c) GO (5wt. %) /TiO₂, and (d) GO (7wt. %) /TiO₂ annealed nanofibers under N₂ atmosphere for 6h at 500°C.

In order to confirm the formation of the TiO₂ and rGO/TiO₂ nanofibers, the Raman spectrum was recorded in the range of 100-2000 cm⁻¹. Figure 2.4.A shows the Raman spectrum of TiO₂, GO (2 wt. %) /TiO₂, GO (5wt. %) /TiO₂, and GO (7wt. %) /TiO₂. For all samples we observe one peak corresponding to the active mode of anatase phase at 144 cm⁻¹ (E_g) and three peaks corresponding to the active modes of rutile phase at 244 cm⁻¹ (B_{1g}), 447 cm⁻¹ (E_g) and 612 cm⁻¹ (A_{1g}) [13]. More importantly, the Raman spectra of the composite GO/TiO₂ with different amounts of GO showed the broadened characteristic frequencies at 1365 cm⁻¹ and 1612 cm⁻¹, which correspond to the D and G band, respectively [14]. These two bands confirm that the GO was successfully introduced into the nanofibers during electrospinning. The detected carbon comes essentially from the addition of GO and not from the initial polymer, as particularly verified by the Raman spectroscopy. In fact, the carbon in graphene oxide sheets is distributed over a honeycomb structure which exhibits a sp²-hybridized carbon system resulting into the D and G vibration modes. The G band (1612 cm⁻¹) is due to the stretching of the C-C bond whilst the D band (1360cm⁻¹) is an in-plane vibrational mode, as clearly shown in the GO (2 wt. %) /TiO₂ sample. When the percentage of GO is increased (5 wt % and 7 wt %), the interaction between the stacked layers will change the spectrum namely by widening the D band and creating a small red shift as shown in Figure 2.4.B. These particularities are obviously not present in the pure TiO₂ sample [15]. The ratio between the intensity of D and G bands has been used as a parameter to evaluate the reduction of GO. Changes in the relative intensities of the D and G bands (D/G) indicate the modifications of the electronic conjugation state of the GO during reduction after N₂ calcination [16]. The D/G ratio can be influenced by edges, charge puddles, ripples and many other defects [17]. After calculation of the D/G ration for different GO amounts, it was found to be 1.1, 1.24, and 1.36 for GO (2 wt. %) /TiO₂, GO (5wt. %) /TiO₂, and GO (7wt. %) /TiO₂, respectively. Since the Raman D/G intensity ratio is inversely proportional to the average size of the sp² domains, the increase of the D/G intensity ratio suggests that smaller in-plane sp² domains are formed during the reduction of GO after N₂ annealing [18], which means that the GO (2 wt. %) /TiO₂ was more reduced than GO (5wt. %) /TiO₂, and GO (7wt. %) /TiO₂. This might be related to the time of the heat treatment. A larger amount of GO required a longer time of calcination for the removal of the oxygen-containing functional groups [19].

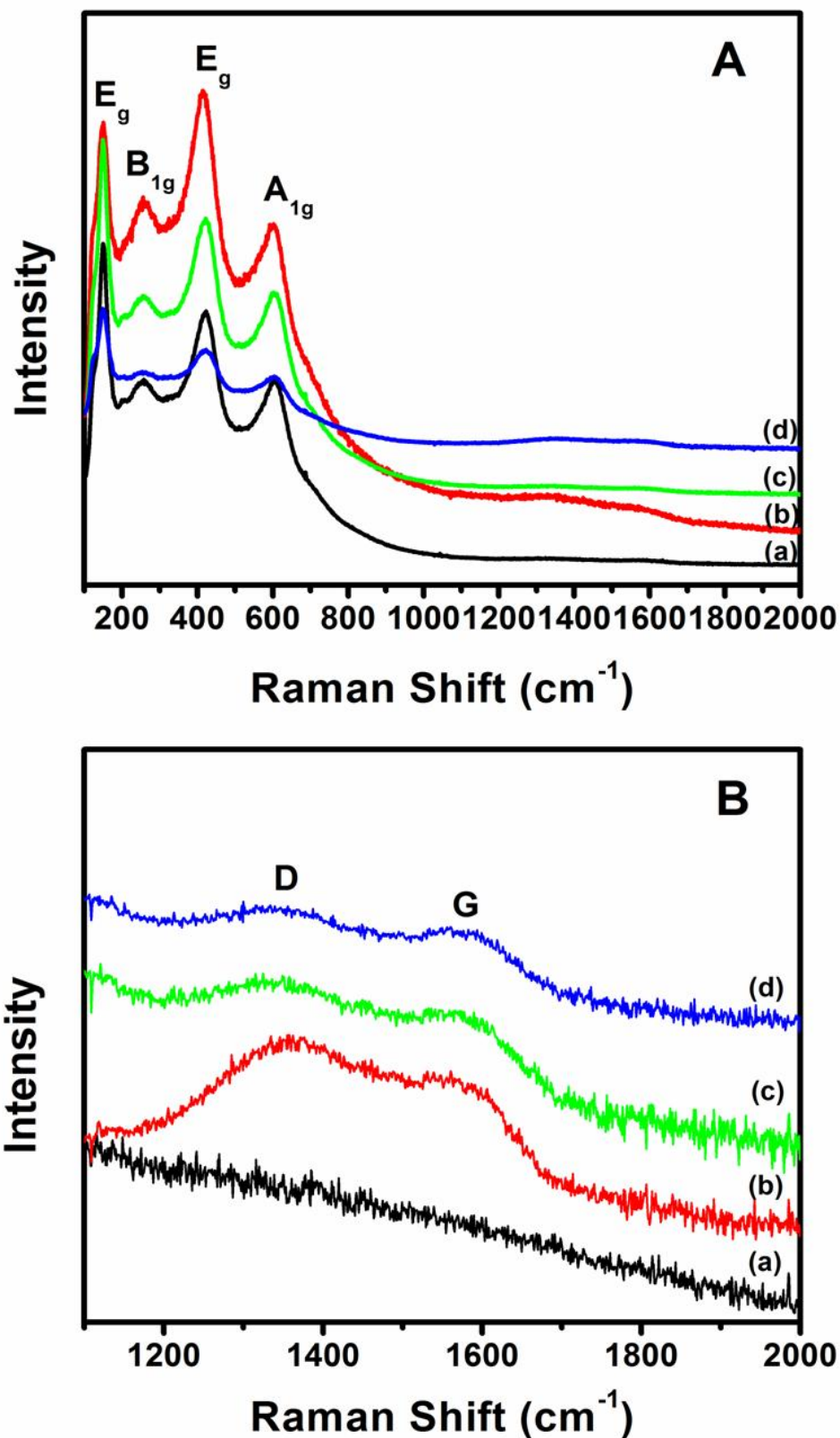


Figure 14. (A-B) Raman Shift of (a) TiO₂, (b) GO (2 wt. %) /TiO₂, (c) GO (5wt. %) /TiO₂, (d) GO (7wt. %) /TiO₂ annealed nanofibers under N₂ atmosphere for 6h at 500°C.

4.3. Optical properties of TiO₂ /rGO nanofibers

The various functional groups present in the TiO₂, GO and rGO/TiO₂ nanofibers were confirmed by using Fourier transform infrared (FTIR) spectroscopy as shown in Figure 2.5. Based on previous studies, the FTIR spectrum of GO illustrates the presence of C=O (1728 cm⁻¹) from stretching vibrations from carbonyl and carboxylic groups, C-OH (1222 cm⁻¹) from stretching vibrations, C-O (1035 cm⁻¹), and C-O (968 cm⁻¹) from carbonyl, carboxylic and epoxy groups, which confirms the presence of oxygen-containing functional groups. The peak at 1600 cm⁻¹ arises due to the C-C vibrations from the graphitic domains. The broad peak at 3423 cm⁻¹ is due to the adsorbed water content in the surface of GO [20]. These functional groups present in the GO renders it hydrophilic while the graphite and graphene are hydrophobic [11]. In the case of the annealed TiO₂ and TiO₂/GO (Figure 2.5.a-d), the characteristic absorption band of TiO₂ at 800–1200 cm⁻¹ is attributed to Ti–O bond. The bands related to the carbon-containing functional groups C=C (indexed in the Figure 2.5) are observed, and increase with the GO amounts. The peak at 1730 cm⁻¹ almost disappears because of the removal of C=O. This proves that many oxygen groups were removed and confirms the transformation from GO/TiO₂ to rGO/TiO₂ during the N₂ calcination [15].

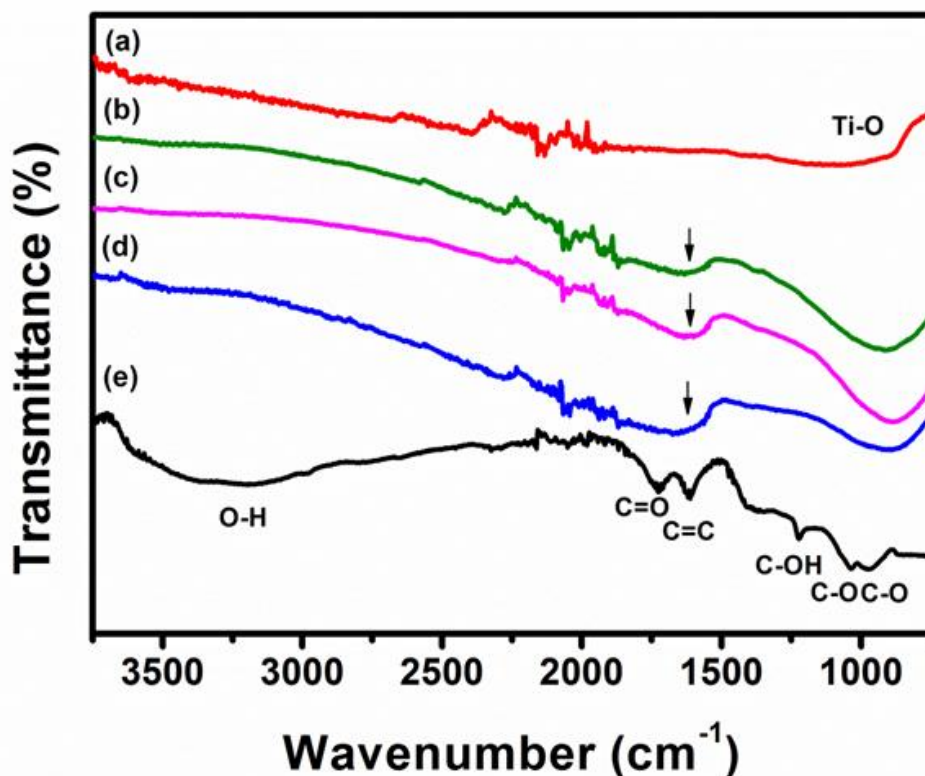


Figure 15. FTIR spectra of (a) TiO₂, (b) GO (2 wt. %) /TiO₂, (c) GO (5wt. %) /TiO₂, (d) GO (7wt. %) /TiO₂ GO annealed nanofibers under N₂ atmosphere and (e) GO.

The UV–Vis absorption spectroscopy measurement of pure TiO₂ NFs and rGO/TiO₂ composite nanofibers was carried out to investigate the optical properties of the samples and the results are shown in Figure 2.6. The UV–Vis absorption spectra of the GO (2 wt. %) /TiO₂, GO (5wt. %) /TiO₂ and GO (7wt. %) /TiO₂ nanocomposite indicates that it absorbs light at 420, 406 and 391 nm (indexed in the Figure 2.6) corresponding to a band gap of 2.95, 3.1 and 3.17 eV, respectively. Compared to the TiO₂ nanofibers (absorption edge: 386 nm, band gap energy: 3.2 eV), the absorption edges of rGO/TiO₂ composite nanofibers are red-shifted [21]. Actually, the GO (2 wt. %) has the lowest band gap since it is the most reduced sample as already confirmed by Raman analyses, and is expected to exhibit enhanced photocatalytic activity compared to other samples. The photoactivity is measured and evaluated in the next section. Thus, we can say that the incorporation of GO sheets into TiO₂ NFs creates energetic levels which decrease the band gap energy of TiO₂ and increase the visible light catalytic activity of TiO₂ nanofibers.

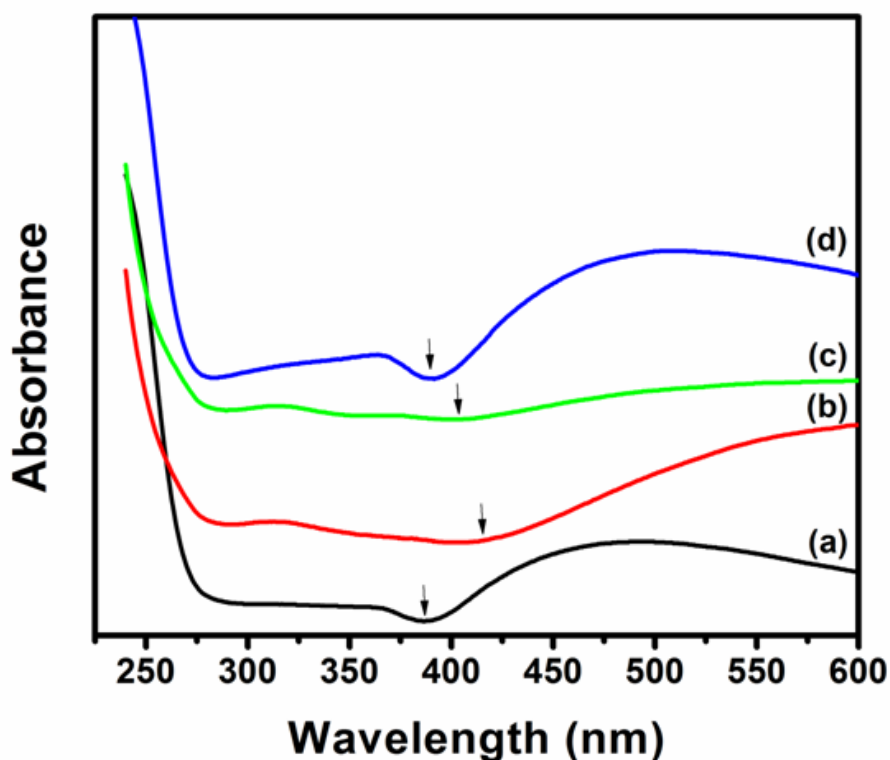


Figure 16. UV-Vis absorption spectra of (a) TiO₂, (b) GO (2 wt. %) /TiO₂, (c) GO (5wt. %) /TiO₂, (e) GO (7wt. %) /TiO₂ nanofibers.

4.4. Photocatalytic degradation of methyl orange by rGO/TiO₂ composite nanofibers

The photocatalytic activities of TiO₂/rGO NFs with different GO amounts were evaluated by degradation of methyl orange (MO) under visible light (wavelength > 400 nm). MO was selected as a model organic pollutant. Figure 2.7.a-f shows the UV-Vis absorbance spectra of MO solution (major absorption band around 462 nm) with different time intervals 0, 30, 60, 90 and 120 min after 60 min storage in dark for excluding the interference of adsorption. For comparison, the photocatalytic activities of TiO₂ NFs and commercial TiO₂-P25 were also tested under identical experimental conditions. The results indicate that MO is stable and difficult to be photodegraded in the absence of photocatalyst. After irradiation for 120 min, MO was degraded up to 40% in the presence of TiO₂ nanofibers, compared to 35% degradation by commercial granular TiO₂-P25 (Figure 2.8). Therefore, in the case of pure TiO₂, it is well known that TiO₂ NFs have a larger active surface area compared to the commercial TiO₂-P25 nanoparticles [22]. Most significant, the GO (2 wt. %) /TiO₂ and GO (5

wt. %) /TiO₂ NFs show remarkably enhanced photocatalytic activities, the MO degradation being 90% and 63% respectively. The GO (2 wt. %) /TiO₂ NFs exhibits the higher photocatalytic activity. With higher GO amount 7 wt. %, the activity of TiO₂/rGO NFs is gradually decreased; the MO degradation was just 26%. For the composites GO (2 wt. %) /TiO₂ and GO (5 wt. %) /TiO₂, the absorption edges are red shifted and the band gap energy decreases with the rGO incorporation. In addition, the photo electrons were quickly transferred to the rGO layers, which reduce the probability of the electron–hole recombination in TiO₂. Thus, more photo electrons were available compared to pure TiO₂ NFs, to take part in the photodegradation process. However, the use of an excessive amount of GO in the GO (7 wt. %) /TiO₂ composite reduced the light absorption on the TiO₂ surface. This leads to a decrease of photoexcited electrons [23]. This excess of GO (7wt. %) also increased the opportunity for the recombination of the photo-generated electron–hole pairs, by increasing the collision among the photogenerated electrons and holes [24].

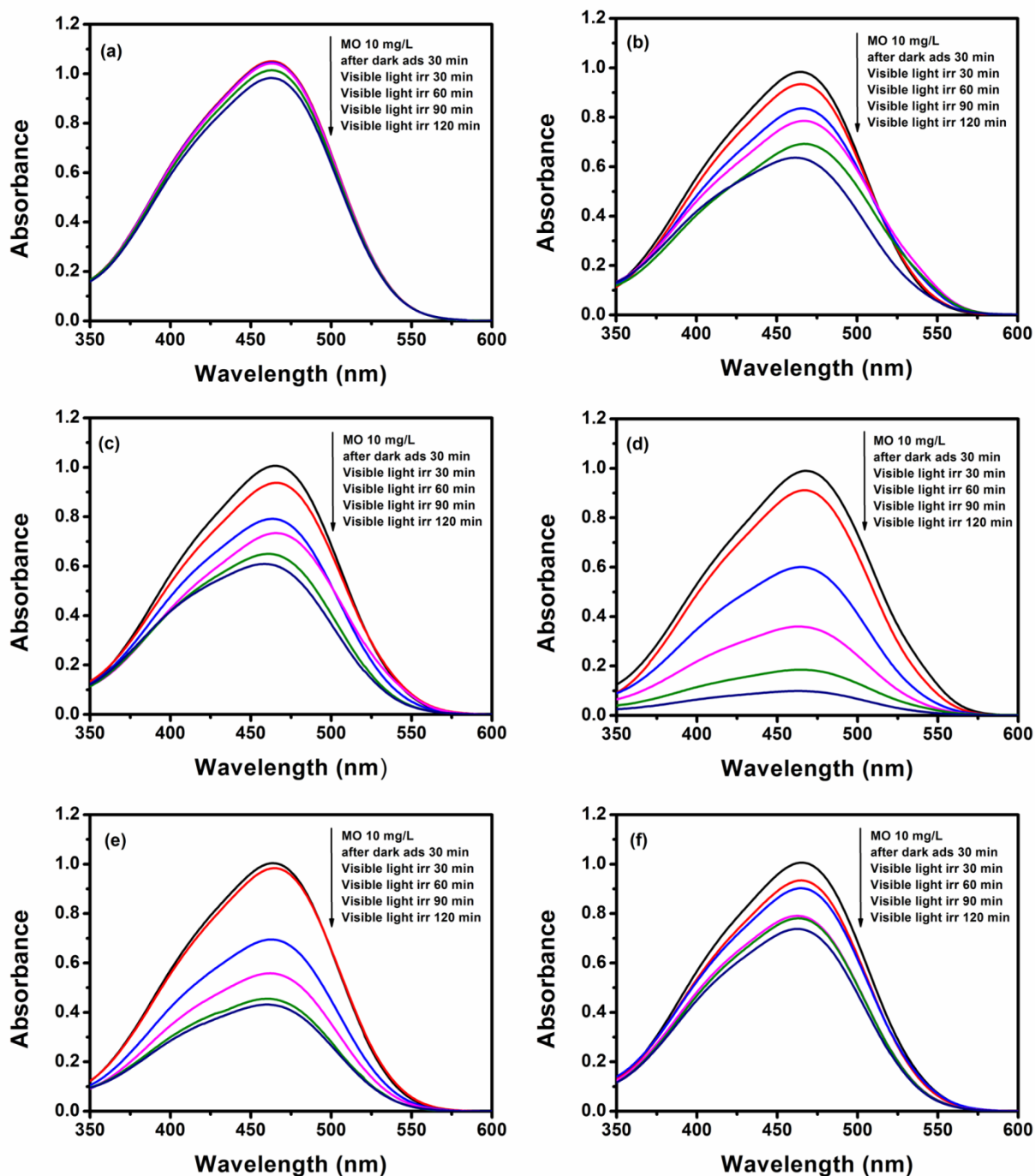


Figure 17. UV-Vis spectra of the photocatalytic degradation of MO under visible light: (a) MO without catalyst, (b) TiO₂-P25, (c) TiO₂ NFs, (d) GO (2 wt. %) /TiO₂, (e) GO (5wt. %) /TiO₂ and (f) GO (7wt. %) /TiO₂.

It was well known that the photocatalytic activity is mainly governed by crystalline phase, light absorption capacity and separation efficiency of electron-hole pairs [25]. From the XRD analysis, the crystallite average sizes of TiO₂ increased after introducing GO sheets for GO (2

wt. %) /TiO₂ NFs. Therefore, the relevant explanation for the high photocatalytic activity of GO (2 wt. %) /TiO₂ NFs should be ascribed to the differences in the GO reduction. As confirmed by Raman analyses and UV-Vis absorption presented above, more GO in GO (2 wt. %) /TiO₂ NFs was reduced than that in GO (5 wt. %) /TiO₂ and GO (7 wt. %) /TiO₂ NFs which means the lowest band-gap energy (2.9 eV). These results indicate that GO (2 wt. %) /TiO₂ composite NFs has excellent absorption capacity of visible light and lower recombination rate of electron–hole pair.

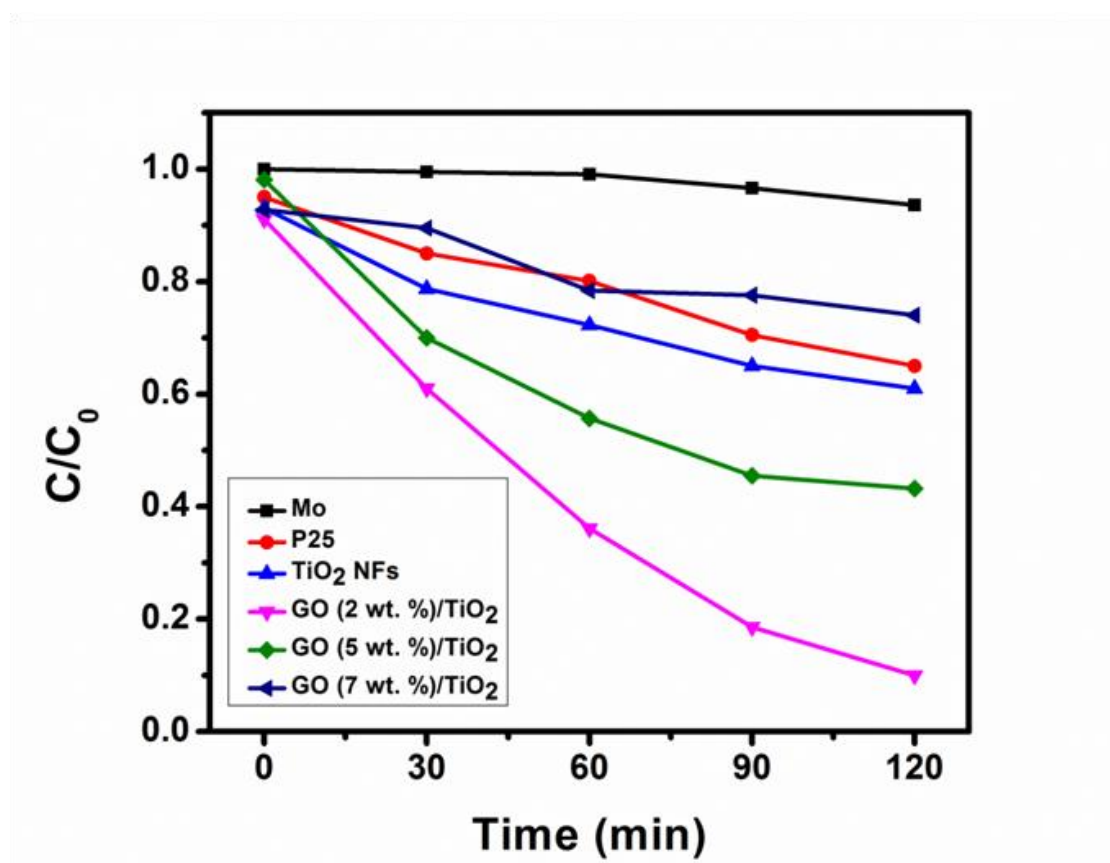


Figure 18. Photodegradation of MO by TiO₂-P25, TiO₂ NFs and rGO/TiO₂ composite nanofibers.

Figure 2.9 shows the different kinetic linear curves. The photodegradation reactions follow a Langmuir–Hinshelwood first-order kinetics model[26]. The explanation is described as follows:

$$r = \frac{dC}{dt} = \frac{kKC}{(1+KC)} \quad (\text{Equation 2})$$

where r is the degradation rate of MO (mg (L min)^{-1}), C is the concentration of a MO solution (mg L^{-1}), t is the irradiation time, k is the reaction rate constant (mg (L min)^{-1}), and K is the adsorption coefficient of MO (mg L^{-1}). Since the initial concentrations ($C_0 = 10 \text{ mg L}^{-1}$) of the MO solutions are very low in the present experiments, this equation can be simplified to an apparent first-order model [26]:

$$\ln (C_0/C) = kKt = k_a t \quad (\text{Equation 3})$$

where k_a is the apparent first-order rate constant (min^{-1}) and C is the concentration at time t . k_a obtained from the linear dependence between $\ln (C_0/C)$ and time (Figure 2.9) are reported in Table 2. The increasing order of the rate constants in the samples is: GO (2 wt. %) /TiO₂ < GO (5wt. %) /TiO₂ < TiO₂ NFs < TiO₂-P25 < GO (7wt. %) /TiO₂ < MO. The rate constant exhibits a maximum of 0.0186 min^{-1} for GO (2 wt. %) /TiO₂ nanocomposites, which is around 6 times higher than that of commercial TiO₂-P25 and TiO₂ NFS. Thus, for the more reduced sample GO (2 wt. %) /TiO₂ NFs as confirmed above, visible-light photocatalytic activity is significantly improved.

In the present work, the fact of using the simple electrospinning technique to synthesize composite nanofibers of rGO/TiO₂ for photocatalytic application is novel. The degradation efficiency (90%) obtained by using the rGO/TiO₂ composite nanofibers in our case is greater in comparison to what has been reported before [14],[21]. The enhancement is induced by the special morphology of the nanofibers that presents improved active surface area in comparison to rGO/TiO₂ nanoparticles [22].

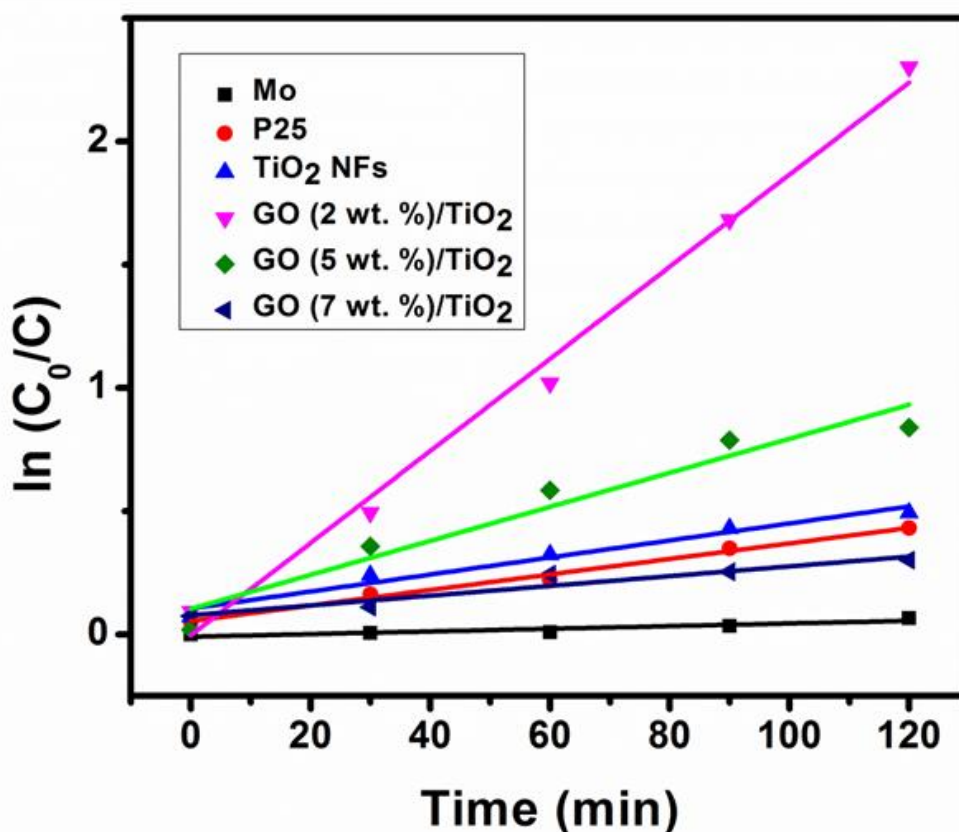


Figure 19. Kinetics of Methyl orange degradation by TiO₂-P25, TiO₂ NFs and rGO/TiO₂ composite nanofibers.

Table 2.2. Kinetic parameters for photocatalytic activities of TiO₂-P25, TiO₂ NFs and rGO/TiO₂ composite nanofibers.

	MO	TiO ₂ -P25	TiO ₂ NFs	GO (2 wt. %) /TiO ₂	GO (5wt. %) /TiO ₂	GO (7wt. %) /TiO ₂
k_a (min ⁻¹)	0.0005	0.0031	0.0034	0.0186	0.0069	0.0019
R^2	0.8146	0.9882	0.9628	0.9885	0.9230	0.8929

5. Conclusion

In summary, rGO/TiO₂ composite nanofibers with different GO amounts were successfully prepared by electrospinning. All the samples were annealed at 500°C in N₂ atmosphere for 6 hours. The SEM images showed an increase in the average diameter with the increase of rGO amount and confirmed that the one dimensional morphology was maintained. The correlation between the domain size of the TiO₂ crystalline structure and the GO incorporation effect was clearly observed in the TEM and XRD results. Raman and

FTIR confirmed the reduction of GO after calcinations in N₂ atmosphere. The decreasing of TiO₂ NFs band gap energy from 3.2 eV to 2.9 eV due to the presence of rGO sheets was confirmed by UV-Vis analysis. The incorporation of rGO significantly increases the visible light photo-response and improves the separation of the photo-induced electron–hole pairs of TiO₂. Remarkably, the optimal percentage of introducing and reducing GO is 2 wt. % / TiO₂. Under this condition, the photocatalytic degradation of methyl orange under visible light is 6 times higher than that of commercial TiO₂-P25. In addition after 120 min 90 % of MO is degraded against 35% degradation by commercial TiO₂. Thus, incorporating rGO into TiO₂ NFs is an efficient and simple way for enhancing the visible-light photocatalytic activity. As a result, we have successfully prepared rGO/TiO₂ composite nanofibers that could be used as catalysts in the degradation of different organic molecules under visible light, as well as electrolyte membrane for fuel cell application and many other membrane applications [27].

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Chapter 3: Enhanced Photocatalytic Performance of Novel Electrospun BN/TiO₂ Composite Nanofibers

Table of Contents

1. Introduction.....	89
2. Abstract.....	89
3. Experimental Section.....	89
3.1. Chemicals and Materials.....	89
3.2. Exfoliation of Boron nitride.....	90
3.3. Preparation of TiO ₂ and BN/TiO ₂ composite nanofibers.....	90
3.4. Physical and Chemical Characterization.....	91
3.5. Photocatalytic activity measurement.....	91
4. Results and discussion.....	92
4.1. Morphological properties.....	92
4.2. Structural properties.....	93
4.3. Optical properties.....	98
5. Photocatalytic activity.....	106
6. Conclusion.....	109

1. Introduction

This chapter focused on using Boron nitride (BN) nanosheets to improve the photocatalytic activity of TiO₂ under UV light. High power sonication was used to obtain the exfoliated boron nitride. This chapter is divided into 3 parts: (1) Elaboration of different BN-TiO₂ composite nanofibers with different amounts of BN nanosheets using electrospinning technique, (2) Studying the impact of BN incorporation on the morphological, structural and optical properties of TiO₂, (3) Evaluating the photocatalytic activity of BN-TiO₂ composites by the photodegradation process of methyl orange. The experiments of the photodegradation were done under UV light and under the same experimental conditions for all samples.

2. Abstract

High activity Boron nitride/Titanium dioxide (BN/TiO₂) composite nanofibers photocatalysts were successfully synthesized for the first time via the electrospinning technique. The as-spun nanofibers with controlled ratio of boron nitride nanosheets (BN) were calcined under air at 500°C for 4 hours. Their morphological, structural and optical properties were studied by Scanning electron microscopy (SEM), X-ray diffraction (XRD), Energy-dispersive X-ray spectroscopy (EDX), BET surface area, Fourier-transform infrared (FTIR), Raman spectroscopy, UV-Visible spectrophotometer and Room temperature photoluminescence (PL). The effect of loading different BN sheets amounts on the photocatalytic degradation of methyl orange (MO) was investigated. The results indicated that the presence of BN sheets improves the separation of the photo-induced electron-hole pairs in TiO₂ and increases the band gap energy and the specific surface area compared to the pure TiO₂ nanofibers. BN/TiO₂ (wt. 10%) composite nanofibers photocatalytic activity is enhanced to 99% compared to 60% and 65% for P25 and TiO₂ nanofibers, respectively. Thus, the composites BN/TiO₂ significantly increases the UV light photo-response and improves the separation of photo-induced electron-hole pairs of TiO₂.

3. Experimental Section

3.1. Chemicals and Materials

Commercial boron nitride (95%, 325 mesh), titanium tetraisopropoxide (TTIP) Ti{OCH(CH₃)₂}₄ (97%), polyvinylpyrrolidone (PVP) (Mw = 13,00,000), acetic acid (98%),

Gelatine from porcine skin, methyl orange and absolute ethanol were purchased from Sigma Aldrich, and used without any further purification.

3.2. Exfoliation of Boron nitride

Boron nitride sheets were exfoliated from boron nitride powder [1], [2]. Briefly, 20g of gelatine were dissolved in 80 ml of hot water (75°C). After gelatine dissolving, 1g of boron nitride powder was added to the mixture. The solution was kept in an ultrasonic homogenizer over night at 50°C. Exfoliated BN was separated by centrifugation at 2697 G for 30 minutes and the supernatant was decanted away. The resultant precipitates were dried at 80°C for 48 hours and then calcined at 600°C in air for 2 hours in order to obtain the pure exfoliated boron nitride.

3.3. Preparation of TiO₂ and BN/TiO₂ composite nanofibers

The BN-incorporated TiO₂ nanofibers were synthesized by an electrospinning technique. The spun solution was prepared as follows: different amounts of boron nitride (0, 3, 5, 7 and 10 wt. % of the mass of Ti) and 2 ml of absolute ethanol were homogenized for 12h to disperse boron nitride into the ethanol solution. Titanium tetraisopropoxide was dissolved in a mixture of 2 ml of acetic acid and 3 ml of ethanol mixed with 0.3 g of polyvinylpyrrolidone (PVP). The precursor mixture was stirred for 1 h at room temperature to obtain sufficient viscosity required for electrospinning. Finally, the BN solution was added to the precursor solution under vigorous magnetic stirring (150 rpm) for 30 min. The homogeneous solution was typically extruded through a stainless steel nozzle with a diameter of 0.7 mm at a constant flow rate of 1 ml/h. The feeding rate was controlled by the syringe pump. The temperature level inside the electrospinning chamber was 38 ±5°C. Nanofibers were collected on a rotating coil covered with an aluminium foil with a rotation speed of 400 rpm. The distance between the tip of the needle and the aluminium foil was maintained at 20 cm, and a DC voltage of 25 kV was applied. In the electrospinning process, the high applied voltage was achieved by connecting the positive and ground terminals to the nozzle and collector, respectively. During electrospinning, the applied electric field overcomes the surface tension of the polymeric solution, thereby ejecting a continuous jet which upon subsequent solvent evaporation and bending produces nanofibers on the

collector surface. The electrospun BN-TiO₂ composite nanofibers were collected and then calcined in a tubular furnace at 500°C with a heating rate of 5°C/min for 5 h in air.

3.4. Physical and Chemical Characterization

X-ray diffraction (XRD) measurements were carried out using a PANalytical Xpert-PRO diffractometer equipped with an X'celerator detector using Ni-filtered Cu-radiation ($\lambda = 1.54 \text{ \AA}$). Fourier-transform infrared (FTIR) spectra were recorded on a Nicolet 370 FTIR spectrometer using an ATR system. Raman spectra have been obtained from Horiba, $\lambda = 659 \text{ nm}$. Scanning electron microscopy (SEM) images were taken with a Hitachi S4800, Japan. Energy-dispersive X-ray spectroscopy analysis (EDX) and elemental mapping were taken with Zeiss EVO HD15 microscope coupled with an Oxford X-MaxN EDX detector. The UV–VIS absorbance spectra were recorded by a Jasco V-570 UV–VIS-NIR spectrophotometer. The surface area of samples was determined from nitrogen adsorption-desorption isotherms at liquid nitrogen temperature using micromeritics ASAP 2010 equipment (outgassing conditions: 200°C-12h). Room temperature photoluminescence (PL) has been measured in the range of 370-800 nm. The PL was excited with nitrogen Nd:YAG laser (266 nm, 10 mW, 1 kHz) and recorded with optical fiber spectrometer (Ocean Optics usb2000).

3.5. Photocatalytic activity measurement

Methyl orange (MO) was used as a reference of organic pollutant to evaluate the photocatalytic activity of the BN/TiO₂ composite nanofibers. The photocatalytic performance of the samples was evaluated by analyzing the decrease in concentration of the MO during exposure to UV light irradiation. The reaction temperature was kept constant at $25 \pm 0.2 \text{ }^\circ\text{C}$ by circulating water in a cylindrical tube surrounding the photo-reactor during the entire experiment. The decomposition was carried out in several beakers containing a suspension of 10 mg of each sample in 25 ml of MO solution (10 mg/L) under visible light irradiation (obtained from a 48 W light source, emission wavelength $< 400 \text{ nm}$). The distance between the lamp and the dye solution was maintained at 10 cm. First, the solution mixture was magnetically stirred for 30 min without irradiation to reach the adsorption-desorption equilibrium of MO. Then, the solution was irradiated with visible light for 75 minutes. Each 15 min, 3 ml of the sample solution was taken out and centrifuged to remove

the catalyst. The centrifuged solutions were analyzed by a UV-VIS spectrometer. The absorbance spectra of MO (major absorption band around 462 nm)[3] were recorded to measure the change in the concentration of MO[4]. After irradiation, the photocatalytic degradation efficiency has been calculated as follows:

$$\text{Degradation efficiency (\%)} = (C_0 - C) / C_0 \times 100 \quad (\text{Equation 1})$$

where C_0 and C are the initial concentration and the final concentration of dye before and after photo-irradiation respectively[5]. This equation shows the dye photocatalyst degradation percentage.

4. Results and discussion

4.1. Morphological properties

The TiO₂ and BN/TiO₂ NFs with different amounts of boron nitride were obtained by electrospinning of a solution of polymer with titanium tetraisopropoxide as precursor. Scanning electron microscopy was used to investigate the morphological features of TiO₂ and BN/TiO₂ nanofibers. Figure 3.1 shows the SEM images of the obtained TiO₂ and BN-containing electrospun nanofibers after calcinations in air at 500°C for 4 hours. The formation of highly interconnected networks of continuous, randomly oriented nanofibers can be clearly seen. As illustrated in Figure 3.1, the nanofibrous morphology was largely preserved after the heat treatment process. The fiber diameters were measured from the SEM images using image analysis software (Image J1.29X). The average diameter was measured on 100 randomly chosen nanofibers of each sample (Figure 3.1). After calcination, we measure average diameters of (187 ± 5 nm), (229 ± 7nm), (269 ± 10 nm), (290 ± 13 nm) and (314 ± 15 nm) for samples with BN weight amount of 0, 3, 5, 7 and 10 wt. %, respectively. In fact, the average diameter of the nanofibers increases with the increase of boron nitride amount. This can be attributed to the increase of the solution viscosity induced by inclusion of BN in the electrospinning solution [6]. This increase reveals the successful incorporation of BN in TiO₂ nanofibers.

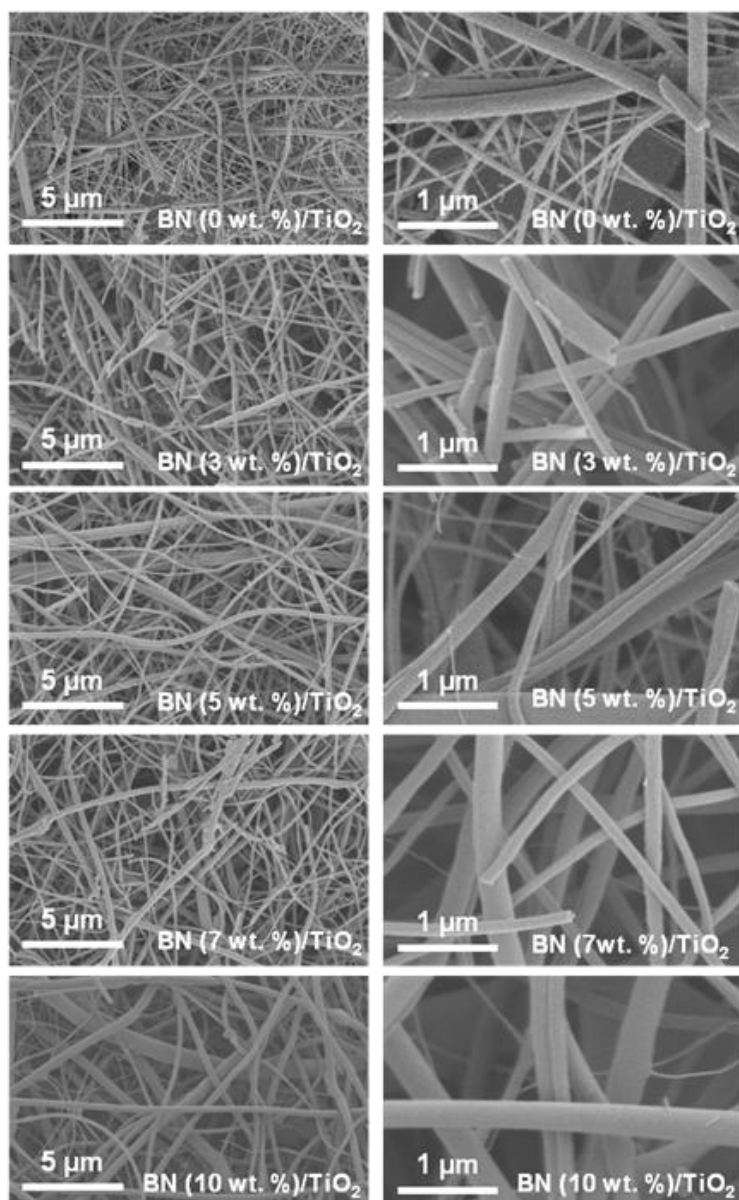


Figure 3.1. Scanning Electron Microscope images of TiO₂ and BN/TiO₂ annealed composite nanofibers in air for 4h at 500°C.

4.2. Structural properties

Table 3.1. EDX data showing the composition of TiO₂, BN (3 wt. %)/TiO₂, BN (5wt. %)/TiO₂, BN (7wt. %)/TiO₂ and BN (10 wt. %)/TiO₂ annealed nanofibers under air.

Samples	Atomic percentages				
	Ti	O	C	B	N
TiO ₂	33.42	61.28	5.3	–	–
BN (3 wt. %)	26.59	53.67	4.16	8.4	7.18
BN (5 wt. %)	24.81	52.45	6.31	9.23	7.2

BN (7 wt. %)	23.84	48.25	5.48	10.59	11.84
BN (10 wt. %)	25.05	46.19	5.13	12.14	11.49

An energy dispersive X-ray spectrum (EDX) of BN/TiO₂ nanofibers recorded along with elemental analysis is presented in Table 3.1. The EDX analysis reveals the molar ratio of Ti and O to be 1:2 for the above described fibers, which is in good agreement with the stoichiometric ratio of TiO₂. Also, the BN doped fibers have a molar ratio of 1:1 for boron and nitrogen. The increase of the atomic percentages of B and N in BN (3 wt. %)/TiO₂, BN (5wt. %)/TiO₂, BN (7wt. %)/TiO₂ and BN (7wt. %)/TiO₂ can be clearly seen from table 3.1. Figure 3.2 shows elemental mapping images on BN (5wt. %)/TiO₂ nanofibers. These images clearly shows that Ti, O, B and N elements evenly spread over the entire area of the sample confirming the good dispersion of BN nanosheets in the TiO₂ nanofibers. Based on these data, the BN/TiO₂ composite nanofibers were successfully fabricated using the electrospinning method.

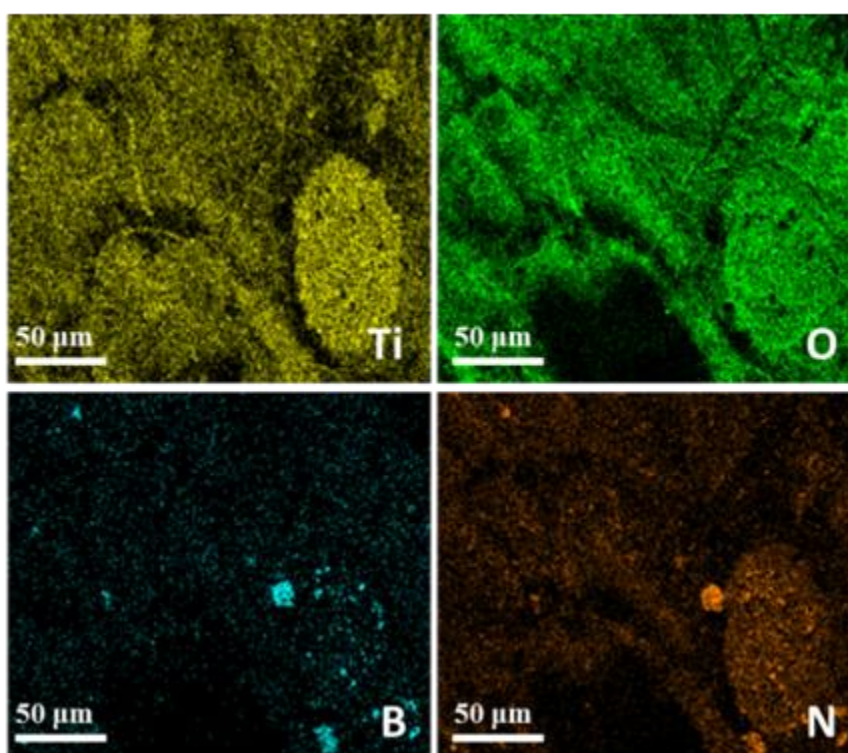


Figure 3.2. Element mapping images of the BN (5 wt. %)/TiO₂ composite nanofibers.

Table 3.2 presents the specific surface area (BET) of prepared BN/TiO₂ nanocomposites. The specific surface area varies between 19 and 50 m²g⁻¹. The increasing of the surface area with the increasing of BN sheets amount is clearly seen from Table 3.2. It is commonly accepted that TiO₂ with a large surface area will have superior photocatalyst activity, because a larger surface area offers more active adsorption sites [7].

Table 3.2. BET surface area of TiO₂ nanofibers and BN/TiO₂ composite nanofibers.

Samples	Surface area (m ² g ⁻¹)
TiO ₂ NFs	19.66
BN (3wt. %)/TiO ₂	31.75
BN (5wt. %)/TiO ₂	34.41
BN (7wt. %)/TiO ₂	48.31
BN (10 wt. %)/TiO ₂	49.64

X-ray diffraction (XRD) was employed for analyzing the crystalline phase of all the obtained nanofibers. The sharp peaks in the diffraction pattern of all samples (Figure 3.3.A) can be assigned to the (101), (004), (200), (105), (211) and (204) crystal plane of pure anatase phase of TiO₂ which correspond to $2\theta = 25.5^\circ, 38.2^\circ, 48.2^\circ, 54.1^\circ, 55.3^\circ$ and 62.9° , respectively[8]. It is worth noting that the diffraction peak at $2\theta = 26^\circ$ of hexagonal BN related to the (002) direction is probably overlapped by the diffraction peak of TiO₂ at the same position [9]. The crystallite average sizes of TiO₂ and BN/TiO₂ with different amounts of BN were estimated using the Scherrer equation [10]. The calculated results show that the grain fineness numbers of BN/TiO₂ fibers are increasing as compared to pure TiO₂ fibers. The crystallite sizes for all samples are shown in Table 3.3. As shown in Figure 3.3.B, the main TiO₂ peak was shifted from the initial position after BN doping in all samples. We may suppose that BN incorporation increases the lattice strain in the TiO₂ cell and it can shift atoms from the initial position and can reduce the formation of the self-trapped excitons

(STE) localized on the TiO₆ octahedral[11]. At the same time, it might cause vacancies formation. These results will be confirmed later by photoluminescence analysis.

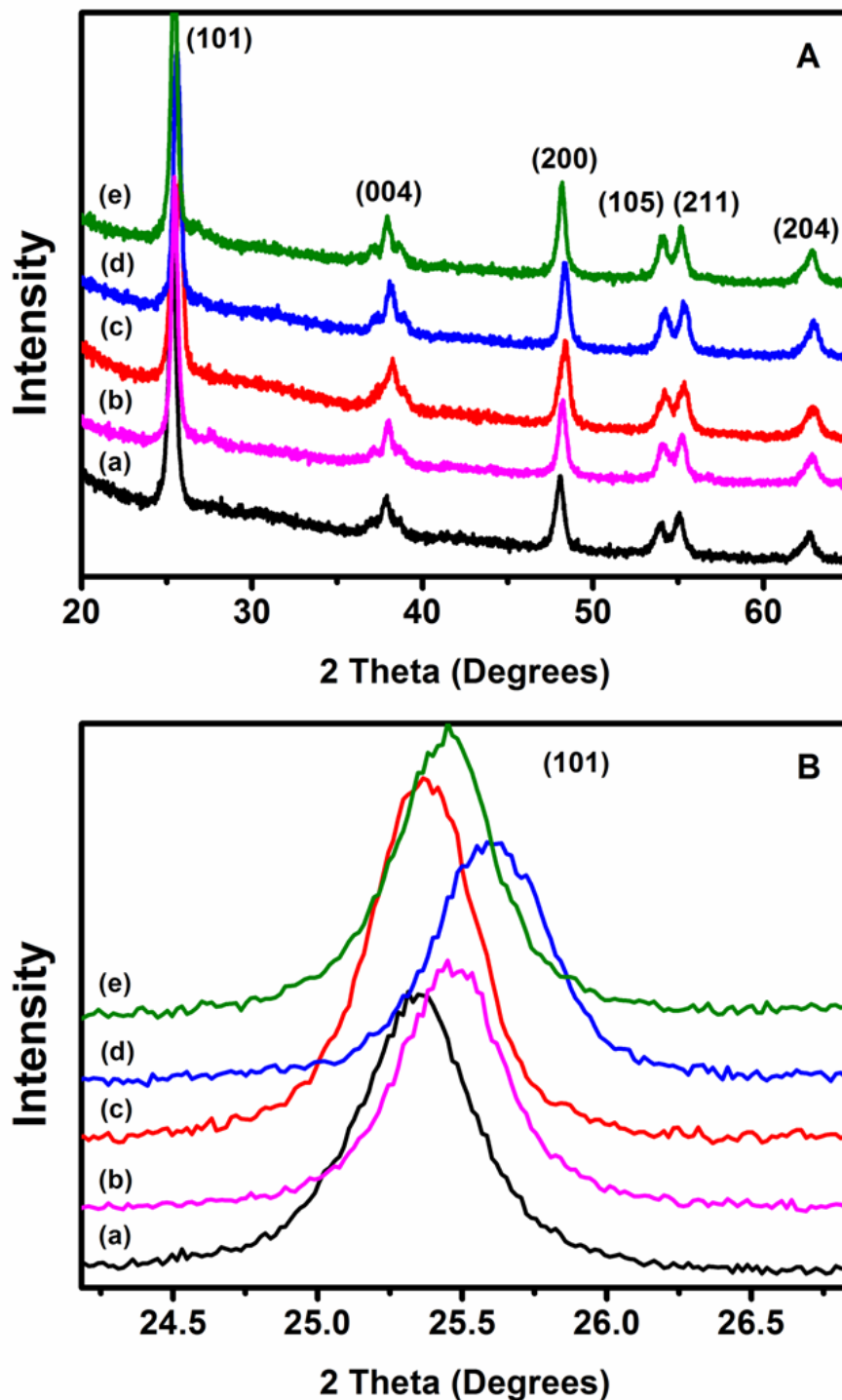


Figure 3.3. (A-B) XRD patterns of (a) TiO₂, (b) BN (3 wt. %) /TiO₂, (c) BN (5wt. %) /TiO₂, (d) BN (7wt. %) /TiO₂ and (e) BN (10wt. %) /TiO₂ annealed nanofibers in air for 4h at 500°C.

Table 3.3. Grain size of TiO₂ NFs and BN/TiO₂ composite nanofibers.

Samples	Grain size (nm)
TiO ₂ NFs	16.4
BN (3wt. %)/TiO ₂	24.3
BN (5wt. %)/TiO ₂	25.2
BN (7wt. %)/TiO ₂	26.3
BN (10wt. %)/TiO ₂	28.7

Raman spectroscopy is a powerful tool to detect the molecular vibrations in order to identify our materials. As shown in Figure 3.4, the Raman spectrum of TiO₂, BN (3 wt. %)/TiO₂, BN (5wt. %)/TiO₂, BN (7wt. %)/TiO₂ and BN (10wt. %)/TiO₂ was recorded in the range of 100-1500 cm⁻¹. For all samples, we identify the six Raman active modes corresponding to the anatase phase of TiO₂ at 144 cm⁻¹ (E_g), 197 cm⁻¹ (E_g), 399 cm⁻¹ (B_{1g}), 513 cm⁻¹ (A_{1g}), 519 cm⁻¹ (B_{1g}) and 639 cm⁻¹ (E_g) (Figure 3.4.A) [12]. Besides, the Raman spectra of BN/TiO₂ samples shows the broadened characteristic frequency located at ~ 1365 cm⁻¹ referring to the hexagonal BN related to E_{2g} mode (Figure 3.4.B) [13]. In addition, the increased intensity of the peak corresponding to h-BN with the amount of doping is visibly noticed. Thus, Raman spectroscopy confirmed the incorporation of the boron nitride in the TiO₂ nanofibers.

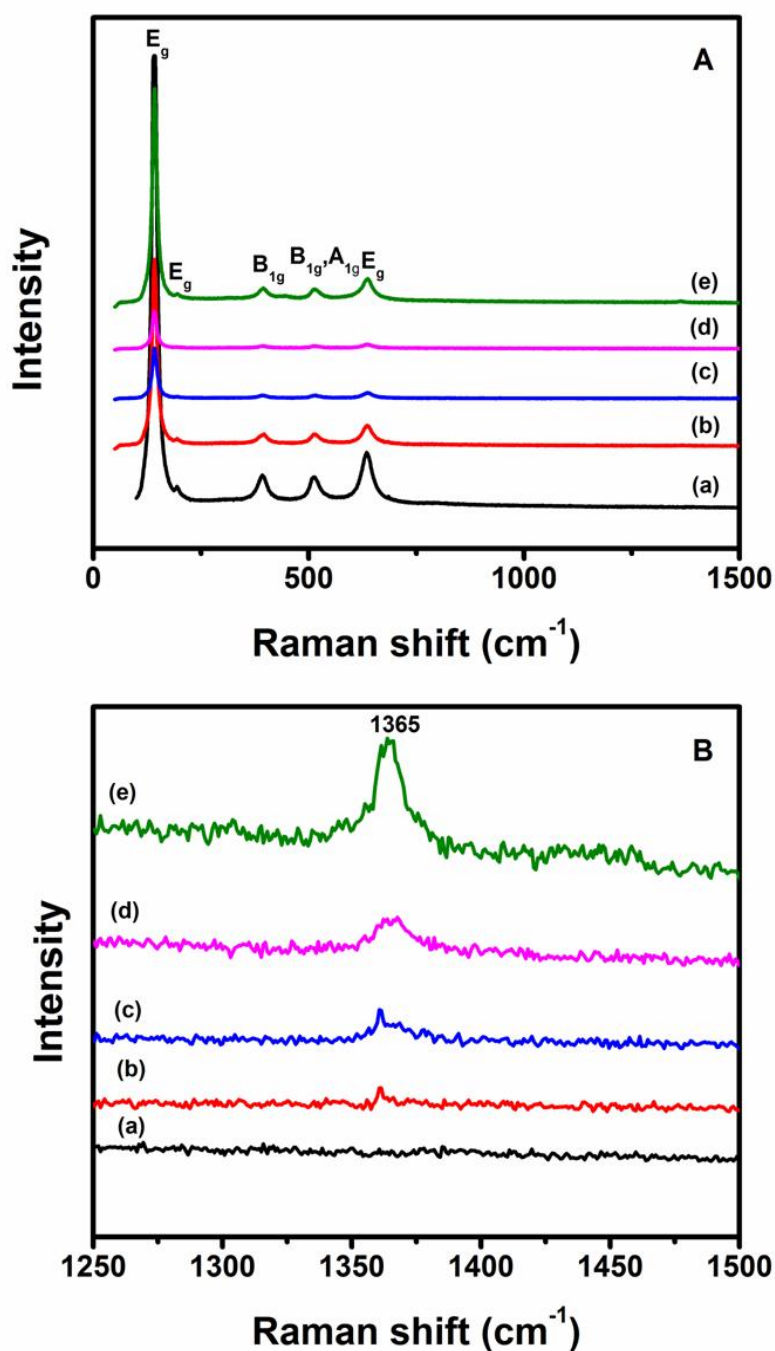


Figure 3.4. (A-B) Raman shift of (a) TiO₂, (b) BN (3 wt. %)/TiO₂, (c) BN (5wt. %)/TiO₂, (d) BN (7wt. %)/TiO₂ and (e) BN (10wt. %)/TiO₂ annealed nanofibers in air for 4h at 500°C.

4.3. Optical properties

The successful incorporation of boron nitride sheets in the TiO₂ nanofibers was revealed by the typical FTIR spectrum (Figure 3.5). For pure TiO₂ nanofibers (Figure

3.5.a), the characteristic absorption band at 650–950 cm⁻¹ is attributed to Ti–O bond [14]. While for the composite BN/TiO₂ nanofibers with different amounts of BN sheets (Figure 3.5.b-e), two main absorption peaks of hexagonal BN were observed around 800 and 1370 cm⁻¹, ascribed to the out-of-plane bending of sp²-bonded B-N-B and the in-plane stretching of sp²-bonded B-N, respectively[15]. In addition, it can be clearly seen, that the intensity of these 2 peaks related to the bands B-N-B and B-N increases by increasing the BN amounts.

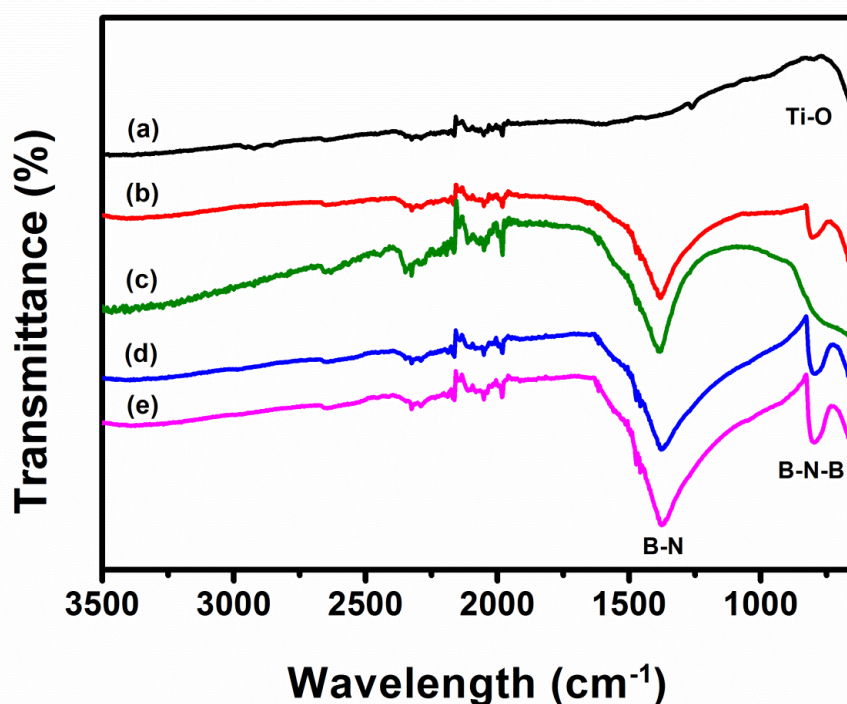


Figure 3.5. FTIR spectra of (a) TiO₂, (b) BN (3 wt. %)/TiO₂, (c) BN (5wt. %)/TiO₂, (d) BN (7wt. %)/TiO₂ and (e) BN (10wt. %)/TiO₂ annealed nanofibers in air for 4h at 500°C.

Figure 3.6 shows the UV–VIS absorption spectra of TiO₂ nanofibers and BN/TiO₂ composite nanofibers with different BN amounts. The energy of the band gap was calculated using the following equation:

$$E_g = hc/\lambda \quad (\text{Equation 2})$$

Where h is Planck's constant, c is the speed of light and λ is the cut off wavelength where the absorbance value is minimum. The UV–VIS absorption spectrum of the pure TiO₂ nanofibers, BN (3 wt. %) /TiO₂, BN (5wt. %) /TiO₂, BN (7wt. %) /TiO₂ and BN (10wt. %) /TiO₂ composite nanofibers indicates that it absorbs light at 380, 348, 345, 344 and 342 nm corresponding to a band gap of 3.2, 3.56, 3.59, 3.6 and 3.62 eV, respectively. Compared to the pure TiO₂ nanofibers, the absorption edges of BN/TiO₂ composite nanofibers are blue shifted. These facts suggest that introducing BN sheets may increase the photocatalytic activity of TiO₂ nanofibers under UV light.

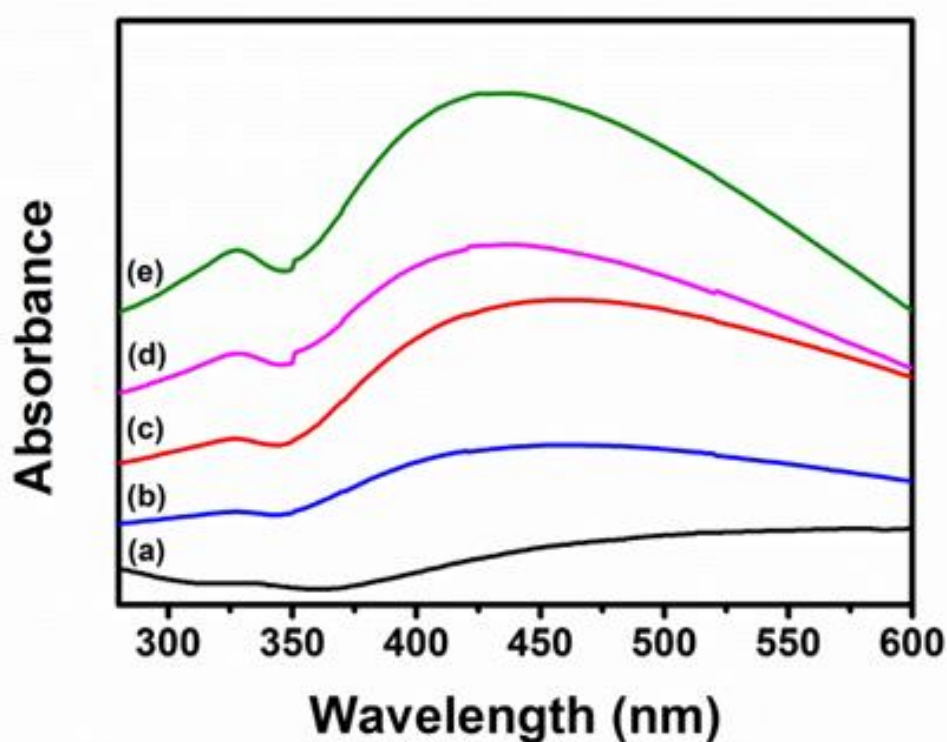


Figure 3.6. UV-VIS absorption spectra of (a) TiO₂, (b) BN (3 wt. %)/TiO₂, (c) BN (5wt. %)/TiO₂, (d) BN (7wt. %)/TiO₂ and (e) BN (10wt. %)/TiO₂ annealed nanofibers in air for 4h at 500°C.

PL spectra of TiO₂ nanofibers are shown in Figure 3.7. The significant increase of the PL intensity was observed for BN (5wt. %)/TiO₂, BN (7wt. %)/TiO₂ and BN (10wt. %)/TiO₂ samples. The PL spectrum of sample BN (3 wt. %)/TiO₂ is approximately equal to the initial TiO₂ PL spectrum. The PL spectra have been deconvoluted to individual peaks with Gaussian fitting using Origin software (Figure 3.8). We can distinguish 3 groups of peaks, centred at 415-430 nm, 544-571 nm and 688-731 nm. In our previous works, we have reported on the

detailed analysis of the PL spectra of TiO₂ based nanostructures [11], [16]. The observed peak at 415-430 nm corresponds to the self-trapped excitons (STE) localized on the TiO₆ octahedral [16],[17]. The peaks in the range of 544-571 nm correspond to oxygen vacancies, localized on the surface, and can also be considered as recombination of free electrons with trapped holes. Peaks at 688-731 nm correspond to structural defects (Ti³⁺, Ti³⁺ interstitials, under coordinated Ti atoms) and can be related to the recombination of free holes with trapped electrons [11],[17]. It is worth saying that no peaks related to rutile phase (800-815 nm) were found.

The PL of TiO₂-BN nanostructures have not been reported before. Therefore, the analysis of the PL properties will be based on other photo-induced properties of TiO₂-BN nanostructures. M. Shanmugam *et al.* reported on BN induced passivation of the surface states on TiO₂ when BN-TiO₂ heterojunctions are formed for solar cell applications. It was discussed that BN passivates dangling bonds on the TiO₂ surface and improves the photocatalytic activity of TiO₂ nanostructures [18],[19]. The improved photocatalytic activity is based on the charge separation at the TiO₂/BN interface and the flow of holes to the BN upper layer. Thus, it is expected to get lower electron-hole recombination rate in BN doped TiO₂ nanostructures. On the basis of the above mentioned BN-TiO₂ interaction the PL intensity in the BN doped TiO₂ nanostructures should decrease [20],[7]. However, in our case, the enhancement of the TiO₂ nanofibers PL was observed when increasing of the doping level of BN.

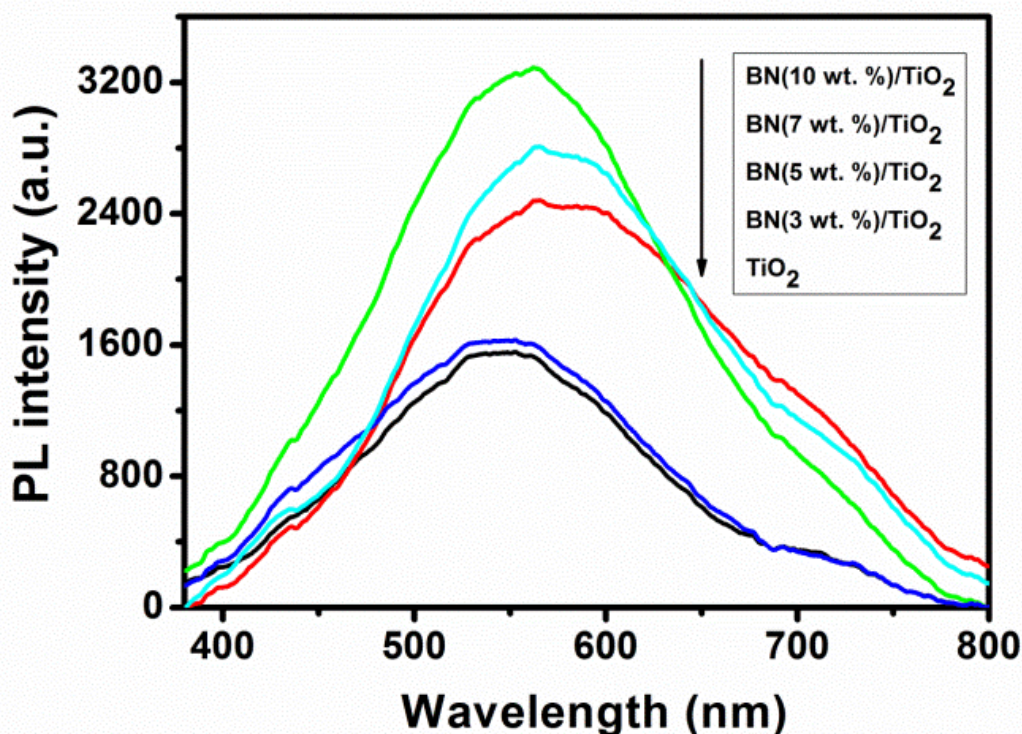


Figure 3.7. Photoluminescence of TiO₂ and BN/TiO₂ NFs annealed in air at 500°C.

The mechanism of BN doping can be explained from comparison of the deconvoluted TiO₂ PL peaks (Figure 3.8). Table 3.4 shows that the normalized integrated STE peak intensity (I₁) decreased with the BN doping ratio. From XRD analysis, it was found that additional lattice strain appeared in the TiO₂ lattice after BN doping. The induced strain reduces the formation of the self-trapped excitons (STE) localized on the TiO₆ octahedral and therefore quenches STE emission. The emission related to surface defects (I₃) has a tendency to decrease because of the BN passivation of the dangling bonds, related to the unsaturated surface atoms and the photo-generated holes migration to BN [18],[20]. We also suppose that BN induced lattice strain in the TiO₂ lattice might cause oxygen vacancies formation. Therefore, the increase of absolute PL value of peaks, related to oxygen vacancies was observed as BN can passivate the surface state of non-radiative recombination and enhance the PL intensity of the whole spectrum. We also assume that due to charge separation on BN-TiO₂ interface, the observed PL emission is due to bulk emission centers rather than surface centers. Thus, the observed results show good

correlation between optical and structural properties of BN-TiO₂ nanofibers. The quantum yield of the samples was calculated as following:

$$QY = N_{em}/N_{abs} \quad (\text{Equation 3})$$

Where N_{abs} and N_{em} are numbers of absorbed and emitted photons. Taking into account that all photons are absorbed by TiO₂ at wavelength of 266 nm, no correlation coefficients for N_{abs} were used. The N_{abs} and N_{em} were calculated on the basis of the obtained experimental values, such as laser power, repetition frequency, sensitivity of fiber optic spectrometer per integration time and the measured signal. The obtained values are shown in the Table 3.5. Typical QY of TiO₂ nanostructures is in the range of 0.001-0.2, as reported by Li et al. [21]. According to the data, obtained in the present work, the QY of TiO₂ nanofibers is one order lower than in other sources. It points to high ratio of charge splitting and non-radiative transitions through surface states [22] what is significantly good for photocatalytic applications.

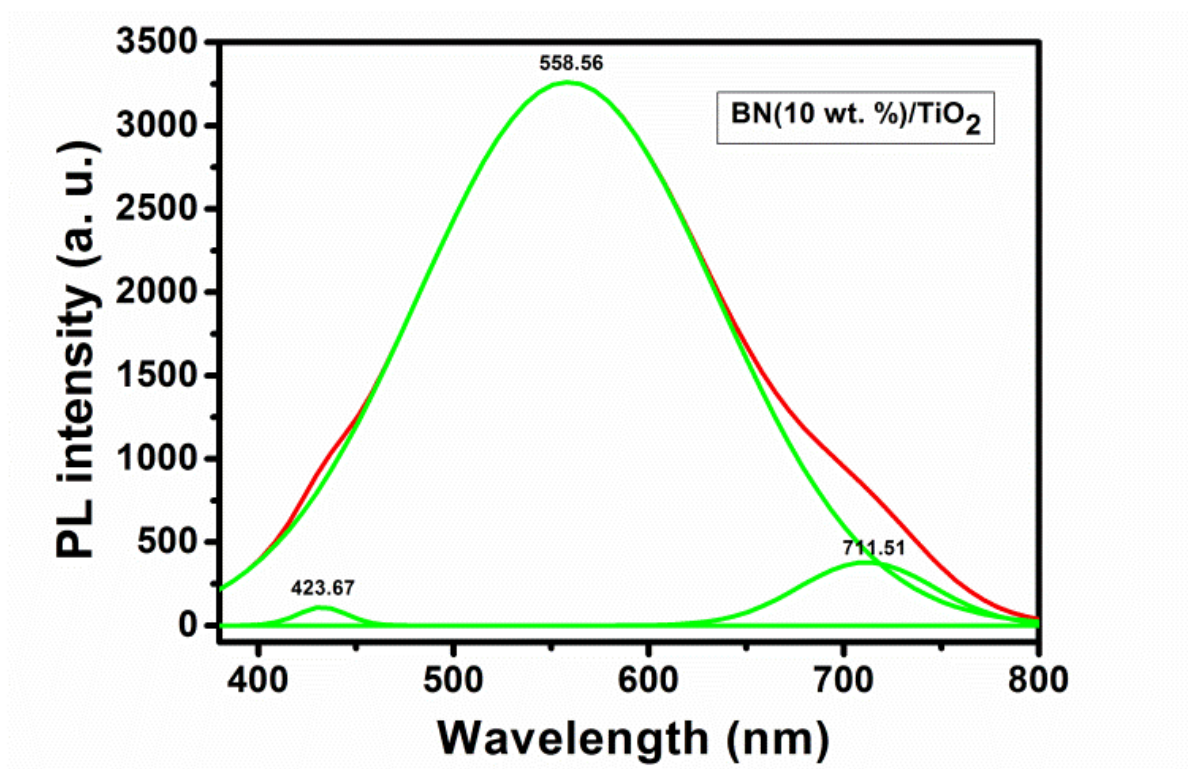


Figure 3.8. One example of a deconvoluted PL spectrum of BN/TiO₂ NFs annealed in air at 500°C.

Table 3.4. Normalized integrated intensity of the TiO₂ PL peaks.

Doping level	I1	I2	I3
BN (0wt. %)/ TiO ₂	0.01481	1	0.05784
BN (3wt. %)/ TiO ₂	0.01898	1	0.04002
BN (5wt. %)/ TiO ₂	0.00841	1	0.835766
BN (7wt. %)/ TiO ₂	0.01279	1	0.15328
BN (10wt. %)/ TiO ₂	0.00558	1	0.05248

Table 3.5. Quantum yield of the pure TiO₂ and BN/TiO₂ composite nanofibers.

	TiO ₂	BN (3wt. %)/TiO ₂	BN (5wt. %)/TiO ₂	BN (7wt. %)/TiO ₂	BN (10wt. %)/TiO ₂
QY(x10 ⁻⁶)	128	137	210	227	246
Error (x10 ⁻⁵)	3.24	3.48	5.34	5.76	6.25

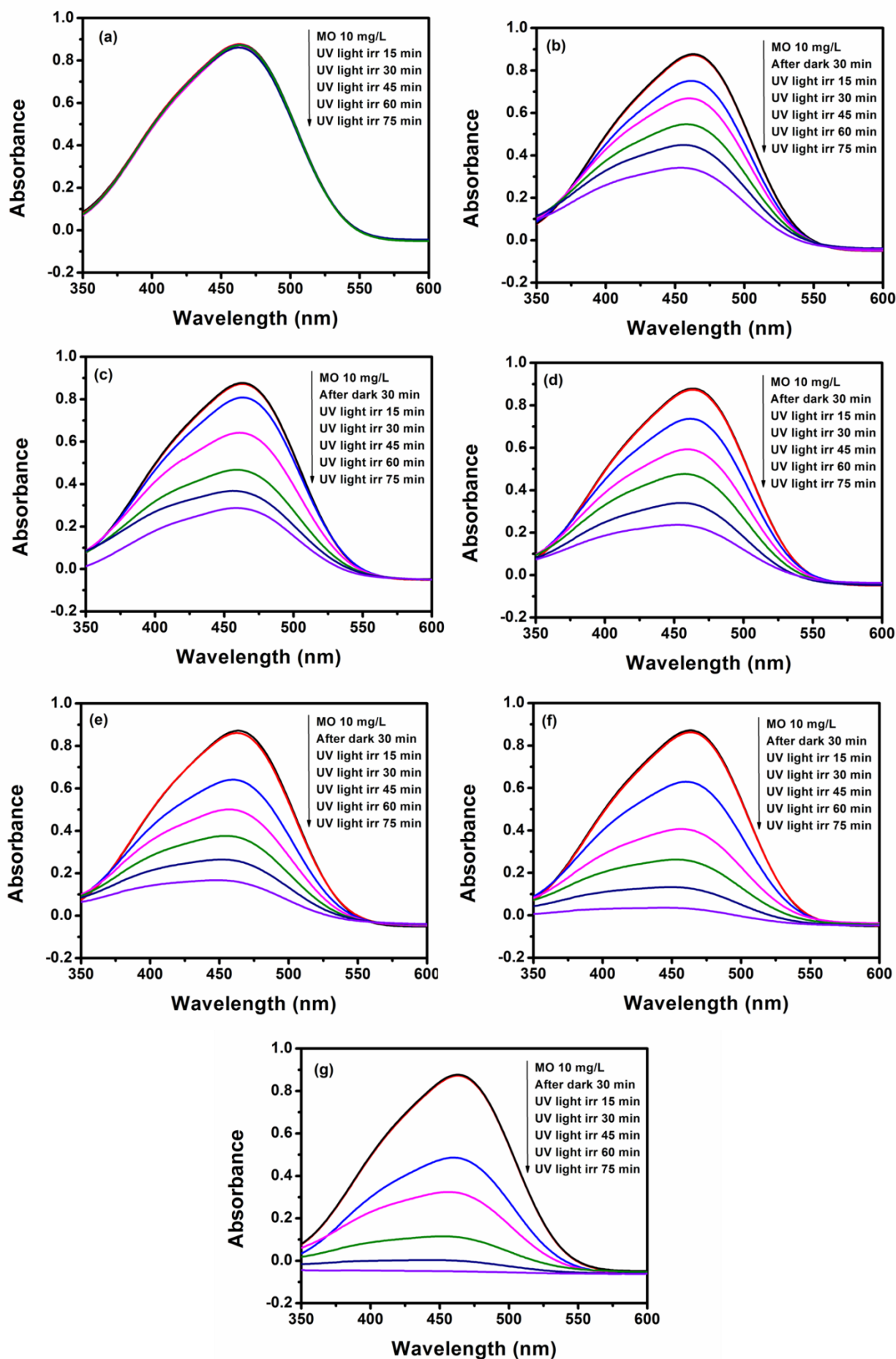


Figure 3.9. UV-Vis spectra of the photocatalytic degradation of MO under UV light: (a) MO without catalyst, (b) P 25, (c) TiO₂ nanofibers, (d) BN (3wt. %)/TiO₂, (e) BN (5wt. %)/TiO₂, (f) BN (7wt. %)/TiO₂ and (g) BN (10wt. %)/TiO₂ composite nanofibers.

5. Photocatalytic activity

The photocatalytic activities of BN/TiO₂ with different BN amounts were evaluated by degradation of methyl orange (MO) under UV light (wavelength < 400 nm). MO was selected as a model organic pollutant. Figure 3.9 (a-g) shows the UV-Vis absorbance spectra of MO solution (major absorption band around 462 nm) with different time intervals 0, 15, 30, 45, 60 and 75 min after 30 min storage in dark for excluding the interference of adsorption. For comparison, the photocatalytic activities of TiO₂ nanofibers and commercial TiO₂-P25 were also tested under identical experimental conditions. The results indicate that methyl orange is stable and difficult to be photodegraded in the absence of photocatalyst. After irradiation for 75 min, MO was degraded up to 65% in the presence of TiO₂ nanofibers, compared to 60% degradation by commercial granular TiO₂-P25 (Figure 3.10). Therefore, in case of pure TiO₂, it is well known that TiO₂ nanofibers have a larger active surface area compared to the commercial TiO₂-P25 nanoparticles which increases its photocatalytic activity [8]. As shown in Figure 3.10, MO was degraded up to 73%, 80%, 93% and 99% in the presence of BN (3wt. %)/TiO₂, BN (5wt. %)/TiO₂, BN (7wt. %)/TiO₂, BN (10wt. %)/TiO₂, respectively. It is well known that the photocatalytic activity is mainly governed by crystalline phase, specific surface area, light absorption capacity and separation efficiency of electron-hole pairs. Therefore, in BN/TiO₂ samples, owing to the pronounced electrostatic interactions, the surface naturally negative charged of boron nitride sheets could lead to the transfer of h⁺ from the activated TiO₂ to the BN sheets when they are connected. Thus, more photo electrons were available compared to pure TiO₂ nanofibers, to take part in the photodegradation process [7],[23]. Thus, the recombination of e⁻ and h⁺ is inhibited as confirmed previously by photoluminescence. However, considering the specific surface area results of BN/TiO₂ nanofibers presented above, a large increase has been achieved compared to the pure TiO₂ nanofibers. From the XRD analysis, the crystallite average size of TiO₂ is increasing after introducing BN sheets. As confirmed by UV-VIS, compared to the pure TiO₂ nanofibers, the absorption edges of BN/TiO₂ composite nanofibers are blue shifted. From the obtained results, it is evident that BN sheets improve the separation

efficiency of e^- and h^+ and therefore enhance the photocatalytic activity of TiO₂ under UV light.

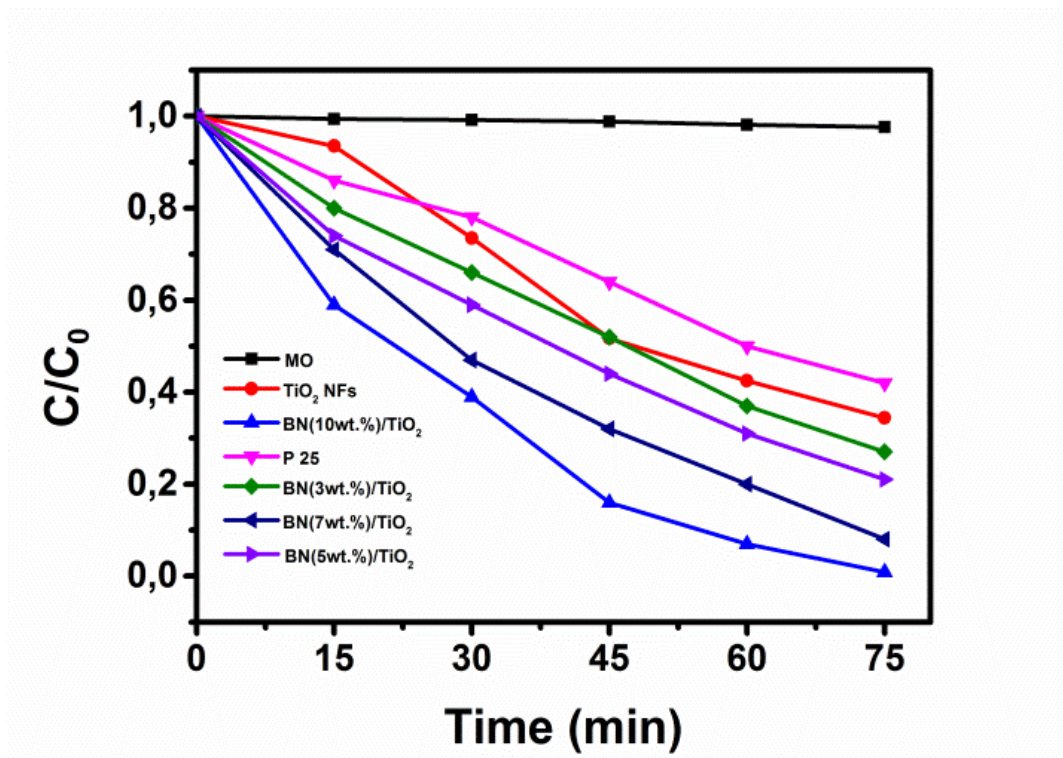


Figure 3.10. Photodegradation of MO by P25, TiO₂ nanofibers and BN/TiO₂ composite nanofibers.

Figure 3.11 shows the different kinetic linear curves. The photodegradation reactions follow a Langmuir–Hinshelwood first-order kinetics model [24]. The explanation is described as follows:

$$r = dC/dt = kKC/(1+KC) \quad (\text{Equation 4})$$

Where r is the degradation rate of methyl orange (MO) ($\text{mg L}^{-1} \text{min}^{-1}$), C is the concentration of the MO solution (mg L^{-1}), t is the irradiation time, k is the reaction rate constant ($\text{mg L}^{-1} \text{min}^{-1}$), and K is the adsorption coefficient of MO (mg L^{-1}). Since the initial concentrations ($C_0 = 10 \text{ mg L}^{-1}$) of the MO solutions are very low in the present experiments, the relationship between $\ln(C_0/C)$ and the reaction time t shows that the decomposition of MO with different photocatalysts accords with a pseudo first order kinetic[24]:

$$\ln(C_0/C) = kKt = k_a t \quad (\text{Equation 5})$$

Where k_a is the apparent first-order rate constant (min^{-1}) and C is the concentration at time t . k_a is obtained from the linear dependence between $\ln(C_0/C)$ and time are reported in Table 3.6. The increasing order of the rate constants in the samples is: BN (10wt. %)/TiO₂ > BN (7wt. %)/TiO₂ > BN (5wt. %)/TiO₂ > BN (3wt. %)/TiO₂ > TiO₂ NFs > P25. The rate constant exhibits a maximum of 0.0586 min^{-1} for BN (10wt. %)/TiO₂, which is 5 and 3.8 times higher than that of P25 and TiO₂ nanofibers, respectively. In addition, all BN/TiO₂ composite nanofibers show higher photocatalytic activity than that of P25 and TiO₂ nanofibers under UV light, which is represented by larger value of k_a . Even though, in the case of BN (10wt. %), the curve of $[\ln(C_0/C) \text{ vs time}]$ is not completely linear, it is still considered as approximately following the Langmuir–Hinshelwood model. This behavior is possibly due to the presence of a higher concentration of BN. When the rate of the reaction is increased with additional BN sheets, the adsorption-desorption equilibrium will be slightly disturbed and the Langmuir behavior is therefore shifting from a perfect linear first order. In our case, the disturbance is relatively small and the $[\ln(C_0/C) \text{ vs time}]$ curve is still giving an acceptable value of k_a . From obtained results it is evident that the fact of introducing BN sheets improves separation of photo-induced electron-hole pairs of TiO₂ and significantly increases its photocatalytic activity under UV.

Table 3.6. Kinetic parameters for photocatalytic activities of the pure TiO₂ nanofibers and BN/TiO₂ composite nanofibers.

	k_a (min^{-1})	R^2
MO	0.00031	0.9743
P25	0.0117	0.9791
TiO₂ NFs	0.0153	0.9706
BN (3wt. %)/TiO₂	0.0173	0.9842
BN (5wt. %)/TiO₂	0.0203	0.9900
BN (7wt. %)/TiO₂	0.0319	0.9541
BN (10wt. %)/TiO₂	0.0586	0.8979

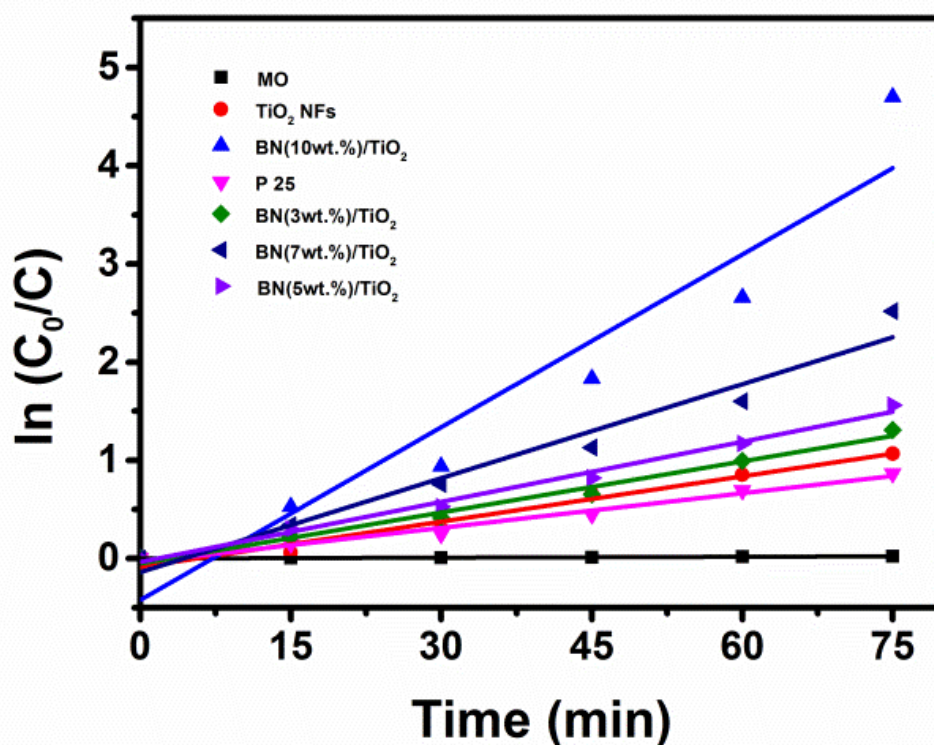


Figure 3.11. Kinetics of Methyl orange degradation by P25, TiO₂ nanofibers and BN/TiO₂ composite nanofibers.

6. Conclusion

In summary, pure TiO₂ nanofibers and BN/TiO₂ composite nanofibers with different BN nanosheets amounts were successfully prepared by electrospinning. All the samples were annealed at 500°C in air for 4 hours. The SEM images showed an increase in the average diameter with the increase of BN amount and confirmed that the one dimensional morphology was maintained. EDX, Raman and FTIR revealed the successful incorporation of the boron nitride in the TiO₂ nanofibers. The specific surface area measurements (BET) confirmed the increasing of the surface area with the increasing of BN sheets amount. A boost of the grain size from 16.4 to 28.7 nm had been recorded for the composite BN (10wt. %)/TiO₂ compared to the pure TiO₂ nanofibers. The increasing of TiO₂ nanofibers band gap energy from 3.2 eV to 3.62 eV due to the presence of BN sheets was confirmed by UV-VIS analysis. XRD and photoluminescence spectra confirmed that BN incorporation increases the lattice strain in the TiO₂ cell and reduce the formation of the self-trapped excitons. Owing to

the electrostatic interaction, BN sheets can promote the immigration of h^+ from the bulk of TiO₂ to its surface and consequently improve the photocatalytic activity of TiO₂ under UV light due to efficient charge separation and reduction of charges carriers' recombination. The photocatalytic degradation of methyl orange under UV light was 5 and 3.8 times higher than that of commercial TiO₂-P25 and TiO₂ nanofibers, respectively. In conclusion, the mixing of TiO₂-based photocatalysts with BN sheets is a challenge worth investigating to enhance efficiency in a simple and economically beneficial manner and could be used as catalysts in the degradation of different molecules for photocatalytic application.

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Chapter 4: High Photocatalytic and Antibacterial Activity of BN-Ag/TiO₂ Composite Nanofibers Under Visible Light

Table of Contents

1. Abstract.....	115
2. Introduction.....	115
3. Experimental Section.....	116
3.1. Materials.....	116
3.2. Boron nitride exfoliation.....	116
3.3. Preparation of Ag-TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.....	116
3.4. Chemical and structural characterizations.....	118
3.5. Photocatalytic activity.....	118
3.6. Antibacterial activity of TiO ₂ nanofibers and BN-Ag/TiO ₂ composite nanofibers.....	119
3.6.1. Bacterial strain and culture medium	119
3.6.2. Preparation of the bacterial suspensions used for the antibacterial tests.....	119
3.6.4. Assessment of the bactericidal properties of TiO ₂ and BN5-Ag ₃ /TiO ₂ nanofibers	120
3.6.5. Quantification of the bactericidal activity	120
4. Results and discussion.....	121
4.1. Morphological and structural properties of Ag/TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.....	121
4.2. Optical properties of TiO ₂ , Ag/TiO ₂ and BN-Ag/TiO ₂ composite nanofibers.....	128
4.3. Photocatalytic application.....	131
4.4. Antibacterial properties.....	136
5. Conclusion.....	137

1. Abstract

To develop material with good photocatalytic properties for organic compound degradation and bacterial removal, we produced Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers that included controlled amounts of boron nitride (BN) nanosheets and silver (Ag). After annealing at 500°C under air, we used scanning electron microscopy, Brunauer-Emmet-Teller analysis, X-ray diffraction, energy-dispersive X-ray spectroscopy, Raman spectroscopy, UV-visible reflectance spectroscopy and room temperature photoluminescence to investigate the morphological, structural and optical properties of all samples. The photocatalytic tests using methylene blue under visible light, in repeated and long-term applications, showed that the photodegradation activity of BN(5 wt%)-Ag(3 wt%)/TiO₂ composite nanofibers was 17.2 and 2.3 times higher than that of pure TiO₂ and Ag(3 wt%)/TiO₂ nanofibers, respectively. In antibacterial tests using Gram-negative *Escherichia coli*, 3 hours of incubation with BN(5 wt%)-Ag(3 wt%)/TiO₂ composite nanofibers killed all bacteria. These results indicate that the synthesized BN(5 wt%)-Ag(3 wt%)/TiO₂ composite nanofibers can be considered to be multifunctional material for photodegradation and antibacterial applications.

2. Introduction

This chapter was devoted to develop an effective material having photocatalytic properties for both organic compound degradation and bacterial removal. Toxic industrial chemical waste is still not properly treated and may directly pollute drinking water.[1] Therefore, it is urgent to develop effective and economic approaches to remove water contaminants, such as organic pollutants and heavy metal ions.[2] Various methods can be employed to remove biological and chemical pollutants from wastewater, such as photocatalysis, adsorption, filtration and sedimentation.[3, 4] We will report on the elaboration of Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers with controlled amounts of boron nitride (BN) nanosheets and silver (Ag). BN and Ag played an important role in the photodegradation process by reducing the recombination rate of electron/hole pairs. The second role of Ag was to shift the absorbance edge of TiO₂ to the visible region, thus reduce the band gap of TiO₂. For environmental applications, the long-term stability of the

photocatalytic materials is also a key property. Therefore, the photodegradation repeatability experiments of methylen blue were carried out for four cycles.

3. Experimental Section

3.1. Materials

Titanium tetraisopropoxide (TTIP) (Ti[OCH(CH₃)₂]₄) (97%), polyvinylpyrrolidone (PVP) (Mw = 13,00,000), acetic acid (98%), absolute ethanol (99%), silver nitrate (AgNO₃; 99%), MB, sodium chloride (NaCl, 99%) and gelatin from porcine skin were purchased from Sigma Aldrich. BN nanosheets were obtained from commercial BN (Combat powders, Saint Gobain, 95%, 325 mesh). The *E. coli* (K12 DSM 423) strain was from DSMZ, Germany. Lysogeny broth (LB)-Miller culture medium (ref. n°1214662) was purchased from Fischer Scientific. Ultra-pure water was produced by using the MilliQ system (Millipore). All chemicals were used without any further purification.

3.2. Boron nitride exfoliation

BN nanosheets were obtained by exfoliation of commercial BN powder with gelatin from porcine skin [5]. Briefly, 20g of gelatin was dissolved in 80 ml of hot water (75°C). Then, 1g of BN powder was added to the mixture and the solution was kept in an ultrasonic homogenizer at 50°C overnight. After centrifugation at 6000 rpm for 30 minutes, precipitates (containing exfoliated BN) were dried at 80°C for 48 hours and then calcined in a muffle furnace at 600°C in air for 2 hours to obtain pure exfoliated BN.

3.3. Preparation of Ag-TiO₂ and BN-Ag/TiO₂ composite nanofibers

Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers were prepared using the electrospinning technique. The Ag and BN content levels were calculated based on TiO₂ weight percentage (wt. %). The spun solution was prepared in three steps. First, different amounts of AgNO₃ (0.5, 1.5 and 3 wt. %) and 2 ml of acetic acid were sonicated for 12h to dissolve AgNO₃. Second, TTIP was dissolved in a mixture that contained 5 ml of ethanol and 0.3 g of PVP (precursor solution) and stirred at room temperature for 1h to obtain the viscosity required for electrospinning. Third, dissolved AgNO₃ was added to the precursor solution with vigorous magnetic stirring (150 rpm) for 30 min (Ag/TiO₂ solution). A similar Ag/TiO₂ solution but with a fixed Ag content (3 wt. %) was used to prepare BN-Ag/TiO₂

composite nanofibers with specific amounts of exfoliated BN (3 and 5 wt. %). The Ag/TiO₂ or BN-Ag/TiO₂ solution was transferred into a syringe with a stainless steel needle, a diameter of 0.7 mm at a constant flow rate of 1 ml/h. The feeding rate was controlled by the syringe pump. The temperature level inside the electrospinning chamber was 38 ± 5°C. A high voltage power supply was used as source of electric field. Nanofibers were collected on a rotating coil covered with aluminum foil with a rotation speed of 400 rpm. Briefly, the solution was electrospun at a DC voltage of 25 KV and 20 cm working distance (the distance between the needle tip and the collector). As the solution progressed through the system (1 ml/h), it became electrified. The tip of the resulting Taylor cone expelled an electrified jet of fibers, forming a fibrous mesh on the grounded collector.[6] Electrospun Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers were then calcined in a muffle furnace at 500°C with a heating rate of 5°C/min for 4 hours in air for polymer removal and TiO₂ crystallization. In addition, the annealing process led to the thermal decomposition of AgNO₃ to Ag₂O and finally to Ag.[7] Table 4.1 lists the produced nanofibers tested in this study.

Table 4.1. TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ samples prepared with different weight amounts of BN nanosheets and AgNO₃.

Sample name	Sample description	AgNO₃ content (%)	BN content (%)
TiO₂	TiO ₂	-	-
Ag0.5/TiO₂	Ag(0.5 wt%)/TiO ₂	0.5	-
Ag1.5/TiO₂	Ag(1.5 wt%)/TiO ₂	1.5	-
Ag3/TiO₂	Ag(3 wt%)/TiO ₂	3	-
BN3-Ag3/TiO₂	BN(3 wt%)-Ag(3 wt%)/TiO ₂	1.5	3
BN5-Ag3/TiO₂	BN(5 wt%)-Ag(3 wt%)/TiO ₂	1.5	5

3.4. Chemical and structural characterizations

X-ray diffraction (XRD) measurements were carried out using a PANalytical Xpert-PRO diffractometer equipped with an X'celerator detector using Ni-filtered Cu-radiation ($\lambda = 1.54 \text{ \AA}$). Raman spectra were obtained using a Labram 1B instrument (Jobin-Yvon S.A., Horiba, France). Spectra were taken at room temperature using a 659 nm laser line as the excitation source. All Raman spectra were recorded in the range of 100-1500 cm^{-1} . Scanning electron microscopy (SEM) images were taken with a Hitachi S4800, Japan. The average diameter of 100 randomly chosen nanofibers for each sample was measured from SEM images using the Image J1.29X software. Energy-dispersive X-ray spectroscopy analysis (EDX) and elemental mapping were performed with a Zeiss EVO HD15 microscope coupled to an Oxford X-MaxN EDX detector. Optical properties were analyzed by diffuse reflectance (Shimadzu UV-3600). The UV-visible (UV-VIS) absorbance spectra of MB were recorded with a Jasco V-570 UV-VIS-NIR spectrophotometer. Each sample surface area was determined from nitrogen adsorption-desorption isotherms at liquid nitrogen temperature using the Micromeritics ASAP 2010 system (outgassing conditions: 200°C-12h). Room temperature photoluminescence (PL) was measured in the range of 400-700 nm. After excitement with a nitrogen Nd:YAG laser (266 nm, 10 mW, 1 kHz), PL was recorded with an optical fiber spectrometer (Ocean Optics usb2000).

3.5. Photocatalytic activity

The photocatalytic activity of Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers was evaluated by monitoring the degradation of MB (used as a reference organic pollutant) under visible light. To this aim, 0.4 g/L of each photocatalyst was added to an aqueous suspension of 20 mg/L MB. After dispersion of the nanofibers by sonication in the dark for 60 min to reach the adsorption-desorption equilibrium, the solution was irradiated with visible light (obtained from a 150W light source with emission wavelength > 400 nm) for 80 minutes. The distance between the lamp and the solution (10 cm) was the same for all samples and the temperature was kept constant at $25 \pm 0.2 \text{ }^\circ\text{C}$ by circulating water in the cylindrical tube that surrounded the photo-reactor during the entire experiment. Every 20 minutes, an aliquot of 2 ml was taken from each sample and centrifuged at 6000 rpm for 2 min in the dark to clear the supernatant because filtration resulted in the loss of some catalysts by sorption. The centrifuged solutions were analyzed with a UV/VIS spectrometer.

MB absorbance spectra (major absorption band around 664 nm) were recorded to measure the concentration changes over time. After irradiation, the photocatalytic degradation efficiency was calculated using equation 1:

$$\text{Degradation efficiency (\%)} = (C_0 - C)/C_0 \times 100 \quad (\text{Equation 1})$$

where C_0 and C are the MB concentrations before and after photo-irradiation, respectively. This equation gives the percentage of MB degradation by the photocatalyst. BN5-Ag3/TiO₂ photocatalytic activity repeatability was assessed with the same experimental set-up and after each degradation cycle, the catalyst was separated from the MB solution by centrifugation.

3.6. Antibacterial activity of TiO₂ nanofibers and BN-Ag/TiO₂ composite nanofibers

3.6.1. Bacterial strain and culture medium

LB-Miller culture medium was used for both liquid and solid bacterial cultures. The non-pathogenic and Gram-negative *E. coli* (K12 DSM 423) strain was selected as model microorganism to assess the samples' antibacterial properties because it is a common indicator of fecal contamination in water.[8]

3.6.2. Preparation of the bacterial suspensions used for the antibacterial tests

For each test, a new bacterial suspension was prepared from frozen *E. coli* aliquots stored at - 20°C. Aliquots were first rehydrated in LB-Miller medium on a rotary shaker at 110 rpm at 37°C for 3 hours. Then, they were inoculated in fresh LB-Miller medium (5% v/v) and incubated overnight at 37°C under constant stirring (110 rpm) until bacteria reached the stationary growth phase. Bacteria were centrifuged at 10°C at 3000g for 10 minutes to remove nutrients and avoid bacterial growth during the antibacterial test. Bacterial pellets were then suspended in spring water (Cristaline Sainte Cécile, France: [Ca²⁺] = 39 mg.L⁻¹, [Mg²⁺] = 25 mg.L⁻¹, [Na⁺] = 19 mg.L⁻¹, [K⁺] = 1.5 mg.L⁻¹, [F⁻] < 0.3 mg.L⁻¹, [HCO₃⁻] = 290 mg.L⁻¹, [SO₄²⁻] = 5 mg.L⁻¹, [Cl⁻] = 4 mg.L⁻¹, [NO₃⁻] < 2 mg.L⁻¹) to avoid osmotic shock and the suspension absorbance was measured at 600 nm to determine the bacterial concentration, according to calibration curves obtained previously in the laboratory. Bacteria were then diluted in spring water to obtain a bacterial suspension of about 7.0 x 10⁸ CFU.mL⁻¹.

3.6.4. Assessment of the bactericidal properties of TiO₂ and BN5-Ag₃/TiO₂ nanofibers

Bactericidal tests were carried out in batch mode, in glass tubes (20mL) equipped with a breathable cap. TiO₂, BN5-Ag₃/TiO₂ and BN5-Ag₃/TiO₂ nanofibers were diluted to a concentration of 10 mg.mL⁻¹ in sterile ultra-pure water in the dark. One mL of bacterial suspension was mixed with 1 mL of spring water and 1 mL of each nanofiber suspension to obtain an initial bacterial concentration (C₀) of $2.3 \pm 0.3 \times 10^8$ CFU.mL⁻¹. After vortexing, samples were incubated at 20°C with constant stirring (110 rpm) on a rotary shaker for 3 hours under normal light. Controls (1 mL of bacterial suspension, 1 mL of spring water and 1 mL of ultra-pure water without any material) were added to determine the initial bacterial concentration and to check that the vortex step did not affect cell viability.

3.6.5. Quantification of the bactericidal activity

After the 3-hour incubation with the different nanofiber samples, bacteria were counted using the conventional plaque assay method.[9] After decanting for 15 minutes to separate bacteria from the nanofiber-containing supernatant, bacteria were immediately ten-fold diluted in saline solution (0.9% NaCl) to neutralize the effect of any Ag that might have been desorbed, and then spread on agar plates. Negative control was a plate without bacteria. After overnight growth at 37°C, bacterial colonies were counted, knowing that each colony stemmed from one bacterium. All experiments were performed twice and the bacterial concentration in the sample was calculated as the average number of colonies divided by the inoculated volume, with the corresponding dilution factor taken into account. The quantification limit was 25 CFU.mL⁻¹. Changes in the bacterial concentrations were correlated with the bactericidal performance of the tested nanofiber sample. The concentration decrease was expressed as log-removal values, as described in the United States Environmental Protection Agency recommendations.[8] The log-removal value was defined as the logarithm (base 10) ratio of the bacterial concentration C (CFU.mL⁻¹) measured at a given time relative to the initial bacterial concentration C₀ (CFU.mL⁻¹). A log-removal value of -log (C₀) was attributed to the specific case of total removal of viable bacteria.[10] For instance, for an initial concentration C₀ fixed at 1.0×10^8 CFU/mL, a log-removal value of -8 corresponded to total removal.

4. Results and discussion

4.1. Morphological and structural properties of Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers

Pure TiO₂ nanofibers and Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers, with different amounts of AgNO₃ and BN nanosheets, were obtained using the simple electrospinning technique (Table 1). The Ag content in the TiO₂ nanofibers was adjusted by controlling the amount of AgNO₃ in the electrospun solution. After the annealing process at 500°C in air, a very light grayish tint was observed in samples with increasingly higher Ag content. Conversely, pure TiO₂ nanofibers were white. Analysis of their morphology by SEM (Figure 4.1) showed the nanofibrous morphology of the obtained Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers after calcination in air at 500°C for 4 hours. Although the electrospinning parameters were the same for all samples, the average diameter of composite nanofibers calculated from SEM images (Table 4.2) was significantly higher than that of pure TiO₂ nanofibers. As our previous findings indicate that there is an important relation between the fiber diameter and the dopant content [11], this diameter increase could be attributed to the inclusion of AgNO₃ and BN sheets that increase both the total metal content and the viscosity of the electrospinning solution. [12]

EDX was used to study the chemical composition and to confirm the successful production of Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers. The EDX data (Table 4.3) revealed the formation of TiO₂ nanofibers with the required atomic ratio of 1:2. For the Ag/TiO₂ composites, the progressive increase of the Ag atom percentage with the AgNO₃ content was clearly observed. In BN-Ag/TiO₂ composite nanofibers, the presence of boron progressively increased with the BN nanosheets amount. It is worth to note that due to the overlap between the energy levels of Ti and N (the L energy of Ti and the K energy of N), N could not be detected. Elemental mapping images of a BN₃-Ag₅/TiO₂ sample (Figure 4.2) clearly showed that Ti, O, Ag and B elements were well distributed over the entire area of the sample, thus confirming the good dispersion of Ag and BN nanosheets in TiO₂ nanofibers. In conclusion, these data indicate that BN-Ag/TiO₂ composite nanofibers were successfully fabricated using the electrospinning technique.

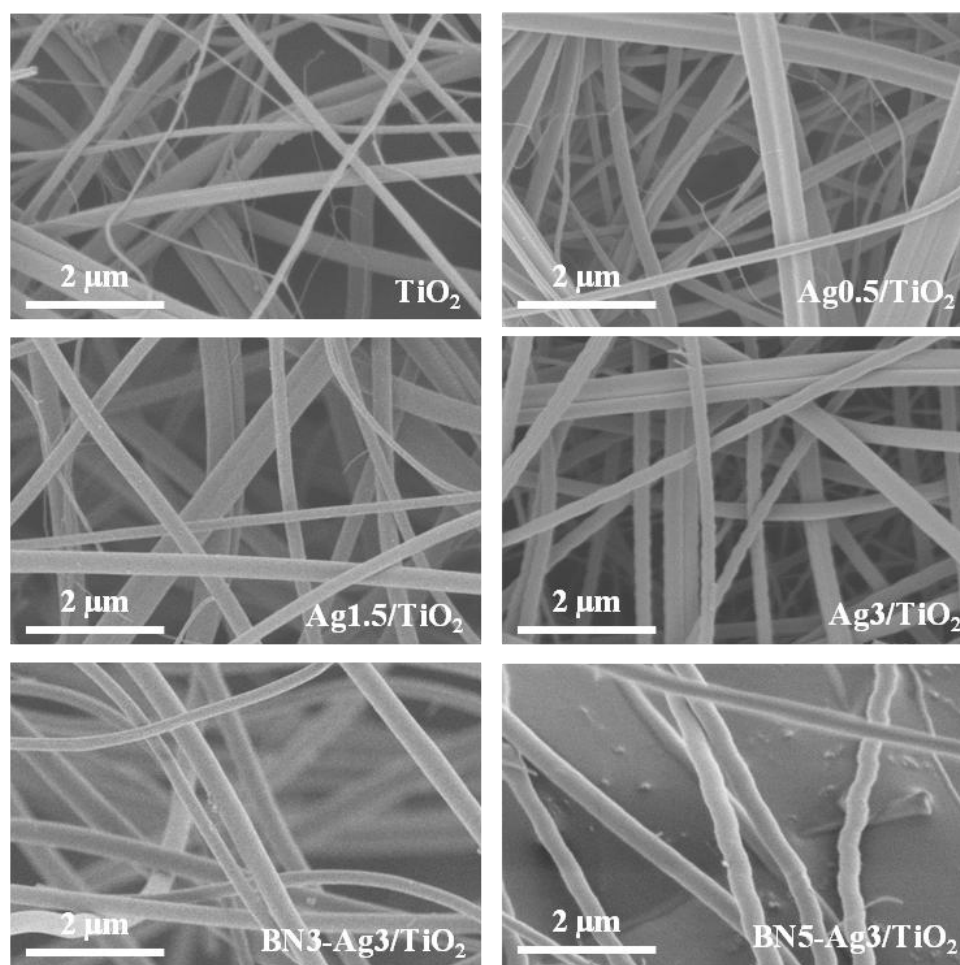


Figure 4.1. Scanning electron microscope images of pure TiO₂ nanofibers, Ag_{0.5}/TiO₂, Ag_{1.5}/TiO₂, Ag₃/TiO₂, BN₃-Ag₃/TiO₂ and BN₅-Ag₃/TiO₂ composite nanofibers after annealing under air at 500°C for 4h.

Table 4.2. Average diameter of annealed TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ nanofibers.

Sample	Average diameter (± 5 nm)
TiO ₂	187
Ag _{0.5} /TiO ₂	192
Ag _{1.5} /TiO ₂	242
Ag ₃ /TiO ₂	319
BN ₃ -Ag ₃ /TiO ₂	286

BN5-Ag3/TiO₂

305

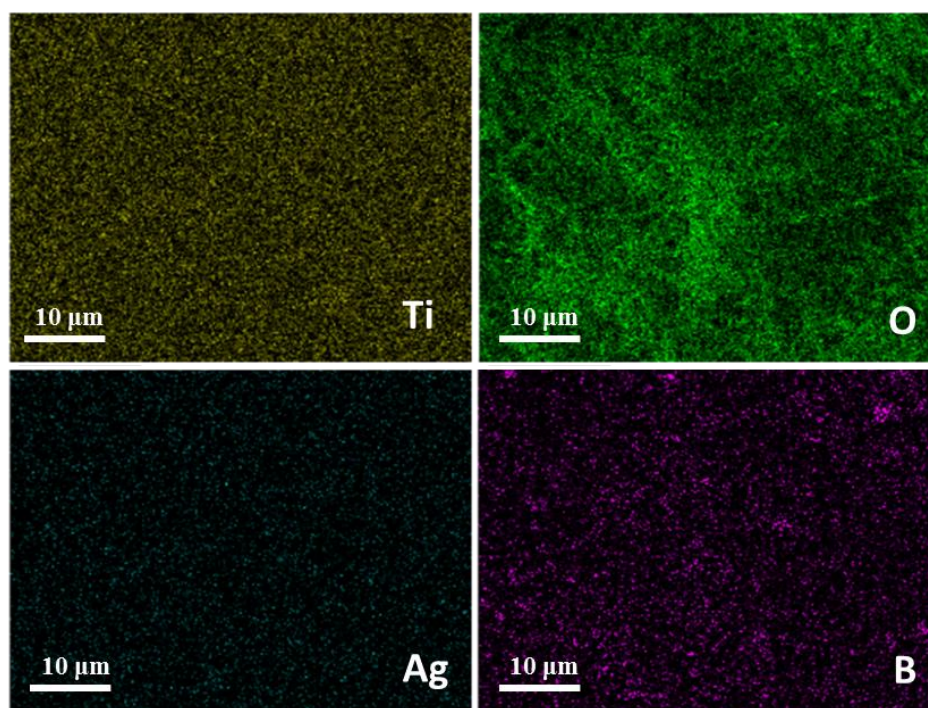


Figure 4.2. Elemental mapping images of BN5-Ag3/TiO₂ composite nanofibers with 5 wt% of BN and 3 wt% of Ag.

Table 4.3. EDX data showing the composition of annealed TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ nanofibers.

	Atomic percentage				
	Ti	O	Ag	B	C
TiO ₂	30.49	60.76	-	-	8.75
Ag0.5/TiO ₂	30.47	64.36	0.31	-	4.86
Ag1.5/TiO ₂	29.08	64.73	0.70	-	5.49
Ag3/TiO ₂	34.46	62.21	0.17	-	3.16
BN3-Ag3/TiO ₂	30.8	60.56	0.3	3.17	5.17
BN5-Ag3/TiO ₂	29.15	58.34	0.27	9.16	3.08

Calculation of the surface area of TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ nanocomposites using the Brunauer-Emmet-Teller (BET) method [13] (Table 4.4) showed that values varied between 19 and 35 m²g⁻¹. The progressive increase of the surface area with the amount of BN and Ag offers more active adsorption sites and consequently should enhance TiO₂ photocatalytic activity.

Table 4.4. Surface area of TiO₂ nanofibers, and Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers.

Samples	Surface area (m ² g ⁻¹)
TiO ₂	19.7
Ag0.5/TiO ₂	19.0
Ag1.5/TiO ₂	25.5
Ag3/TiO ₂	31.2
BN3-Ag3/TiO ₂	31.8
BN5-Ag3/TiO ₂	34.4

Analysis of the XRD patterns of the synthesized TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ nanofibers (Figure 4.3.A) indicated that all patterns had sharp diffraction peaks located at $2\theta = 25.5^\circ, 38.1^\circ, 48.2^\circ, 54.1^\circ, 55.3^\circ$ and 62.9° relative to the crystal planes of the pure anatase phase of TiO₂ (101), (004), (200), (105), (211) and (204), respectively.[14] The standard peaks of AgNO₃ and BN could not be detected by XRD due to their low amount in the samples. However, a small peak of Ag (at $2\theta \sim 38^\circ$) could be seen in the XRD spectra of Ag3/TiO₂ and BN3-Ag3/TiO₂ composite nanofibers, indicating Ag presence (Figure 4.3.B) [15, 16]. Moreover, the main peak of hexagonal BN (at $2\theta \sim 26^\circ$) overlapped with the sharp peak of TiO₂ (at $2\theta \sim 25.5^\circ$). After Ag and BN doping, the diffraction peaks of Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers were shifted, compared with the peak of pure TiO₂ nanofibers (Figure 4.3.A). We suggest that the slight shifting of the TiO₂ peak is related to peak overlapping between BN and TiO₂. Alternatively, this shift could be due to Ag and BN

sheet incorporation that increases the density of surface defects and the lattice strain in the TiO₂ cell, causing vacancy formation. At the same time, it can shift atoms from the initial position and can reduce the formation of the self-trapped excitons (STE) localized on the TiO₆ octahedral.

According to Bragg's law:[17]

$$n\lambda = 2d \sin\theta \quad (\text{Equation 2})$$

the d spacing decreases with the increase of the $\sin\theta$ value. Therefore, we can say that the d spacing value decreased with the increase of the Ag and BN amounts. This suggests that Ag ions have diffused into the TiO₂ lattice. The average crystal size of TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ samples with different amounts of AgNO₃ and BN was estimated using the following Scherrer-Debye equation: [18]

$$D = k\lambda/\beta\cos\theta \quad (\text{Equation 3})$$

where D is the average size in nm, k is the shape factor constant (0.9), λ is the X-ray wavelength (0.154 nm), β is the line broadening of the diffraction line measured by the full width at half maximum of the peak intensity (FWHM) and θ is the Bragg angle (in degrees). The results showed that the grain size of the composite nanofibers was higher than that of pure TiO₂ nanofibers (Table 4.5).

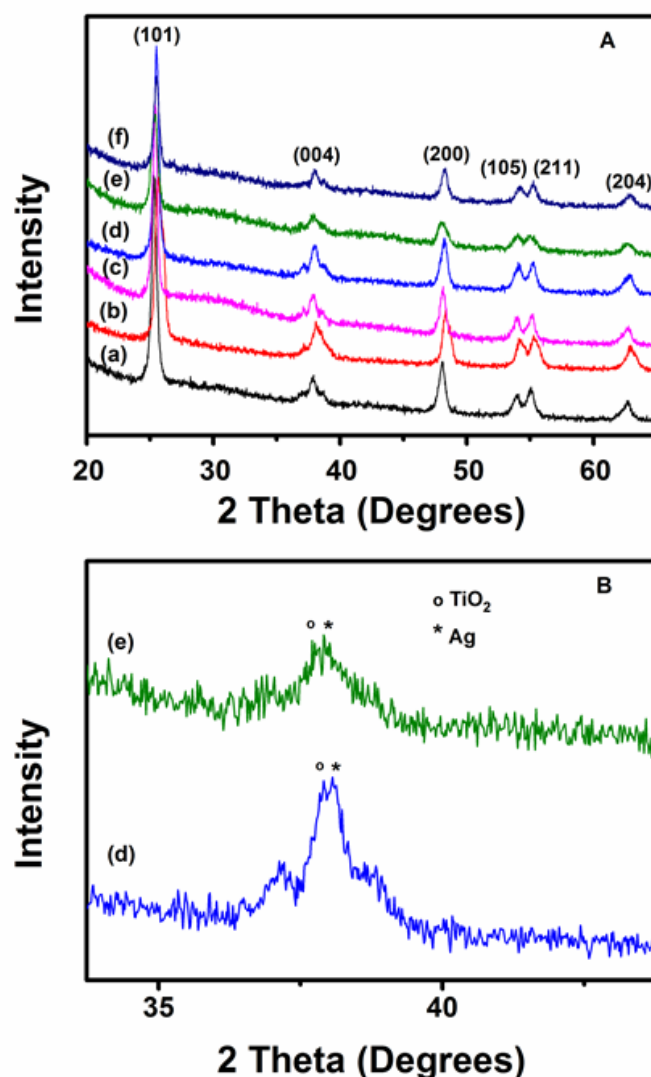


Figure 4.3. (A-B) XRD patterns of (a) TiO₂, (b) Ag_{0.5}/TiO₂, (c) Ag_{1.5}/TiO₂, (d) Ag₃/TiO₂, (e) BN₃-Ag₃/TiO₂ and (f) BN₅-Ag₃/TiO₂ nanofibers annealed in air at 500°C for 4h.

Table 4.5. Grain size of annealed TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ nanofibers.

	TiO ₂	Ag _{0.5} /TiO ₂	Ag _{1.5} /TiO ₂	Ag ₃ /TiO ₂	BN ₃ -Ag ₃ /TiO ₂	BN ₅ -Ag ₃ /TiO ₂
Grain size (nm)	18.2	20.4	21.95	17.1	25.8	26.15

The formation of BN-Ag/TiO₂ composite nanofibers was further confirmed by Raman spectroscopy. The Raman peaks of all samples at 144 cm⁻¹ (E_g), 197 cm⁻¹ (E_g), 399 cm⁻¹ (B_{1g}), 513 cm⁻¹ (A_{1g}), 519 cm⁻¹ (B_{1g}) and 639 cm⁻¹ (E_g) corresponded to the pure anatase phase of

TiO₂ (Figure 4.4.A). [19] The main peak of TiO₂, located at 141 cm⁻¹, was shifted to a larger frequency after Ag and BN doping. This frequency shift could be attributed to the pressure effect induced by Ag particles and BN sheets that strongly affects the lattice vibrational characteristics of TiO₂ [20]. For BN-Ag/TiO₂ composite nanofibers, a Raman active mode located at ~ 1365 cm⁻¹ was identified and was due to hexagonal BN related to the E_{2g} mode (Figure 4.4.B) [21]. In addition, an increase in the intensity of the peak corresponding to hexagonal BN with the amount of doping could be clearly observed. No peak related to silver oxide was detected in the Raman and XRD spectra. This confirmed the thermal decomposition of AgNO₃ and the formation of Ag nanoparticles.

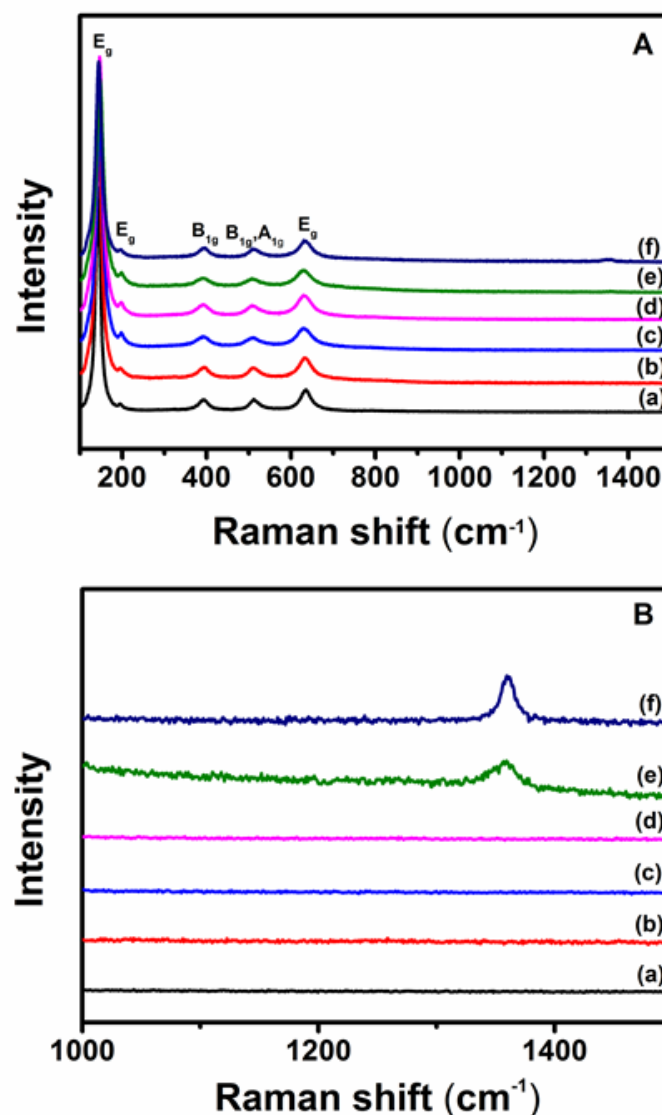


Figure 4.4. (A-B) Raman shifts of a) TiO₂, (b) Ag_{0.5}/TiO₂, (c) Ag_{1.5}/TiO₂, (d) Ag₃/TiO₂, (e) BN₃-Ag₃/TiO₂ and (f) BN₅-Ag₃/TiO₂ nanofibers annealed in air at 500°C for 4h.

4.2. Optical properties of TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers

Incorporation of AgNO₃ and BN nanosheets strongly influenced the optical properties of the produced nanofibers. The shift of TiO₂ absorption edges was clearly seen in the reflectance spectra of the different samples (Figure 4.5). The band gap values of pure TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers were calculated from the reflectance spectra using the Kubelka–Munk formula [22]:

$$F = \frac{(1-R)^2}{2R} \quad (\text{Equation 4})$$

$$(Fh\nu)^{1/2} \sim (h\nu - E_g) \quad (\text{Equation 5})$$

where F , R , $h\nu$ and E_g represent the Kubelka–Munk function, reflectance, photon energy and band gap, respectively. The E_g values were calculated from the intersection of the linear part of the curve with the $h\nu$ axis. The fitting was performed automatically using the Origin 9.0 software (Figure 4.5.B). Calculation of the photo-absorption edge wavelengths and band gap values (Figure 4.5 and Table 4.6) showed that, compared with pure TiO₂ nanofibers, the absorption edges of Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers were red-shifted (from 392 to 435 nm) and the band gap values decreased remarkably with the increase of the Ag amount (from 3.16 to 2.85 eV). According to previous studies, this red shift is due to the Ag content because BN has no absorbance edge in the visible range [23]. Ag₃/TiO₂, BN₃-Ag₃/TiO₂ and BN₅-Ag₃/TiO₂ composite nanofibers had the lowest band gap values. The decrease of TiO₂ band gap value with Ag doping can be explained by TiO₂ lattice changes and/or by the formation of shallow sites near the conductance band in TiO₂ band gap [24].

Table 4.6. Photo-absorption edge and band gap values of pure TiO₂ nanofibers, Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers.

Sample	Absorption edge (nm)	Band gap (eV)
TiO ₂	392	3.16
Ag0.5/TiO ₂	413	3.00

Ag1.5/TiO ₂	417	2.97
Ag3/TiO ₂	429	2.89
BN3-Ag3/TiO ₂	430	2.88
BN5-Ag3/TiO ₂	435	2.85

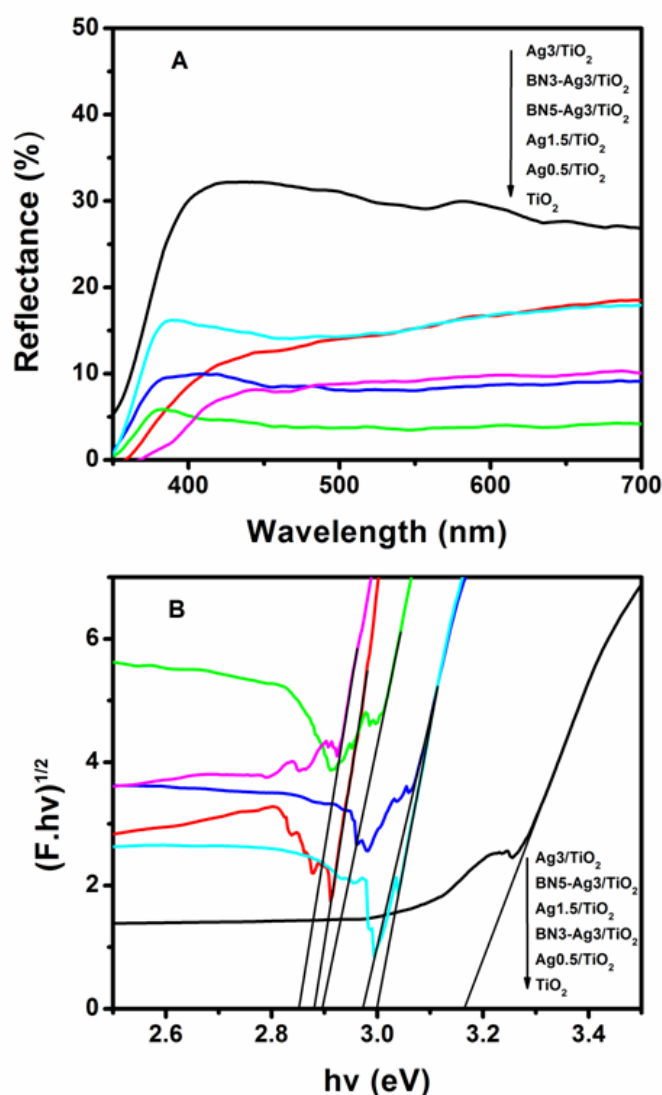


Figure 4.5. (A) Reflectance spectra and (B) Band gap calculation from the reflectance spectra of TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers.

As PL emission results from the recombination of free carriers, PL spectra have been used to investigate the efficiency of charge carrier trapping, migration and transfer in order

to understand the fate of electron–hole pairs in semiconductors.[14] In other words, a lower recombination rate or a higher transfer of electrons and holes can result in a lower PL intensity. Many studies have reported PL emissions of pure TiO₂ in photocatalysis research [25, 26]. The PL of BN/TiO₂ nanostructures was investigated for the first time by our group [27]. In this work, we report the PL emission spectra of BN-Ag/TiO₂ nanostructures. As photocatalytic activity improvement is based on the charge separation at the BN-Ag/TiO₂ interface, a lower electron–hole recombination rate in nanocomposites was expected. Consequently, the PL intensity in the BN-Ag/TiO₂ nanostructures should decrease. Analysis of the PL emission spectra of TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers with different Ag and BN sheets amounts (Figure 4.6) showed that pure TiO₂ nanofibers had high intensity and broad-band PL signals in the 400–700 nm region, which could be assigned to the radiative recombination of self-trapped excitons (STE) [14]. Ag and BN doping significantly reduced the PL intensities of all nanocomposites compared with pure TiO₂ nanofibers. Particularly, the Ag1.5/TiO₂, Ag3/TiO₂, BN3-Ag3/TiO₂ and BN5-Ag3/TiO₂ samples showed a very weak PL intensity, indicating that they might have the lowest photo-induced electron-hole recombination rate. XRD analysis showed that additional lattice strain appeared in the TiO₂ lattice after BN and Ag doping. This reduces STE formation on the TiO₆ octahedral and therefore, quenches their emission. PL intensity decrease can be mainly explained by the BN and Ag doping effect that leads to the formation of defects on the interface that provide non-radiative recombination and surface charge transfer.[28, 29] The surface charge separation between TiO₂ and BN is expected to improve the photocatalytic activities [27].

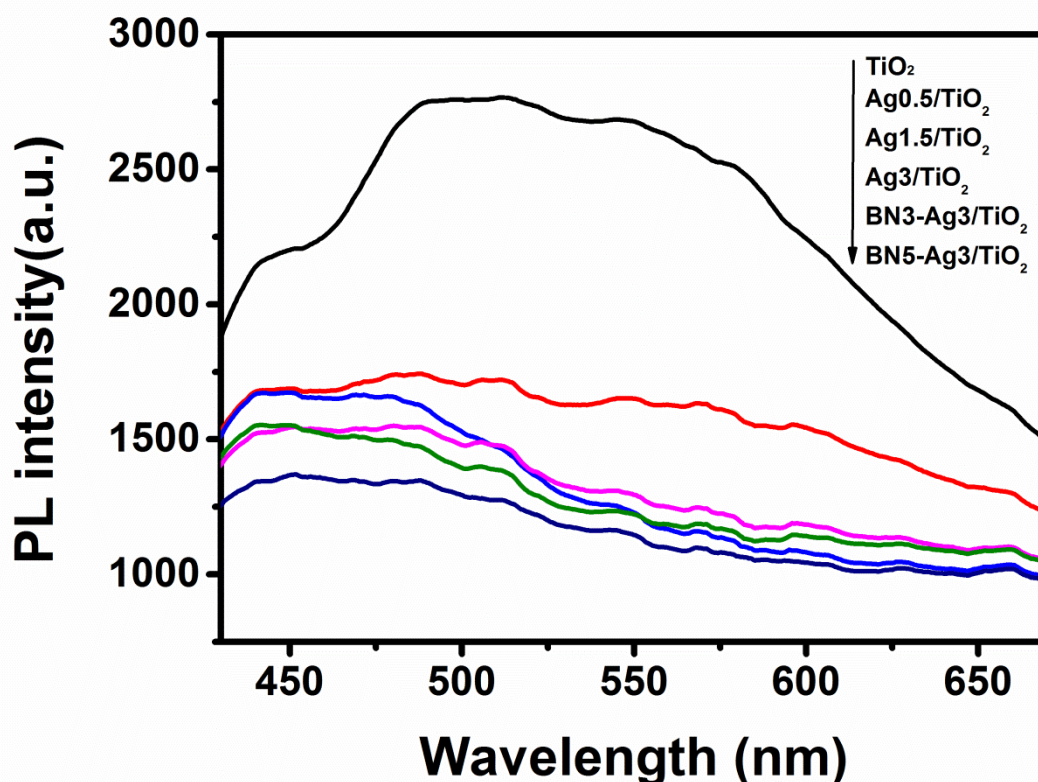


Figure 4.6. Photoluminescence spectra of pure TiO₂ nanofibers, and Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers.

4.3. Photocatalytic application

The photocatalytic degradation efficiency of MB by TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ nanofibers with different Ag and BN contents was assessed by calculating the UV–VIS absorbance spectra of the MB solutions (major absorption band around 664 nm) at different time points after exposure to light (0, 20, 40, 60, and 80 min) (Figure 4.7.A for BN5-Ag3/TiO₂). The results obtained with the different nanofibers (Figure 4.7.B) indicated that MB was stable and difficult to be photodegraded under visible light in the absence of photocatalyst. After 80 min of exposure to light, up to 25% of MB was degraded in the presence of pure TiO₂ nanofibers. We previously reported that due to its larger active surface area, the photocatalytic activity of TiO₂ nanofibers is higher than that of commercial TiO₂-P25.[11, 27] The percentage of degraded MB increased gradually with the Ag content: 62% with Ag0.5/TiO₂, 73% with Ag1.5/TiO₂, and 77% with Ag3/TiO₂. It is well accepted that the photocatalytic effect in solid-state catalysis is caused by the electron - hole pairs created from photon adsorption and interaction with molecules close to the catalyst

surface.[1] The observed degradation increase could be attributed to the deposition of Ag species onto the surface of TiO₂ nanofibers that can capture the photo-induced electrons and holes. In addition, photo-induced electrons can quickly transfer to the oxygen adsorbed on TiO₂ surface [28, 30]. The improved photocatalytic activity of Ag/TiO₂ composites under visible light compared with pure TiO₂ nanofibers could mainly be ascribed to the lower band gap value, as confirmed by the diffuse reflectance spectra. MB degradation efficiency further increased to 85% with BN3-Ag3/TiO₂ and to 98% with BN5-Ag3/TiO₂ composites. The higher photocatalytic activity of BN-Ag/TiO₂ compared with Ag/TiO₂ composites, with the same amount of Ag, is explained by the efficient electron transfer from photo-excited Ag/TiO₂ to the BN nanosheets of the plasmonic photocatalyst. The efficient charge transfer is related to the pronounced electrostatic interactions. The naturally negatively charged surface of BN sheets could lead to h⁺ transfer from the activated Ag/TiO₂ to the BN sheets when they are connected [31, 32]. Therefore, more photo-electrons are available, compared with Ag/TiO₂ samples, to take part in the photodegradation process, in agreement with the photoluminescence analysis.

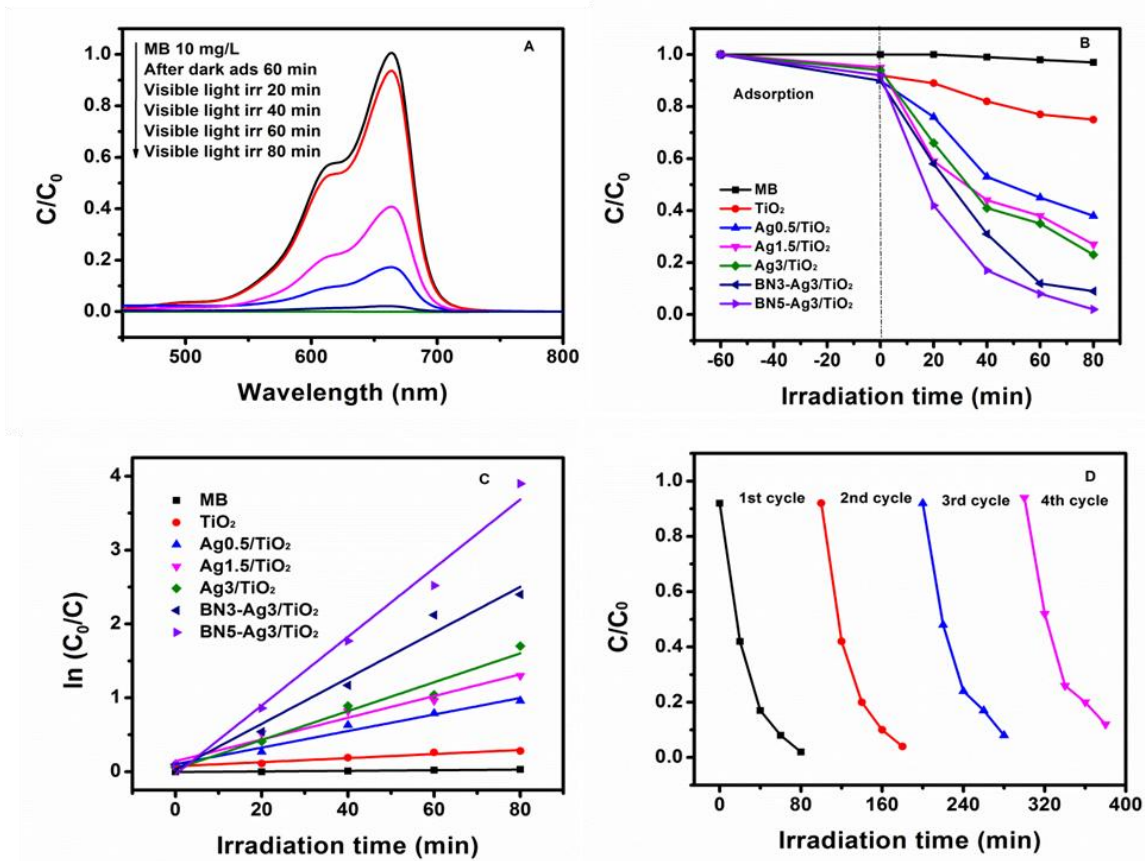


Figure 4.7. (A) Absorbance spectra of MB degradation in the presence of BN5-Ag3/TiO₂ composite nanofibers. (B) MB photodegradation by the TiO₂, Ag/TiO₂ and BN-Ag/TiO₂ photocatalysts under visible light. (C) Kinetics of MB degradation. (D) Long-term catalytic stability of BN5-Ag3/TiO₂ nanofibers in four repeated cycles of MB degradation under visible light.

The kinetic linear curves for all samples are shown in Figure 4.7.C. The photodegradation reactions followed a Langmuir–Hinshelwood first order kinetics model, as described by equation 6:

$$r = dC/dt = kKC/(1+KC) \quad (\text{Equation 6})$$

where r is MB degradation rate (mg (L min)^{-1}), C is the MB solution concentration (mg L^{-1}), t is the irradiation time, k is the reaction rate constant (mg (L min)^{-1}), and K is MB adsorption coefficient (mg L^{-1}). As the initial concentration ($C_0 = 10 \text{ mg L}^{-1}$) of the MB solutions was very low in the present experiments, the relationship between $\ln(C_0/C)$ and the reaction time t showed that MB decomposition with different photocatalysts agreed with a pseudo first-order kinetic:[33]

$$\ln(C_0/C) = kKt = k_a t \quad (\text{Equation 7})$$

where k_a was the apparent first-order rate constant (min^{-1}) and C the concentration at time t . The obtained k_a values from the linear dependence between $\ln(C_0/C)$ and time are reported in Table 4.7. The increasing order of the rate constants in the samples was: BN5-Ag3/TiO₂ > BN3-Ag3/TiO₂ > Ag3/TiO₂ > Ag1.5/TiO₂ > Ag0.5/TiO₂ > TiO₂ NFs > MB. The rate constant exhibited a maximum of 0.0465 min^{-1} for BN5-Ag3/TiO₂. This was 17.2 and 2.3 times higher than that of pure TiO₂ nanofibers and Ag3/TiO₂ composite nanofibers, respectively. Thus, compared with other samples, BN5-Ag3/TiO₂ nanocomposites showed the highest photocatalytic activity under visible light, which is represented by their larger k_a value. These results indicate that, compared with TiO₂ and Ag/TiO₂ nanofibers, the coupling effect between BN and Ag/TiO₂ greatly improves the photocatalytic activity under visible light.

Table 4.7. Kinetic parameters of the photocatalytic activities of pure TiO₂ nanofibers, and Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers.

	k_a (min^{-1})	R^2
MB	0.0004	0.9215
TiO₂	0.0027	0.9544
Ag0.5/TiO₂	0.0112	0.9707
Ag1.5/TiO₂	0.0147	0.9581
Ag3/TiO₂	0.0195	0.9622
BN3-Ag3/TiO₂	0.0309	0.9686
BN5-Ag3/TiO₂	0.0465	0.9819

The catalyst stability has always been the critical issue for long-term repeated use in practical applications [34]. Previous studies reported that TiO₂ nanofibers and Ag/TiO₂ composite nanofibers show high stability in photocatalytic repeatability experiments [28, 35]. Assessment of the photocatalytic activity repeatability in the same conditions showed

that MB degradation by BN5-Ag₃/TiO₂ composites remained high after four cycles (Figure 4.7.D). This indicates that BN5-Ag₃/TiO₂ is stable during the photocatalytic reaction. Also, the used nanofibers had the same light grey color as newly prepared samples. These results confirm that BN5-Ag₃/TiO₂ nanofibers have higher photodegradation efficiency compared with pure TiO₂ nanofibers and Ag/TiO₂ composites and long-term stability in photocatalytic activity repeatability tests. As the experimental conditions are different, the photocatalytic activities of BN5-Ag₃/TiO₂ composite nanofibers could be only broadly compared with those of previously described Ag/TiO₂ composites (Table 4.8). Nevertheless, BN5-Ag₃/TiO₂ composite nanofibers showed the best visible-light photocatalytic activity compared with the other Ag/TiO₂ composites [15, 28, 30, 36-39].

Table 4.8. Comparison of the photocatalytic activity of different Ag/TiO₂ nanocomposites.

Photocatalysts	Photocatalyst concentration in dye solution (g/L)	Irradiation light source	Time (min)	Degradation efficiency (%)	Ref.
Ag(NPs) /TiO ₂ -P25 composite	0.5	Visible (125 W)	180	86	[38]
Ag/TiO ₂ nanocomposites	–	Visible (500 W)	360	80	[39]
Ag/TiO ₂ Composite NFs	0.1	UV (1000 W)	20	100	[15]
Ag/TiO ₂ nanowires	0.6	UV (150 W)	80	100	[30]
Ag/TiO ₂ nanotubes	1	Visible (500 W)	240	100	[37]
Ag(NPs)/TiO ₂ nanofibers	1	UV (125 W)	60	98	[36]
Ag(NPs)/TiO ₂ nanofibers	1	Visible (150 W)	120	54	[36]
Ag-AgBr(NPs)/TiO ₂ nanofibers	1	Visible (150 W)	300	92	[28]
BN5-Ag ₃ /TiO ₂ composite NFs	0.4	Visible (150 W)	80	98	This work

4.4. Antibacterial properties

Besides their photocatalytic properties to degrade toxic organic compounds, BN-Ag/TiO₂ nanofibers should also have antibacterial effects. Antibacterial tests were carried out in liquid phase instead of using the disc diffusion method (agar phase) to favor contact [40] between *E. coli* bacteria and TiO₂ nanofibers and BN5-Ag₃/TiO₂ composites (under visible light and in the dark). Control reactions without nanofibers showed that bacteria remained viable for 3 hours in the tested conditions (Table 4.9). Similarly, pure TiO₂ nanofibers had no bactericidal or adsorption effect after 3 hours of contact time under visible light.[10] On the other hand, total *E. coli* removal (-8 log) was observed with BN5-Ag₃/TiO₂ under visible light, while in the dark no antibacterial activity was detected. This indicates that despite the Ag amount (3 wt. %) in the composite, Ag has no bactericidal effect. This can be explained by the fact that Ag is not deposited on the TiO₂ surface, but incorporated in the nanofibers, and thus cannot diffuse to the bacteria. By comparing the results obtained with BN5-Ag₃/TiO₂ under visible light and in the dark (Table 4.9), it can be concluded that BN sheets have no antibacterial effect in the tested conditions [41]. Therefore, the high antibacterial efficiency of BN5-Ag₃/TiO₂ composite nanofibers can be attributed to the stronger photocatalytic activity of TiO₂ under visible light due to Ag and BN doping, in agreement with the photocatalytic results. This study, thus, highlights the strong bactericidal activity of BN5-Ag₃/TiO₂ composite nanofibers under visible light. Moreover, the total removal of bacteria (Table 4.9) and MB (Figure 4.7) by BN5-Ag₃/TiO₂ under visible light demonstrates the good agreement between antibacterial activity and MB degradation.

Table 4.9. *E. coli* log-removal values after incubation with pure TiO₂ nanofibers or BN5-Ag₃/TiO₂ composite nanofibers at 20°C for 3 hours ($C_0 = 2.3 \pm 0.3 \times 10^8$ CFU.mL⁻¹).

Samples	Removal (Log-values)
Control (3h)	0 ± 1
Pure TiO ₂ (Light)	0 ± 1
BN5-Ag ₃ /TiO ₂ (Light)	-8 ± 1
BN5-Ag ₃ /TiO ₂ (Dark)	0 ± 1

5. Conclusion

This study shows that Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers with different amounts of Ag and BN nanosheets can be successfully prepared using the electrospinning technique. After annealing at 500°C, SEM images show an increase of the average diameter of the composite nanofibers compared with pure TiO₂ nanofibers. TEM images, EDX data and Raman spectra confirm the incorporation of Ag and BN nanosheets in TiO₂ nanofibers. BET measurements and XRD data show the higher specific surface area and grain size of BN-Ag/TiO₂ nanofibers compared with Ag/TiO₂ and TiO₂ nanofibers, respectively. The red shift of the absorbance edge and the decrease of the TiO₂ band gap value from 3.16 to 2.85 eV were confirmed by diffuse reflectance analysis. Ag/TiO₂ and BN-Ag/TiO₂ composites exhibit very weak photoluminescence intensity, and therefore low photo-induced electron-hole recombination compared with pure TiO₂ nanofibers. Moreover, Ag/TiO₂ composite nanofibers have significantly enhanced photocatalytic activity when mixed with BN nanosheets. This higher activity is due to the efficient electron transfer from photo-excited Ag/TiO₂ to BN nanosheets to retard TiO₂ charge recombination. MB degradation efficiency with BN5-Ag3/TiO₂ as catalyst is 17.2 and 2.3 times higher than that of pure TiO₂ nanofibers and Ag3/TiO₂ composites, respectively. Moreover, photocatalytic activity repeatability experiments confirmed the long-term stability of BN5-Ag3/TiO₂ composite nanofibers for MB photodegradation. Antibacterial tests showed that BN5-Ag3/TiO₂ composite nanofibers can kill *E. coli* cultures under visible light, indicating that this effect is related to the enhanced TiO₂ photocatalytic activity upon doping with BN and Ag. In conclusion, the multifunctional BN5-Ag3/TiO₂ composites display photodegradation and antibacterial applications. TiO₂-based photocatalysts doped with Ag and BN nanosheets can be considered as efficient and long-term stable antibacterial materials for biomedical use and water disinfection.

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Chapter 5: Optical and structural properties of Al₂O₃ doped ZnO nanotubes by ALD and their photocatalytic application

Table of Contents

1. Abstract.....	143
2. Introduction.....	143
3. Experimental section.....	144
3.1. Chemicals and materials.....	144
3.2. Preparation of PAN nanofibers.....	144
3.3. ALD sequences.....	145
3.4. Chemical and structural characterization.....	146
3.5. Measurement of photocatalytic activity.....	146
4. Results and discussion.....	147
4.1. Morphological and Structural properties of ZnO and Al ₂ O ₃ /ZnO nanotubes.....	147
4.2. Optical properties of ZnO and Al ₂ O ₃ /ZnO nanotubes.....	150
4.3. Photocatalytic activity.....	156
5. Conclusion.....	158

1. Abstract

Al₂O₃ doped ZnO nanotubes with controlled ratio of Al₂O₃ were successfully designed by combining the two techniques of atomic layer deposition (ALD) and electrospinning. In order to study the effect of Al₂O₃ doping on optical and structural properties of Al₂O₃ doped ZnO nanotubes, the prepared samples were analyzed by scanning electron microscopy (SEM), X-ray diffraction (XRD), energy-dispersive X-ray spectroscopy (EDX), Fourier-transform infrared (FTIR), reflectance emission and room temperature photoluminescence (PL). The photocatalytic activity of these materials under UV light was studied by the photodegradation of methyl orange (MO). The results indicate that Al₂O₃ doping increases the disorder (defects and oxygen vacancies formation) in the ZnO nanostructure which improves the separation efficiency of electron-hole pairs and therefore enhances the photocatalytic activity (5 times higher) of Al₂O₃ doped ZnO in comparison to pure ZnO nanotubes.

2. Introduction

This chapter focused on the synthesis of ZnO and Al₂O₃ /ZnO nanotubes by combining the two techniques electrospinning and atomic layer deposition (ALD). The morphological, structural and optical properties were analyzed with different characterization techniques. Different parameters have been calculated such as nanofibers' average diameter, grain size, lattice constants, interplane distance, strain values, Urbach energy and band gap. After evaluating the photocatalytic activity of the nanotubes under UV light, the impact of the optical properties on the photocatalytic activity was analyzed.

The green technology, "photocatalysis", is one of the less expensive and more efficient methods for wastewater treatment. In recent years, the attention of the researchers has been given to the semiconducting oxide photocatalysts due to their potential applications in solar energy conversion[1] and environmental purification [2]. Zinc oxide (ZnO) with a wide band gap (3.3 eV) is one of the most effective photocatalysts under UV light due to its high activity, low cost and environmental safety [3]. However, the fast electron-hole pairs' recombination in ZnO limits the high efficiency of the photocatalytic reaction [4]. In previous studies, many efforts have been developed to improve the separation efficiency of the photogenerated pairs, including doping ZnO with other oxides

(In₂O₃, SnO₂, NiO ...).[5-7] It is well known that doping ZnO with Aluminum oxide (Al₂O₃) improves its optical and structural properties which will influence its photocatalytic activity [8]. Therefore, in order to study the effect of the optical properties on the photocatalytic activity, Al₂O₃ doped ZnO nanotubes were synthesized by combining the two techniques of Atomic Layer Deposition (ALD) and Electrospinning. ALD is a unique and powerful vapor-phase deposition technique to fabricate different oxides materials. The ALD technique ensures a precise thickness control, chemical composition, high quality conformal and homogenous deposited layers [9]. Electrospinning is a simple and cost effective technique that took much attention because of its capability in generating large amounts of nanofibers with the use of high electrical field [10]. In the present work, as a first step, PAN nanofibers were synthesized by electrospinning technique [11]. The second step is metal oxides deposition by ALD [12]. After the heat treatment, the prepared samples were characterized in order to study their structural, morphological and optical properties. The photodegradation of methyl orange under UV was investigated to study the photocatalytic activity of the ZnO and Al₂O₃/ZnO nanotubes.

3. Experimental section

3.1. Chemicals and materials

Diethyl zinc {(DEZ), Zn (CH₂CH₃)₂, 95%} and trimethylaluminum {(TMA), Al (CH₃)₃, 97%} were used as precursors for ZnO and Al₂O₃ respectively. N,N-dimethylformamide (DMF; 99.8%) and polyacrylonitrile (PAN; MW = 500 000) were used to elaborate PAN nanofibers. Methyl orange (MO) was used as a pollutant to evaluate the photocatalytic activity of the samples. All chemicals were purchased from Sigma Aldrich and used without any further purification.

3.2. Preparation of PAN nanofibers

The electrospinning process was used to synthesize PAN nanofibers. The polymer solution was prepared by dissolving 10 wt% of polyacrylonitrile in dimethylformamide. The mixture was maintained under agitation for 4 hours and then was loaded into a plastic syringe having a stainless steel needle with a diameter of 0.7 mm. The electrospinning process was performed at 38 ± 5°C with an applied voltage of 25 kV. The flow rate was fixed at 1 ml.h⁻¹ and the distance between the tip of the needle and the aluminum foil was

maintained at 20 cm. Nanofibers were collected on a rotating coil covered with an aluminum foil with a rotation speed of 400 rpm.

3.3. ALD sequences

A homemade ALD reactor was used for the synthesis of ZnO and Al₂O₃/ZnO nanotubes. All the ALD depositions were performed at 60°C using the following sequence mentioned in Table 5.1. The precursor pulses were coupled with 25 sccm Ar flow as a gas vector; purge was performed with 100 sccm Ar flow as a gas vector. PAN nanofibers were heated at 500°C after the ALD deposition with a heating rate of 1°C.min⁻¹ for 8 hours in air to eliminate the core of carbon in order to obtain ZnO and Al₂O₃/ZnO nanotubes. As shown in Table 5.2, Al₂O₃ doped ZnO nanotubes with different ratios of Zn/Al were obtained by alternating the deposition sequences of Al₂O₃ and ZnO cycles on the PAN nanofibers.

Table 5.1. Step time investigation of Al₂O₃ and ZnO deposition on PAN nanofibers.

	Pulse	Exposure	Purge	Water Pulse	Exposure	Purge
Time	Al₂O₃ (TMA)					
	0.2s	30s	40s	2s	30s	40s
	ZnO (DEZ)					
	0.4s	20s	40s	2s	30s	40s

Table 5.2. Deposition sequences of Al₂O₃ and ZnO cycles on the PAN nanofibers.

Samples	Deposition sequences		
	ZnO cycle	Al ₂ O ₃ cycle	Repetition
ZnO	1	0	100
Al ₂ O ₃ /ZnO (5 wt%)	20	1	5
Al ₂ O ₃ /ZnO (10 wt%)	10	1	10

Al ₂ O ₃ /ZnO (20 wt%)	5	1	20
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3.4. Chemical and structural characterization

Scanning electron microscopy (SEM) images were taken with a Hitachi S4800, Japan. Energy-dispersive X-ray spectroscopy analyses (EDX) were taken with a Zeiss EVO HD15 microscope coupled with an Oxford X-MaxN EDX detector. X-ray diffraction (XRD) measurements were carried out using a PANalytical Xpert-PRO diffractometer equipped with an X'celerator detector using Ni-filtered Cu-radiation ($\lambda = 1.54 \text{ \AA}$). Optical properties were analyzed by diffuse reflectance (Shimadzu UV-3600). Photoluminescence (PL) spectra of Al₂O₃/ZnO nanotubes were measured in the range of 350-850 nm using HR2000+ Ocean Optics spectrometer (USA). Excitation of photoluminescence was performed by nitrogen laser LGI (Russia) ($\lambda = 337 \text{ nm}$, output power 2.5 mW, 100 Hz).

3.5. Measurement of photocatalytic activity

The photocatalytic activity of ZnO and Al₂O₃ doped ZnO nanotubes was evaluated by the degradation of methyl orange (MO) solution under UV light irradiation (obtained from a 400 W light source, emission wavelength < 380 nm). The reaction temperature was kept constant at $25 \pm 2^\circ\text{C}$ by circulating water in a cylindrical tube surrounding the photo-reactor during the entire experiment. MO was used as a reference for organic pollutants. The decomposition was carried out in several beakers containing a suspension of 10 mg from each photocatalyst and 25 mL of MO solution ($20 \text{ mg}\cdot\text{L}^{-1}$). Prior to light irradiation, the suspension was stirred for 1 h in the dark to obtain a good dispersion and to reach the adsorption-desorption equilibrium. Then, the solution was irradiated with UV light for 45 minutes. The distance between the lamp and the dye solution was maintained at 10 cm. Every 15 min, 3 ml of the sample solution was taken out and centrifuged to remove the catalyst. The centrifuged solutions were analyzed by a UV-VIS spectrometer in order to evaluate the decrease in the dye concentration. After irradiation, the photocatalytic degradation efficiency percentage has been calculated as follow [13]:

$$\text{Degradation efficiency (\%)} = (C_0 - C) / C_0 \times 100 \quad (\text{Equation 1})$$

Where C_0 is the initial concentration and C is the final concentration of dye before and after photo-irradiation respectively.

4. Results and discussion

4.1. Morphological and Structural properties of ZnO and Al₂O₃/ZnO nanotubes

The nanotubes of ZnO and Al₂O₃ doped ZnO were elaborated by combining the two techniques: Electrospinning and ALD. After the heat treatment, the morphological properties of the as-prepared samples were analyzed by scanning electron microscopy. The SEM images in Figure 5.1 show the well-defined nanotubes morphology of ZnO, Al₂O₃/ZnO (5 wt%), Al₂O₃/ZnO (10 wt%) and Al₂O₃/ZnO (20 wt%). The average diameter was measured on 100 randomly chosen nanotubes of each sample. The diameters were measured from the SEM images using image analysis software (Image J1.29X). No significant changes were detected in the average diameter of the prepared nanotubes; the obtained value was 300 ± 20 nm for all samples. EDX data of ZnO and Al₂O₃/ZnO nanotubes reported in table 5.3 show the presence of the three elements Zn, Al and O without detection of any impurities. In addition, the increase of the atomic percentage of Al with the doping amount of Al₂O₃ can be clearly seen from table 5.3.

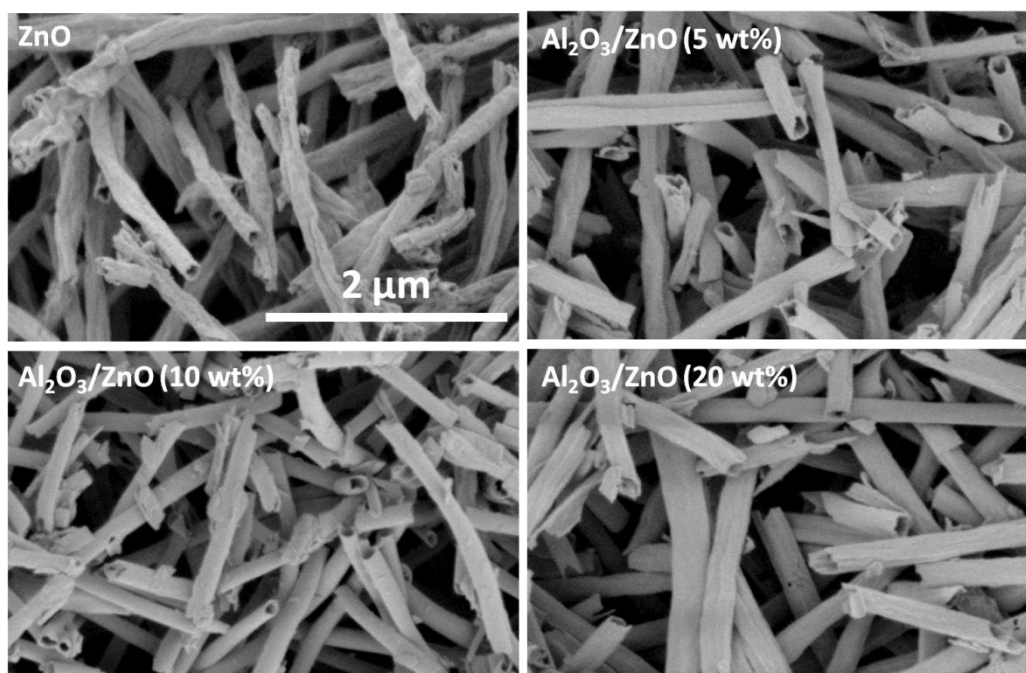


Figure 5.1. Scanning Electron Microscope images of ZnO and Al₂O₃ doped ZnO annealed nanotubes in air for 8h at 500°C.

Table 5.3. EDX data showing the atomic percentage composition of ZnO and Al₂O₃/ZnO prepared samples.

Samples	Atomic percentage		
	Zn	Al	O
ZnO	48.24	-	51.76
Al ₂ O ₃ /ZnO (5 wt%)	48.92	3.70	47.37
Al ₂ O ₃ /ZnO (10 wt%)	36.66	7.98	55.35
Al ₂ O ₃ /ZnO (20 wt%)	36.34	13.62	50.03

The XRD patterns of the prepared samples presented in Figure 5.2 show the diffraction peaks of the hexagonal wurtzite crystalline phase of zinc oxide (100), (002), (101), (102), (110), (103), (200), (112) and (201) corresponding to $2\theta = 31.7^\circ, 34.4^\circ, 36.2^\circ, 47.5^\circ, 56.5^\circ, 62.8^\circ, 66.3^\circ, 67.9^\circ$ and 69.0° , respectively.[14] The peak shift towards higher values of 2θ and the peak widening were observed with the increase of Al₂O₃ concentration. Lattice

constants (a and c), and interplane distances (d) were calculated from XRD data (Table 5.4). The increase of Al₂O₃ concentration results in a decrease of the lattice constants and interplane distances. The mechanism of these structural changes is related to the substitution of Zn²⁺ ions with Al³⁺ ions. As the radius of Al³⁺ ion (0.053 nm) is much lower than the radius of Zn²⁺ ion (0.074 nm), a decrease of lattice constants is expected with an increase of Al₂O₃ dopant concentration [15]. The average grain size D (nm) was calculated using Debye-Scherrer equation [16]:

$$D = k\lambda/\beta\cos\theta \quad (\text{Equation 2})$$

where k is the shape factor constant (0.9), λ is the X-ray wavelength (0.154 nm), β is the line broadening of the diffraction line measured by the full width at half maximum of the peak intensity (FWHM) and θ is the Bragg angle (in degrees). The obtained grain size values were 16 nm, 10 nm, 9 nm and 9 nm for ZnO, Al₂O₃/ZnO (5 wt%), Al₂O₃/ZnO (10 wt%) and Al₂O₃/ZnO (20 wt%), respectively. The decrease of the crystalline structure of ZnO with Al₂O₃ doping amount is due to the amorphous state of Al₂O₃. Thus, the growth of ZnO crystals is stopped by the amorphous Al₂O₃ layers. [8] Strain values (ϵ) were calculated due to the following equation:

$$\epsilon = \beta/4\tan(\theta) \quad (\text{Equation 3})$$

where θ and β are diffraction angle and full width of half maximum, respectively. The obtained strain values were 0.0068, 0.01, 0.011 and 0.012 for ZnO, Al₂O₃/ZnO (5 wt%), Al₂O₃/ZnO (10 wt%) and Al₂O₃/ZnO (20 wt%), respectively.

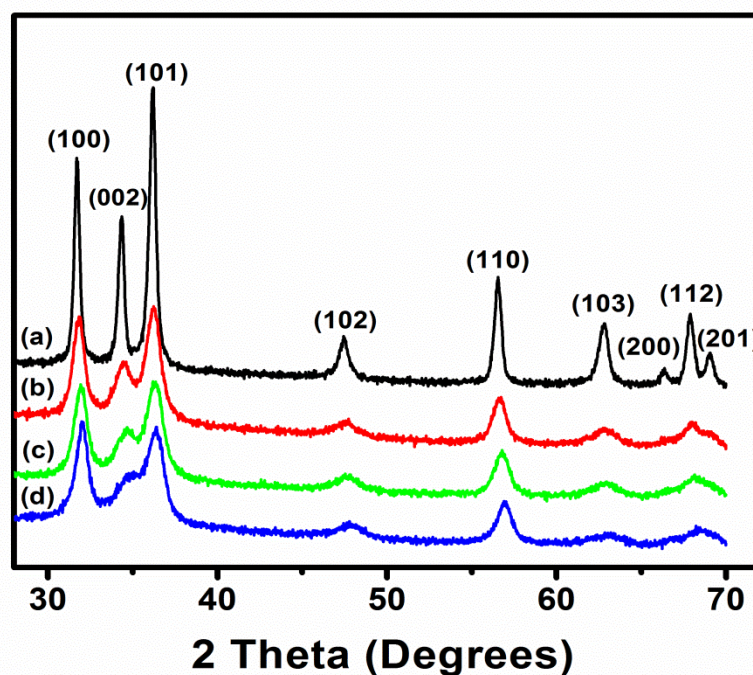


Figure 5.2. XRD spectra of (a) ZnO, (b) Al₂O₃/ZnO (5 wt%), (c) Al₂O₃/ZnO (10 wt%) and (d) Al₂O₃/ZnO (20 wt%) annealed nanotubes.

Table 5.4. Lattice constants and interplane distances of the prepared nanotubes.

	a (nm)	c (nm)	d (100)	d (002)	d (101)
ZnO	0.325	0.521	0.282	0.261	0.248
Al₂O₃/ZnO (5 wt%)	0.324	0.519	0.281	0.260	0.247
Al₂O₃/ZnO (10 wt%)	0.323	0.517	0.280	0.258	0.246
Al₂O₃/ZnO (20 wt%)	0.322	0.516	0.279	0.258	0.245

4.2. Optical properties of ZnO and Al₂O₃/ZnO nanotubes

Reflectance spectra of ZnO and Al₂O₃/ZnO nanotubes samples are shown in Figure 5.3. A blue shift of the absorption edge of Al₂O₃/ZnO samples was found with the increase of Al₂O₃ doping concentration compared to ZnO nanotubes. Band gap energies of the samples were calculated from the reflectance spectra:[9]

$$(Fhv)^2 \sim (E_g - hv) \quad (\text{Equation 4})$$

where hv and E_g are the photon energy and the band gap, respectively. Parameter F , related to the absorption coefficient of the sample, was calculated as follow:[9]

$$F = \frac{(1-R)^2}{2R} \quad (\text{Equation 5})$$

where R is diffuse reflectance of the sample. The calculated band gap values are shown in Table 5.5. The increase of band gap of Al₂O₃/ZnO samples was observed with the increase of Al₂O₃ dopant amount. Previously, we have reported on optical properties of Al₂O₃/ZnO nanolaminates [17]. It was shown that Al₂O₃ sublayers changed the growth of ZnO nanolayers. Analysis of XRD and optical constants (refractive index and extinction coefficient) showed that Al₂O₃ do not dope ZnO during the growth. The blue shift of the band gap was supposedly due to the quantum confinement effect. In the present work, doping of ZnO with Al₂O₃ was proved by XRD data. The obtained grain size values are much higher than Bohr radius for ZnO (2.37 nm). Therefore, the blue shifted band gap value is due to Burstein-Moss effect [18]. The band gap of Al₂O₃/ZnO nanotubes (E_g) depends on the concentration of free electrons (n) as follow [15]:

$$E_g = E_{g0} + \frac{h^2}{8 \cdot m^*} \cdot \left(\frac{3}{\pi}\right)^{2/3} \cdot n^{2/3} \quad (\text{Equation 6})$$

where, E_{g0} , h and m^* are the band gap of undoped ZnO nanotubes, the Plank's constant and the effective mass of electron, respectively. The obtained dependence of n vs Al₂O₃ dopant concentration is plotted in Figure 5.4. The concentration of free electrons linearly increased with Al₂O₃ doping. Therefore more electrons are available to take part in the photodegradation process compared to pure ZnO nanotubes. Urbach tail energy is an important parameter, which can assist the analysis of disorder in metal oxide nanostructure. It can be calculated from absorption spectrum using the following equation [17]:

$$F = F_0 \cdot e^{\frac{hv-E_0}{E_u}} \quad (\text{Equation 7})$$

F_0 and E_0 are specific parameters of the material; hv and E_u are the photon energy and Urbach energy, respectively. Parameter F was calculated using equation 7. The obtained E_u values are plotted in Figure 5.4. The increase of Al₂O₃ dopant concentration resulted in an

increase of E_u , which can be related to the formation of defect states in the band gap of ZnO (Al^{3+} states, zinc interstitials, zinc vacancies ...). From the obtained results, the photocatalytic activity under UV irradiation of Al₂O₃ doped ZnO is expected to be enhanced compared to pure ZnO nanotubes.

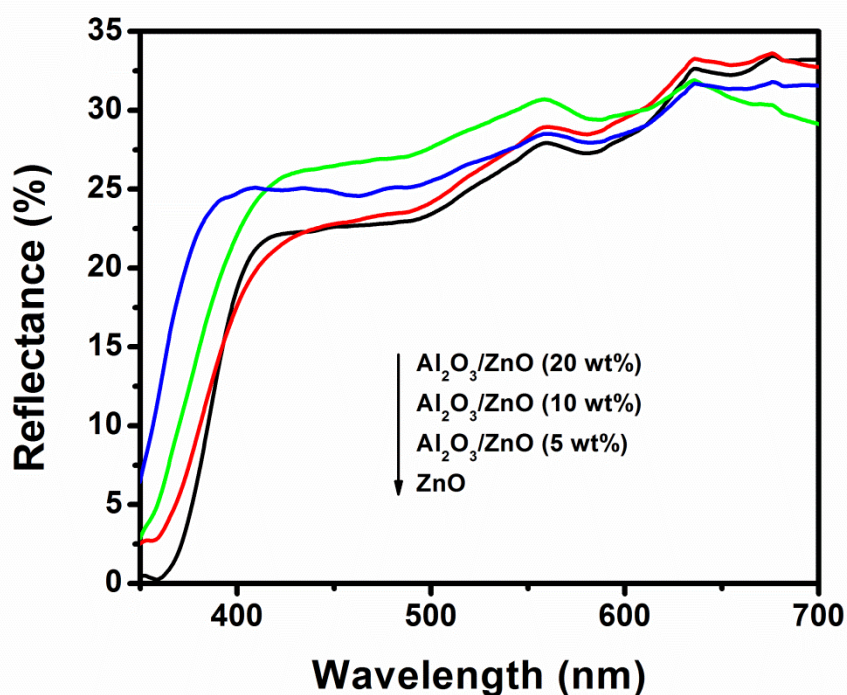


Figure 5.3. Reflectance spectra of ZnO, Al₂O₃/ZnO (5 wt%), Al₂O₃/ZnO (10 wt%) and Al₂O₃/ZnO (20 wt%) nanotubes.

Table 5.5. Band gap energies of ZnO and Al₂O₃/ZnO nanotubes.

Nanotubes	ZnO	Al ₂ O ₃ /ZnO (5 wt%)	Al ₂ O ₃ /ZnO (10 wt%)	Al ₂ O ₃ /ZnO (20 wt%)
E_g (eV)	3.18	3.24	3.31	3.42

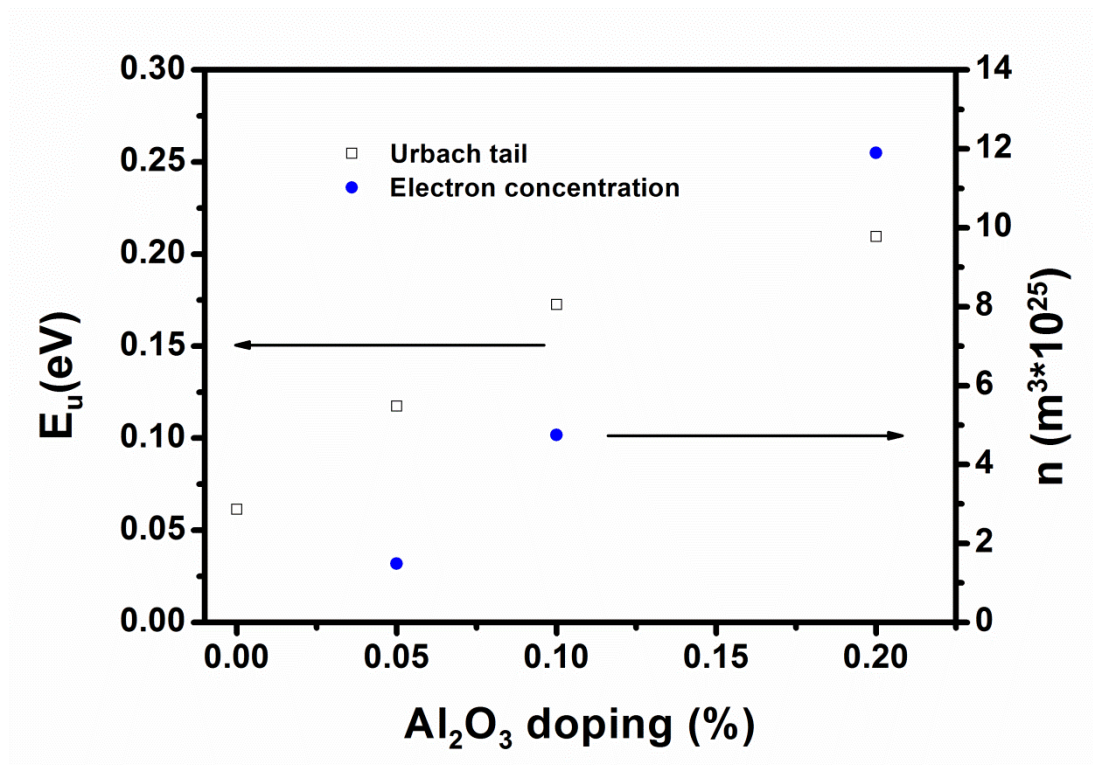


Figure 5.4. Evaluation of Urbach tail and free electron concentration with Al₂O₃ doping amounts.

Photoluminescence spectra of ZnO and Al₂O₃/ZnO nanotubes are shown in Figure 5.5. ZnO nanotubes showed PL spectrum with two emission bands in UV and Visible regions, centred at 385 and 570 nm, respectively. Al₂O₃ doped ZnO resulted in a change of the PL spectra. The wide emission bands were found at 420-440 nm and 490-560 nm for doped ZnO nanotubes with different concentration of Al₂O₃. Deconvolution of the PL spectra was performed with Gauss fitting using Origin software and the calculated peak positions are summarized in Table 5.6. For undoped ZnO, the PL peaks correspond to exciton emission (385 nm), shallow defects (406 nm), oxygen vacancies (502 and 550 nm) and oxygen interstitials (621 nm) [19]. PL spectra of Al₂O₃/ZnO drastically depend on Al₂O₃ dopant concentration. At low doping concentration (5 wt%) a new peak related to Zn interstitials was observed at 416 nm. PL peaks in the range of 425-436 nm could correspond to Zn vacancies. PL peaks in the range of 470-595 nm correspond to oxygen vacancies with different charge states (neutral, single and double ionized). PL peaks in the range of 630-710 nm correspond to donor-acceptor pairs, formed by Al³⁺ donor level and acceptor sites.[20, 21] As shown in Figure 5.5, PL spectra shift towards IR region when Al₂O₃ dopant amount

increases. It was shown that Al₂O₃ dopant induced compressive strain and therefore defect formation. Oxygen vacancies are mostly formed within Al₂O₃ doping as discussed by Jule et al. [20] Therefore, IR shift of PL for highly doped ZnO is related to oxygen vacancies. Appearance of new peaks in the region of 634-710 could be due to the optical transitions between Al³⁺ donor sites and ionized oxygen vacancies.

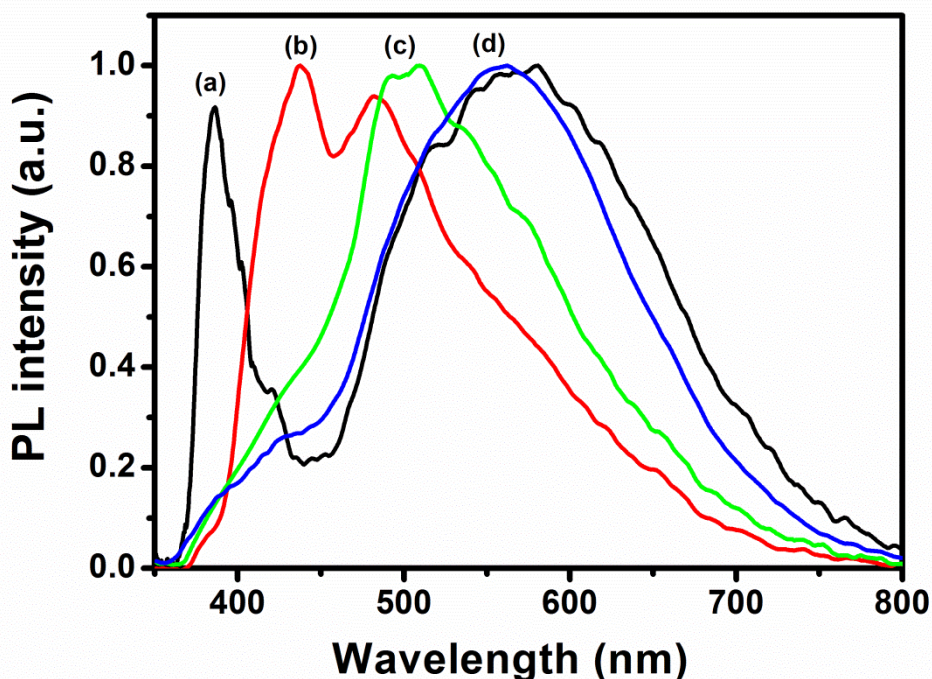


Figure 5.5. Photoluminescence spectra of (a) ZnO, (b) Al₂O₃/ZnO (5 wt %), (c) Al₂O₃/ZnO (10 wt%) and (d) Al₂O₃/ZnO (20 wt%) nanotubes.

Table 5.6. Peak positions of ZnO and Al₂O₃/ZnO nanotubes with different Al₂O₃ amounts.

	ZnO	Al ₂ O ₃ /ZnO (5 wt%)	Al ₂ O ₃ /ZnO (10 wt%)	Al ₂ O ₃ /ZnO (20 wt%)
Peak positions (nm)	385	416	434	425
	406	439	496	498
	502	475	536	546

550	521	560	595
621	604	634	653
-	-	709	680

The infrared spectrum of Al₂O₃ doped ZnO with different amounts of Al₂O₃ in the range 400–3500 cm⁻¹ are represented in Figure 5.6. The FTIR analysis allows us to observe two bands around 656 cm⁻¹ and 715 cm⁻¹. The first one can be assigned to the Al-O stretching mode in octahedral structure and the second one corresponds to the tetrahedral Al-O bonds.[22] As we can note, the intensity of these bands is slightly increasing with Al₂O₃ amount deposited by ALD. Thus, the presence of Al₂O₃ phase in the prepared samples was detected as well by IR spectroscopy.

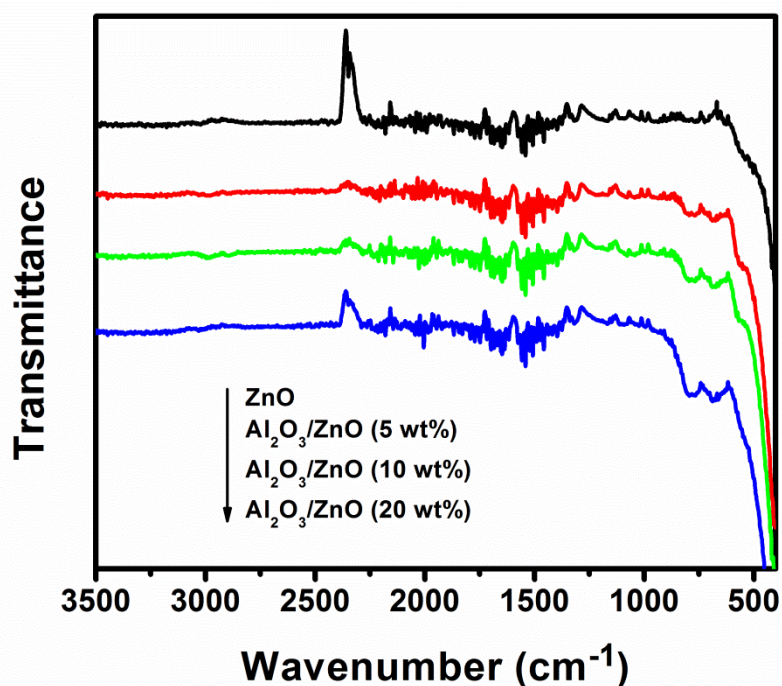


Figure 5.6. FTIR spectra of ZnO, Al₂O₃/ZnO (5 wt%), Al₂O₃/ZnO (10 wt%) and Al₂O₃/ZnO (20 wt%) nanotubes.

4.3. Photocatalytic activity

To evaluate the photodegradation efficiency of the as prepared samples under UV light (< 380 nm), MO (major absorption band around 462 nm) was selected as model pollutant. Figure 5.7 shows the photodegradation curves of MB after 45 minutes with ZnO and Al₂O₃/ZnO nanotubes as catalysts. As results, it was found that in the absence of photocatalysts, MB was stable and difficult to be photodegraded under UV light. Under identical experimental conditions, the photodegradation percentages of Methylene blue were 57%, 80%, 89% and 98% in the presence of ZnO, Al₂O₃/ZnO (5 wt%), Al₂O₃/ZnO (10 wt%) and Al₂O₃/ZnO (20 wt%) nanotubes, respectively. As confirmed above by optical and structural analysis, the concentration of free electrons and the defects formation linearly increased with Al₂O₃ doping amount, thus the recombination of electron-hole pairs decreased. Therefore, the photodegradation activity of Al₂O₃/ZnO under UV light is increased with Al₂O₃ doping concentration. As shown in Figure 5.8, the photocatalytic reactions follow a Langmuir–Hinshelwood first order kinetics model [23]:

$$r = dC/dt = kKC/(1+KC) \quad (\text{Equation 8})$$

where r , C , t , k and K are the degradation rate of MB (mg (L min)^{-1}), the concentration of the MB solution (mg L^{-1}), the irradiation time, the reaction rate constant (mg (L min)^{-1}), and the adsorption coefficient of MB (mg L^{-1}), respectively. The relationship between $\ln(C_0/C)$ and reaction time t is presented as follow:

$$\ln (C_0/C) = kKt = k_a t \quad (\text{Equation 9})$$

where k_a and C are the apparent first-order rate constant (min^{-1}) and the concentration at time t , respectively. The k_a and R square value are reported in Table 5.7. The maximum rate constant (0.0884 min^{-1}) correspond to Al₂O₃/ZnO (20 wt%) sample which is 5, 3 and 2 times higher than that of pure ZnO, Al₂O₃/ZnO (5 wt%) and Al₂O₃/ZnO (10 wt%), respectively. Thus the Al₂O₃ doping effect improves the photocatalytic activity of ZnO under UV light.

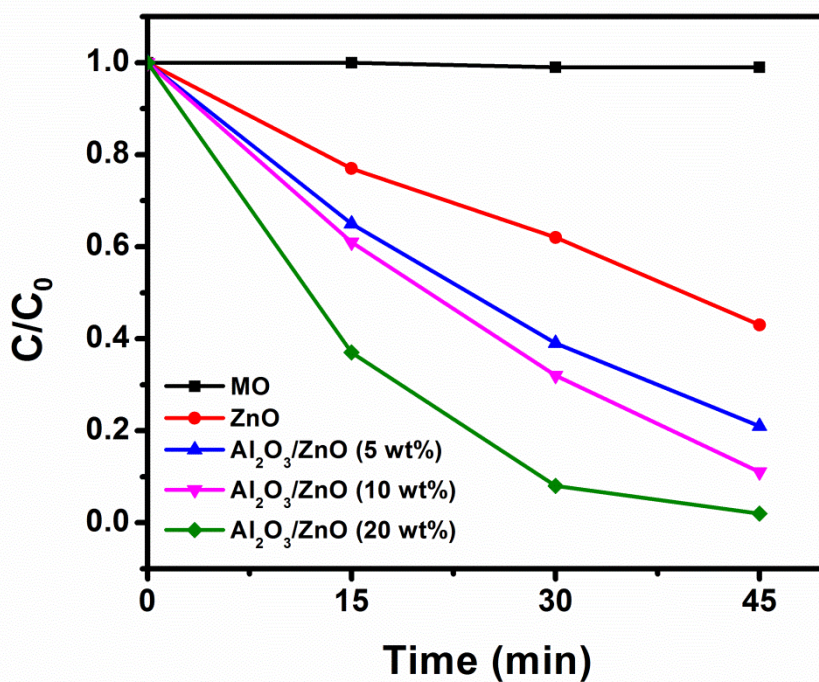


Figure 5.7. Photodegradation of MO by ZnO, Al₂O₃/ZnO (5 wt%), Al₂O₃/ZnO (10 wt%) and Al₂O₃/ZnO (20 wt%) photocatalysts under UV light.

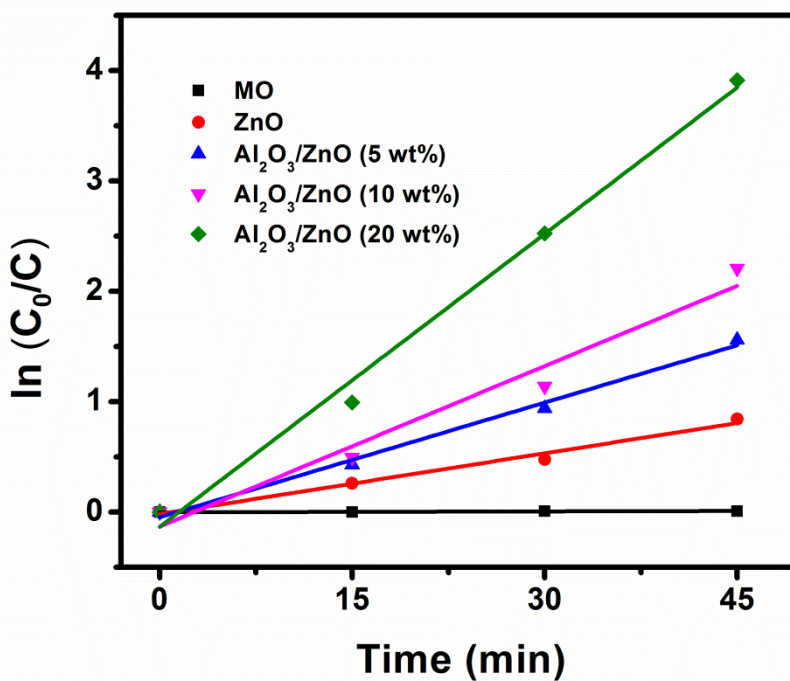


Figure 5.8. Kinetics of methyl orange degradation by the prepared samples.

Table 5.7. Kinetic parameters of ZnO and Al₂O₃/ZnO nanotubes.

	k_a (min ⁻¹)	R ²
MO	0.0002	0.9428
ZnO	0.0183	0.9819
Al₂O₃/ZnO (5 wt%)	0.0346	0.9901
Al₂O₃/ZnO (10 wt%)	0.0484	0.9527
Al₂O₃/ZnO (20 wt%)	0.0884	0.9895

5. Conclusion

ZnO and Al₂O₃/ZnO nanotubes with controlled doping ratio of Al₂O₃ are successfully prepared by electrospinning and atomic layer deposition techniques. All prepared samples were annealed at 500°C in air. After calcination, SEM images showed the nanotubes' morphology of ZnO and Al₂O₃/ZnO samples. EDX data confirmed the increase of Al atomic percentage with the increasing of Al₂O₃ doping amount. The decrease of the crystalline structure due to the amorphous structure of Al₂O₃ and the increase of the strain values with Al₂O₃ doping concentration were detected from XRD data. The blue shift of Al₂O₃/ZnO band gap value due to the Burstein-Moss effect and the defect formation was confirmed by diffuse reflectance analysis. PL spectra analysis revealed that oxygen vacancies results in the IR shift of doped ZnO nanotubes. The photocatalytic degradation of methyl orange under UV light by Al₂O₃/ZnO (20 wt%) was 5 times higher than that of ZnO nanotubes. In conclusion, the defects formation and oxygen vacancies due to Al₂O₃ doping increase the charge separation efficiency of ZnO, thus enhancing its photoactivity under UV light. Therefore, the photocatalytic activity is greatly depending on the optical and structural properties of the material. The ability to tune the optical and structural properties of our synthesized materials could be promising in different applications such as the production of optical sensors and biosensors [24-27].

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Chapter 6: Synthesis of Novel ZnO/ZnAl₂O₄ Multi Co-Centric Nanotubes and their Photocatalytic Application

Table of Contents

1. Abstract.....	163
2. Introduction.....	163
3. Experimental Section.....	164
3.1. Chemicals and Materials.....	164
3.2. Preparation of PAN nanofibers.....	164
3.3. ALD sequences.....	165
3.4. Chemical and Structural Characterization.....	166
3.5. Photocatalytic activity measurement.....	166
4. Results and discussion.....	167
4.1. Morphological, Structural and Optical properties of ZnO/ZnAl ₂ O ₄ multi co-centric nanotubes.....	167
4.3. Photocatalytic degradation of methyl orange by multi co-centric nanotubes of ZnO/ZnAl ₂ O ₄	176
5. Conclusion.....	181

1. Abstract

Based on the Kirkendall effect, novel double, triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ have been successfully fabricated by combining the two techniques of Electrospinning and Atomic Layer Deposition. The as-prepared samples were annealed at 900°C under air. Their morphological, structural and optical properties were studied by Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Energy-Dispersive X-ray spectroscopy (EDX), UV-Visible spectrophotometry and Raman spectroscopy. The performances and long-term stability of these multi co-centric nanotubes for photocatalytic applications have been evaluated under the same conditions. As result, the triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ exhibit a higher activity (94% and 99%, respectively) compared to the pure ZnO reported in previous studies (28%) in the photodegradation of methyl orange (MO) under UV irradiation. Thus, the fact of coupling these two semiconductors ensured a high photocatalytic activity and long term stability.

2. Introduction

Zinc aluminate (ZnAl₂O₄) is a spinel type oxide, which has high chemical and thermal stability, low surface acidity and high mechanical resistance as a bulk [1]-[2]. Zinc aluminate was considered as an attractive material for different applications, such as optical coating or host matrix, high temperature ceramic material, catalyst and catalyst support [3]-[4]. ZnAl₂O₄ is a naturally available mineral commonly called gahnite with a normal spinel structure having all zinc cations in the tetrahedral and all aluminum cations in the octahedral sites of the cubic face-centered lattice of oxygen anions [5]. ZnAl₂O₄ is also a semiconductor material suitable for ultraviolet (UV) photoelectronic application due its wide energy bandgap (about 3.8 eV) [6]. Few studies involving the degradation of organic dyes using ZnO/ZnAl₂O₄ as a photocatalyst are reported in the literature [4]-[7]-[8]. Zhang et al. [9] prepared ZnO/ZnAl₂O₄ composite hollow microspheres using hydrothermal method. Zhao et al. [10] dispersed the ZnAl₂O₄ nanoparticles inside a network of ZnO. They reported that the effect of coupling both ZnO and ZnAl₂O₄ phase in the ZnO/ZnAl₂O₄ nanocomposite ensured the efficient separation of photogenerated e⁻ and h⁺ pairs, which was prerequisite for the enhancement of the photocatalytic performance. Therefore, in order to enhance the

photocatalytic activity and the long term stability, novel ZnO/ZnAl₂O₄ multi co-centric nanotubes were synthesized by combining the two techniques: electrospinning and atomic layer deposition (ALD).

In this chapter, we report the fabrication of a novel morphology of multi co-centric nanotubes of ZnO/ZnAl₂O₄ and we study for the first time their long term stability in photocatalytic performance. Herein, we combine the electrospinning and ALD techniques to elaborate double, triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ based on the Kirkendall effect between aluminum oxide and zinc oxide [11]. Electrospun PAN was used as template for the multi co-centric nanotubes of ZnO/ZnAl₂O₄. The structural, morphological and optical properties of the prepared samples were analyzed. The re-use of photocatalysts is so important, therefore the performances of these materials for long term stability and the photocatalytic degradation of methyl orange (MO) under UV have also been evaluated.

3. Experimental Section

3.1. Chemicals and Materials

Diethyl Zinc ((DEZ), Zn (CH₂CH₃)₂, 95%), Trimethylaluminum ((TMA), Al (CH₃)₃, 97%), N, N-Dimethylformamide (DMF; 99.8%), Polyacrylonitrile (PAN; MW= 500 000) and methyl orange (MO) were purchased from Sigma Aldrich. All chemicals were used without any further purification.

3.2. Preparation of PAN nanofibers

Electrospinning solution was prepared by dissolving 10 wt. % of polyacrylonitrile in dimethylformamide [12]. The solution was maintained under agitation for 4 hours. The polymer solution was loaded into a plastic syringe having a stainless steel needle with a diameter of 0.7 mm at a constant flow rate of 1 ml/h. The electrospinning process was performed at 38 ± 5°C in an ambient atmosphere under an applied voltage of 25 kV. Nanofibers were collected on a rotating coil covered with an aluminum foil with a rotation speed of 400 rpm. The distance between the tip of the needle and the aluminum foil was maintained at 20 cm.

3.3. ALD sequences

The ALD was performed using a homemade reactor [13]. All the ALD depositions were performed at 60°C using the following sequence mentioned in Table 6.1. All precursor pulses were coupled with 25 Sccm Ar flow as gas vector; purge was performed with 100 Sccm Ar flow as gas vector. After ALD deposition PAN fibers were heated at 450°C with a heating rate of 1°C.min⁻¹ for 8 h in air to eliminate the core of carbon, and then calcined at 900°C for 12 h in order to obtain ZnO/ZnAl₂O₄ co-centric nanotubes. As shown in Table 6.2, double, triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ were obtained by alternating the deposition sequences of Al₂O₃ and ZnO cycles on the PAN nanofibers.

Table 6.1. Step time investigation of Al₂O₃ and ZnO deposition on PAN nanofibers.

	Pulse	Exposure	Purge	Water Pulse	Exposure	Purge
Time	Al₂O₃ (TMA)					
	0.1s	30s	40s	2s	30s	40s
	ZnO (DEZ)					
	0.2s	20s	40s	2s	30s	40s

Table 6.2. Deposition sequences of Al₂O₃ and ZnO cycles on the PAN nanofibers.

ZnO/ZnAl ₂ O ₄ co-centric nanotubes	Deposition sequences
Double	100Al ₂ O ₃ /200ZnO/100Al ₂ O ₃
Triple	100Al ₂ O ₃ /200ZnO/100Al ₂ O ₃ /200ZnO/100Al ₂ O ₃
Quadruple	100Al ₂ O ₃ /200ZnO/100Al ₂ O ₃ /200ZnO /100Al ₂ O ₃ /200ZnO/100Al ₂ O ₃

3.4. Chemical and Structural Characterization

X-ray diffraction (XRD) measurements were carried out using a PANalytical Xpert-PRO diffractometer equipped with an X'celerator detector using Ni-filtered Cu-radiation ($\lambda = 1.54 \text{ \AA}$). Scanning electron microscopy (SEM) images were taken with a Hitachi S4800, Japan. The UV-Vis absorbance spectra of methyl orange were recorded by a Jasco V-570 UV-VIS-NIR spectrophotometer. Raman spectra have been obtained with a Horiba spectrometer, $\lambda = 659 \text{ nm}$. Energy-Dispersive X-ray spectroscopy analysis (EDX) was taken with Zeiss EVO ED15 microscope coupled with an Oxford X-MaxN EDX detector. Photoluminescence and reflectance measurements have been performed using fiber optic technique measurement system. Nitrogen laser (340 nm, 0.4 mW, 100 Hz) has been used as excitation source. The emission spectra have been measured with Ocean Optic spectrometer HR2000+, equipped with optical fiber and collecting lenses. The SpectraSuit software was used for collecting spectra in MSExcel files. Reflectance spectra were measured using reflectance Y-probe and UV-Vis Ocean Optics light source (DT-MINI-2-GS). The PL and reflectance spectra were recorded in the range of 360-750 nm and 380-800 nm, respectively.

3.5. Photocatalytic activity measurement

Methyl orange (MO) was used as a reference for organic pollutant to evaluate the photocatalytic activity of the ZnO/ZnAl₂O₄. The photocatalytic performance of the samples was evaluated by analyzing the decrease in concentration of the MO during exposure to UV light irradiation. The reaction temperature was kept constant at $25 \pm 0.2 \text{ }^\circ\text{C}$ by circulating water in a cylindrical tube surrounding the photo-reactor during the entire experiment. The decomposition was carried out in many beakers containing a suspension of 10 mg of each sample in 25 ml of MO solution (10 mg/L) under UV light irradiation (obtained from a 400 W light source, emission wavelength 300 - 400 nm). The distance between the lamp and the dye solution was maintained at 10 cm. The solution was irradiated with UV light for 3 hours. Each 1 hour, 3 ml of the sample solution was taken out and centrifuged to remove the catalyst. The centrifuged solutions were analyzed by a UV/Vis spectrometer. The absorbance spectra of MO (major absorption band around 462 nm) were recorded to measure

the change in the concentration of MO [14]. After irradiation, the photocatalytic degradation efficiency has been calculated using equation 1 [15]:

$$\text{Degradation efficiency (\%)} = (C_0 - C) / C_0 \times 100 \quad (\text{Equation 1})$$

Where C_0 is the initial concentration and C is the final concentration of dye before and after photo-irradiation respectively. This equation shows the dye photocatalyst degradation percentage.

4. Results and discussion

4.1. Morphological, Structural and Optical properties of ZnO/ZnAl₂O₄ multi co-centric nanotubes

SEM has been used to insure the feasibility of multi co-centric nanotubes of ZnO/ZnAl₂O₄ by combining the two techniques, Electrospinning and ALD. As shown in Figure 6.1, the new morphology of ZnO/ZnAl₂O₄ double (3 sequences), triple (5 sequences) and quadruple (7 sequences) co-centric nanotubes is well-defined. The nanotubes are separated by voids due to the Kirkendall effect and surface diffusion as will be explained later in the section dedicated to the mechanism. The nanotubes thickness was measured from the SEM images using image analysis software (Image J1.29X). The average thickness was measured on 50 randomly chosen nanotubes of each sample. After calcination, we measured an average thicknesses of $(100 \pm 5 \text{ nm})$, $(150 \pm 7 \text{ nm})$ and $(200 \pm 9 \text{ nm})$ for double, triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄, respectively. Also a uniform thickness of $(50 \pm 5) \text{ nm}$ for each individual nanotube in all samples was measured. Therefore, we can assume that the increase of the thickness may cause an increase of the surface area. A larger surface area provides more surface active sites for the adsorption of reactants molecules, making the photocatalytic process more efficient. An energy dispersive X-ray spectrum (EDX) of all multi co-centric nanotubes recorded along with elemental analysis is presented in Table 6.3. The EDX analysis reports the Al, Zn and O presence without any residual carbon confirming the ALD complete reaction and the polymer removal with the setup mentioned above in Table 6.1.

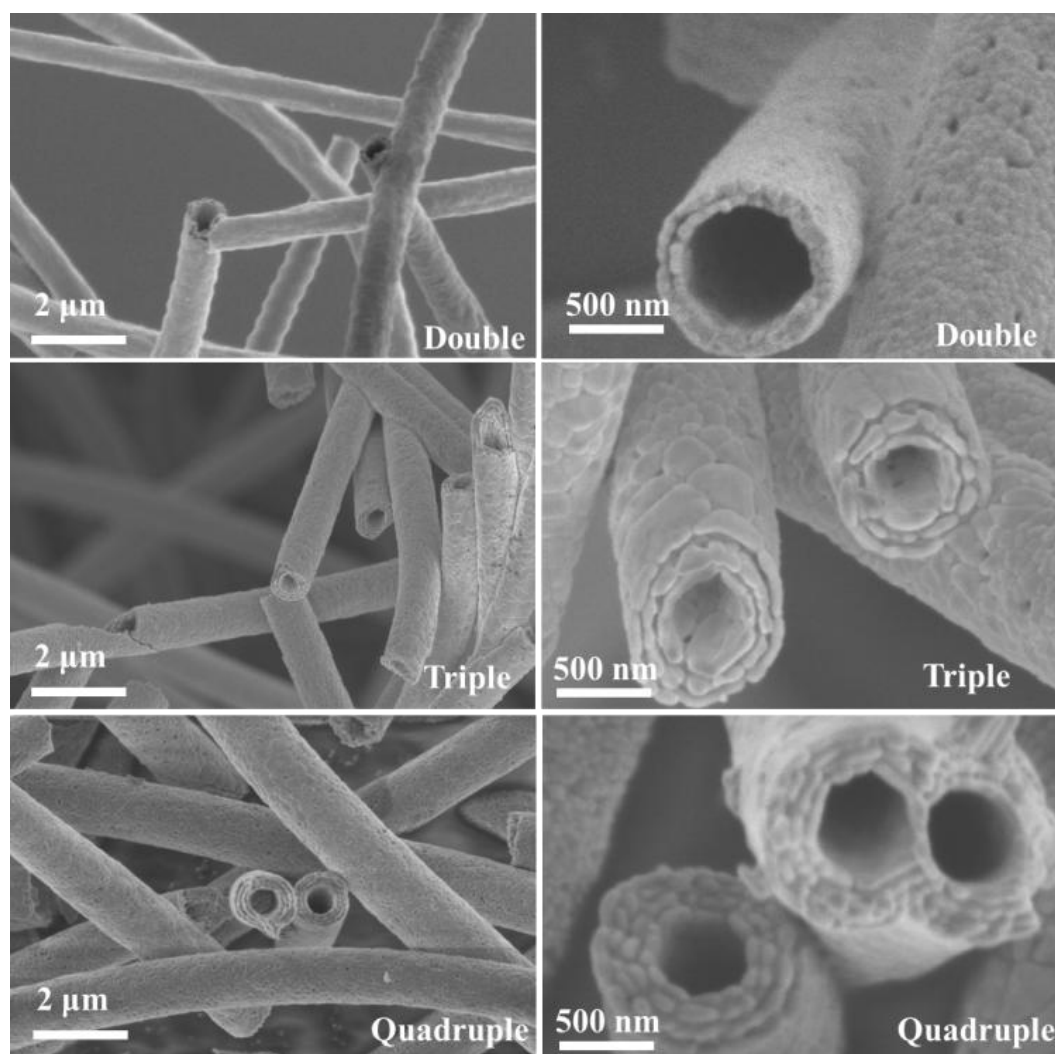


Figure 6.1. Scanning Electron Microscope images of ZnO/ZnAl₂O₄ double, triple and quadruple co-centric nanotubes annealed in air at 900°C.

Table 6.3. EDX data showing the composition of multi co-centric nanotubes of ZnO/ZnAl₂O₄ annealed under air.

Samples	Atomic percentages		
	Zn	Al	O
Double	20.52	30.4	49.08
Triple	22.1	29.06	48.84
Quadruple	22.77	27.96	49.27

Figure 6.2 illustrates the TEM images of double, triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄. These images reveal that both ZnO and ZnAl₂O₄ phase are highly crystallized and all the nanotubes were composed of nanosized grains. The grain size was measured using ImageJ, a Java-based image processing program. It was found to be (30 ± 3 nm), (40 ± 5 nm) and (50 ± 5 nm) for the double, triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄, respectively. In addition, the increased darkness of the nanotubes with the number of layers can be clearly seen in Figure 6.2.

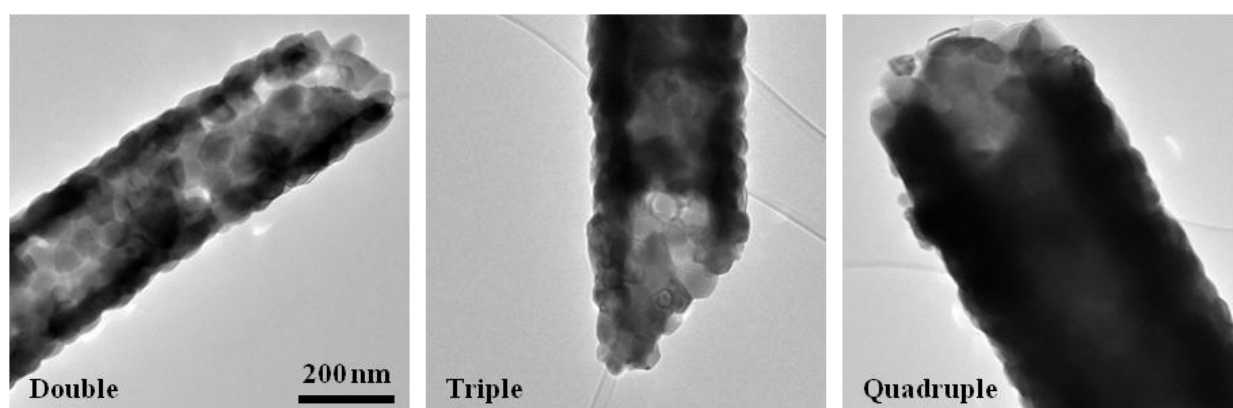


Figure 6.2. Transmission Electron Microscope images of ZnO/ZnAl₂O₄ double, triple and quadruple co-centric nanotubes.

The crystal structure was examined by X-ray diffraction. Figure 6.3 (A-B) shows XRD patterns of ZnO/ZnAl₂O₄ multi co-centric nanotubes prepared by combining the two techniques electrospinning and ALD. The XRD patterns of Figure 6.3.a-c are very similar. They show the diffraction peaks of the hexagonal wurtzite crystalline phase of zinc oxide (100), (002), (101), (102), (110), (103), (200), (112) and (201) corresponding to $2\theta = 31.7, 34.4, 36.2, 47.5, 56.5, 62.8, 66.3, 67.9$ and 69.0 , respectively [16]. In addition to the ZnO peaks, we can observe seven diffraction peaks of the spinel ZnAl₂O₄ (220), (331), (400), (311), (422), (333/511) and (440) corresponding to $2\theta = 31.4, 37, 45, 49.2, 55.7, 59.5$ and 65.3 , respectively. This is in good agreement with what have been reported before [17]. The average crystalline size of ZnO and ZnAl₂O₄ in the four samples was estimated by the Scherrer equation [18]. The high grain fineness numbers of both ZnO and ZnAl₂O₄ in all samples are

clearly seen in Table 6.4. Thus, XRD analysis confirmed the successful synthesis and the good crystalline structure of ZnO/ZnAl₂O₄ multi co-centric nanotubes by combining electrospinning and ALD.

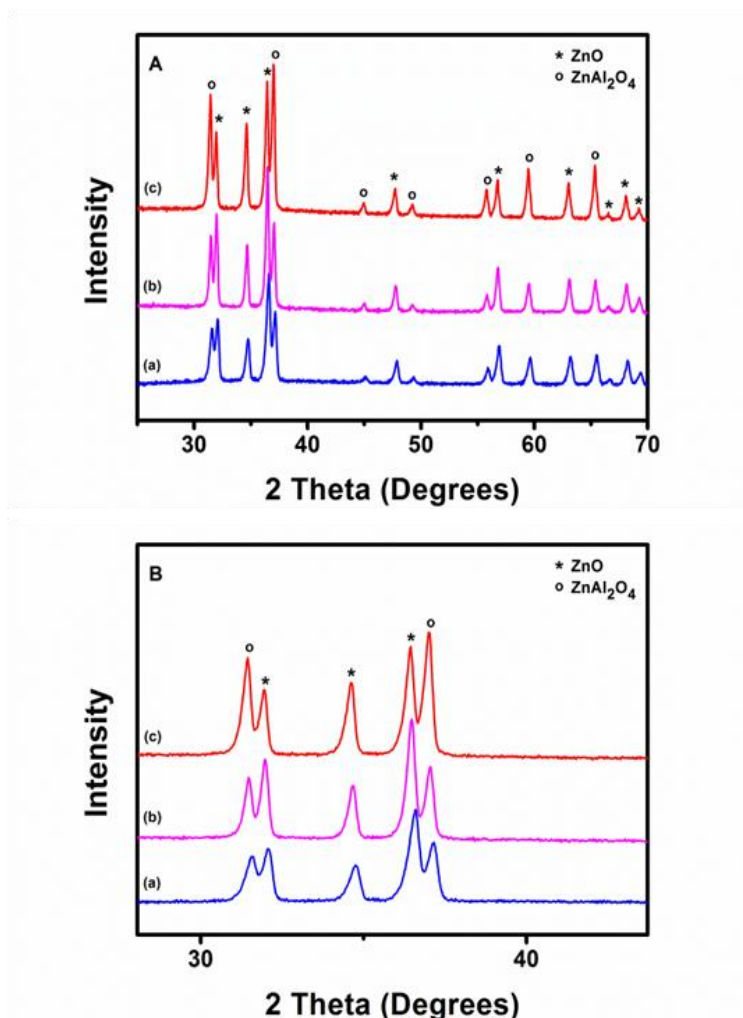


Figure 6.3. (A-B) XRD patterns of (a) Double, (b) Triple and (c) Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄.

Table 6.4. Grain size of ZnO and ZnAl₂O₄ multi co-centric nanotubes.

		Double	Triple	Quadruple
Grain size (nm)	ZnO	29	35	47
	ZnAl ₂ O ₄	31	42	50

It is well known that Raman spectroscopy is a characterization method to measure the frequencies of the long-wavelength lattice vibrations (phonons). Raman spectroscopy can provide useful information on crystal symmetry, impurity, grain size, residual stress, disorder etc [17]. The Raman spectra shown in Figure 6.4 were measured at room temperature. Raman signals are sensitive to the crystal structures and the defects. For all the samples, we observed 3 peaks corresponding to the active modes of ZnO. A dominant sharp peak was observed at 432 cm⁻¹ corresponding to the Raman active optical phonon mode E₂ which is the characteristic of hexagonal wurtzite ZnO. Other small peaks were also observed at 327 cm⁻¹ and 578 cm⁻¹. The peak at 327 cm⁻¹ (E_{2H-2L}) is due to multiple phonons scattering, and the small peak at 578 cm⁻¹ (E_{1L}) is observed due to structural defects like oxygen deficiency [19]. The intensity of the peak at 432 cm⁻¹ as compared to other peaks is very high which indicates high crystal quality for all samples. In particular, it can be seen that the intensity of this peak is increasing going from double (a) to quadruple tubes (c) which is consistent with the XRD results presented above. As shown in Figure 6.4.a-c corresponding to the Raman spectra of ZnO/ZnAl₂O₄ double, triple and quadruple co-centric nanotubes respectively, two peaks located at 414 and 654 cm⁻¹ are clearly observed. Based on our knowledge, there is no previous study on the Raman spectroscopy of ZnAl₂O₄. Thus, these two peaks may correspond to the active modes of ZnAl₂O₄ since they are not observed in the previous study of the pure ZnO.

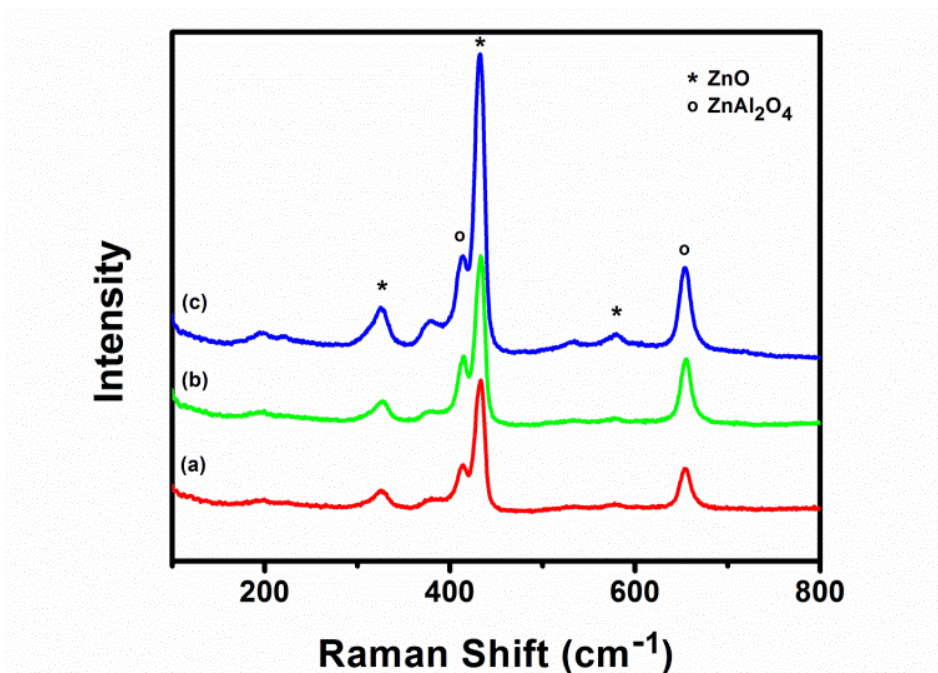


Figure 6.3. Raman Shift of (a) Double, (b) Triple and (c) Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄

Reflectance spectra of the samples are shown in Figure 6.5. Due to restrictions of the light source, the absorption of ZnAl₂O₄ phase (310-330 nm) was not detected.[20] Only ZnO absorption has been revealed. The band gap value of ZnO in bare ZnO, double, triple and quadruple ZnO/ZnAl₂O₄ nanotubes have been calculated according to the following equations [20]:

$$2F = (1 - R)^2 / 2.R \quad (\text{Equation 2})$$

$$(h\nu.F)^2 \sim (h\nu - E_g) \quad (\text{Equation 3})$$

Where F, R, $h\nu$ and E_g are Kubelka-Munk function, reflectance, photon energy and band gap, respectively. The calculations of band gap showed almost no change in band gap for ZnO, D, T and Q samples) ($E_g = 3.21 \pm 0.008$ eV).

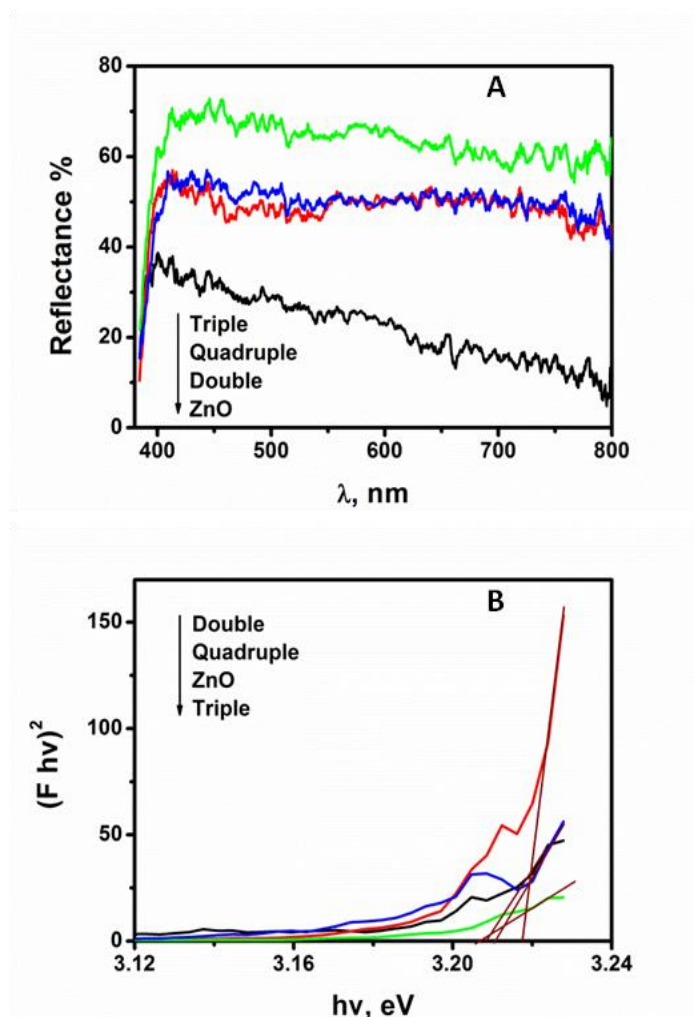


Figure 6.4. (A) Reflectance spectra and (B) band gap calculation from reflectance spectra of ZnO nanotubes and double, triple, quadruple co-centric nanotubes of ZnO/ZnAl₂O₄.

Table 6.5. Ratio of intensities of visible and UV emissions.

Sample	I(DLE)/I(NBE)
ZnO	0.15 ± 0.03
Double	0.2 ± 0.05
Triple	0.26 ± 0.1
Quadruple	0.97 ± 0.08

PL spectra of ZnO and nanotubes are shown in Figure 6.6. ZnO has demonstrated high intensive UV peak and broad band in visible range with significantly lower intensity,

related to exciton (near band NBE) and defect (deep level DLE) emission.[21] According to Chaya at al.,[22] the observed results point to high crystalline structure and high emission rate, due to lower rate of non radiative recombination through surface states and other defects. Development of double, triple and quadruple nanowires resulted in significant quenching of photoluminescence. It is known that the band gap of ZnAl₂O₄ is over 3.77 eV and it cannot be seen using the excitation source applied in the present work [23]. The first obvious reason is a reduction of ZnO ratio and therefore, the emission intensity. However, due to low laser power the most significant factor could be a charge separation due to complex structure on the surface. Chen et al. [23] has reported that the decrease of UV peak in ZnO/ZnAl₂O₄ could be due to additional forming defects on the interface which provide non radiative recombination. Ratio of intensities of visible and UV is shown emissions in Table 6.5. It is clearly seen that with increase of the number of ZnO/ZnAl₂O₄ layers the concentration of defects increased similarly as described in Chaya at al. [22] Thus, the forming of double, triple and quadruple ZnO/ZnAl₂O₄ nanotubes results in defect formation, stimulation of nano radiative recombination and/or surface charge transfer.

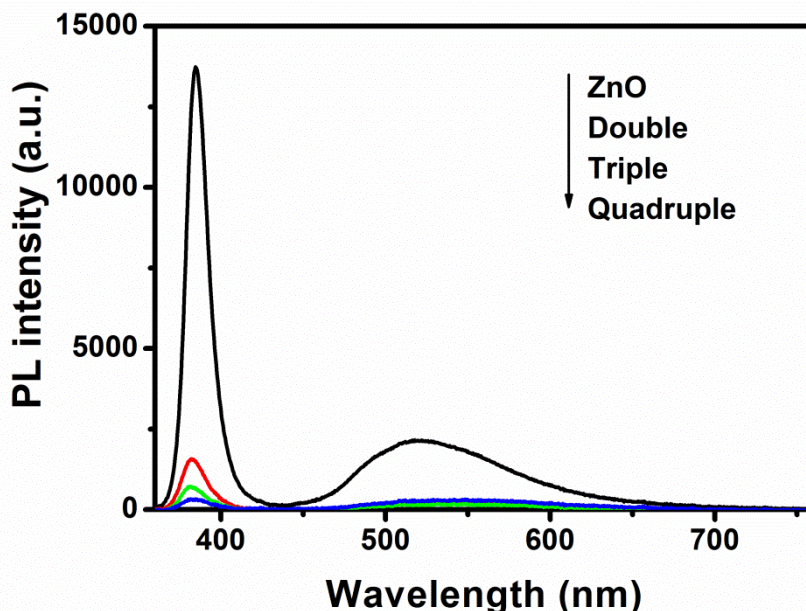


Figure 6.5. Photoluminescence spectra of ZnO and double, triple, quadruple co-centric nanotubes of ZnO/ZnAl₂O₄.

5.2. Mechanism of ZnO/ZnAl₂O₄ formation

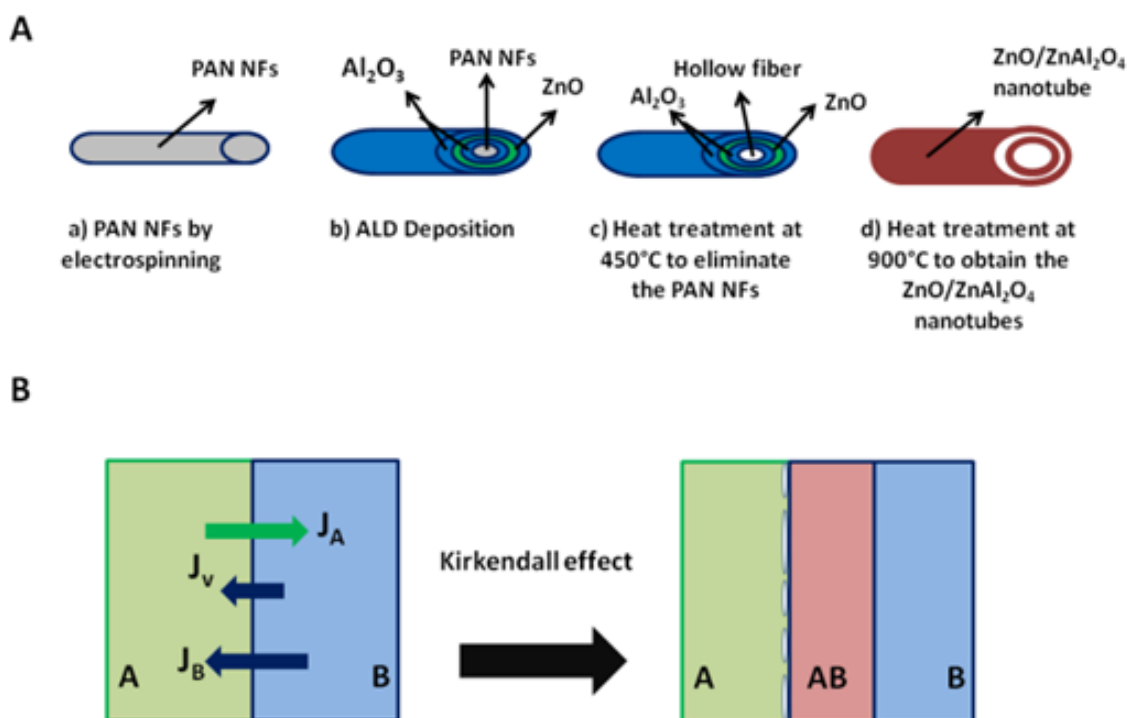


Figure 6.6. (A) Different steps of ZnO/ZnAl₂O₄ nanotubes formation. **(B)** Kirkendall effect and surface diffusion process, where J_A , J_B , and J_V are diffuse flux of metal A, B, and void, respectively.

Based on the Kirkendall effect, multi co-centric nanotubes of ZnO/ZnAl₂O₄ were elaborated. All the steps for the ZnO/ZnAl₂O₄ elaboration were described in Figure 6.7.A. The Kirkendall effect is a classical phenomenon in metallurgy [24]. It basically refers to a non-equilibrium mutual diffusion process through an interface of two metals A and B (in our case A and B refer to ZnO and Al₂O₃, respectively) so that vacancy diffusion occurs to compensate for the unequal material flow [25]-[26]. In planar metallic bi-layers, this effect can give rise to void formation near the bond interface and within the fast-diffusion side, thus deteriorating the bonding strength of the interface [11]. Figure 6.7.B shows schematically the generalized model for hollow structure formation based on the Kirkendall effect and surface diffusion. For the diffusion flux, we assume $J_A > J_B$. In the initial stage, Kirkendall voids are generated near the A/AB interface during vacancy assisted exchange of material via bulk inter-diffusion. The voids are the sinks for subsequent inward flux of vacancies ($J_V = J_A - J_B$) and thus grow in size. The voids coalesce into bigger ones and touch

the compound layer AB, in one sense breaking the connection for lattice diffusion and in the other sense establishing new bridges as fast transport paths for the remaining material A [27]-[28]-[29]. Herein, we synthesized photocatalysts multi co-centric nanotubes of ZnO/ZnAl₂O₄ with relatively high surface area. The hollow nanotubes allow multiple reflections of UV light within the interior cavity that facilitates more efficient use of the light source. Moreover, the void between ZnO and ZnAl₂O₄ allows more efficient transport for the reactant molecules to get to the active sites and inhibiting charge recombination, hence enhancing the efficiency of photocatalysis.

4.3. Photocatalytic degradation of methyl orange by multi co-centric nanotubes of ZnO/ZnAl₂O₄

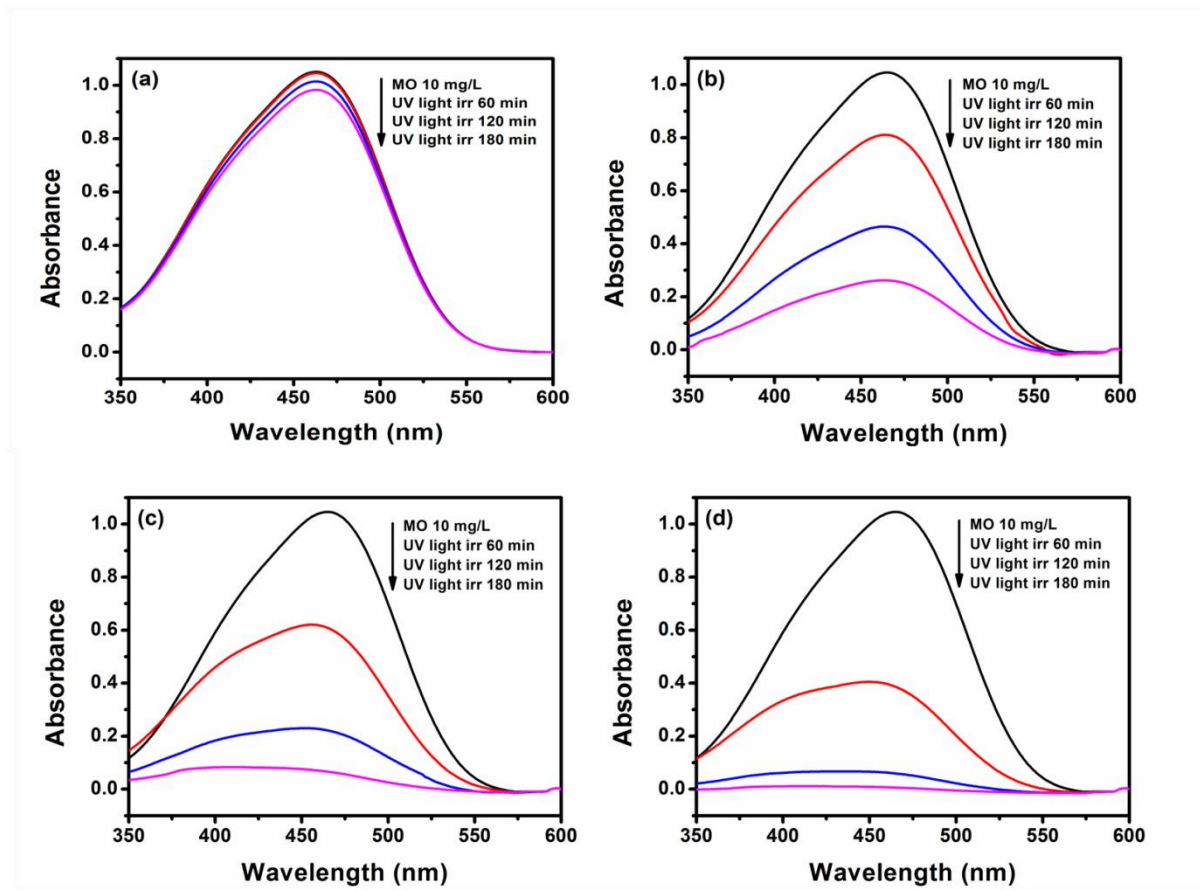


Figure 6.7. UV-Vis spectra of the photocatalytic degradation of MO under UV light: (a) MO without catalyst, (b) Double, (c) Triple and (d) Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄.

The photocatalytic activities of the ZnO/ZnAl₂O₄ multi co-centric nanotubes were evaluated by the photodegradation of methyl orange (MO) under UV light (wavelength < 360 nm). MO was chosen as a model organic pollutant. Figure 6.8 shows the dye adsorption without catalysts under UV irradiation and photocatalytic degradation of organic dye in the presence of catalysts under UV irradiation at different periods of time (0, 60, 120, 180 min). The major absorption peak of MO is positioned at 462 nm. As shown in Figure 8.6.a, the concentration of MO without any catalysts almost does not change for every measurement under UV irradiation. Thus, light irradiation in the absence of any catalysts does not work in the photocatalysis of MO, indicating that the photodegradation of MO can be neglected. As shown in Figure 6.8.b-d, after 3 hours and under identical experimental conditions, MO was degraded up to 70%, 94% and 99% in the presence of ZnO/ZnAl₂O₄ double, triple and quadruple co-centric nanotubes respectively (Figure 6.9). When ZnO and ZnAl₂O₄ are coupled together, photons may be absorbed in both ZnO and ZnAl₂O₄ and form the electron-hole pairs. The electrons at the bottom of the Conduction Band (CB) of ZnAl₂O₄ would migrate to that of the ZnO; whereas holes at the Valence Band (VB) at the top of ZnAl₂O₄ would remain there. On the other hand, the holes at the VB at the top of the ZnO would migrate to that of ZnAl₂O₄, with electrons at the CB bottom of ZnO remaining there [16]-[10]. Such process, which is energetically favorable and reduces the probability of the electron-hole recombination, is regarded as the key factor for the enhancement of photocatalytic activities of the ZnO/ZnAl₂O₄ nanotubes compared to the pure ZnO [9]. According to the EDX results presented above, in the case of double co-centric nanotubes (photodegradation: 70%) when the content of ZnO decreases (Zn: 20 at. %), ZnO will reduce the catalytic efficiency of ZnO/ZnAl₂O₄, which is attributed to complete or sparse coverage of ZnO on the ZnAl₂O₄. It displays low photocatalytic activity of ZnO or ZnAl₂O₄ itself, which can only use about 3–5% of UV light in sunlight.

Also, it was well known that the photocatalytic activity is mainly governed by crystalline phase, light absorption capacity and active surface area [30]. For comparison, the ZnO/ZnAl₂O₄ quadruple and triple co-centric nanotubes exhibit the higher photocatalytic activity (99% and 94%, respectively) compared to the ZnO/ZnAl₂O₄ double co-centric nanotubes (70%). From SEM results, we assume a

bigger active surface area with a bigger number of layers so $S_{\text{Quadruple}} > S_{\text{Triple}} > S_{\text{Double}}$. From the XRD analysis, the grain fineness number of both ZnO and ZnAl₂O₄ is increasing as follow $D_{\text{Quadruple}} > D_{\text{Triple}} > D_{\text{Double}}$. Therefore, the important reason for the high photocatalytic activity under UV light should be ascribed to the UV-Vis absorption presented above. The ZnO/ZnAl₂O₄ triple and quadruple co-centric nanotubes have the two highest band gap (3.39 and 3.25 eV, respectively). These results indicate that ZnO/ZnAl₂O₄ triple and quadruple co-centric nanotubes have excellent absorption capacity of UV light, large active surface area, high crystallite sizes and lower recombination rate of electron–hole pair.

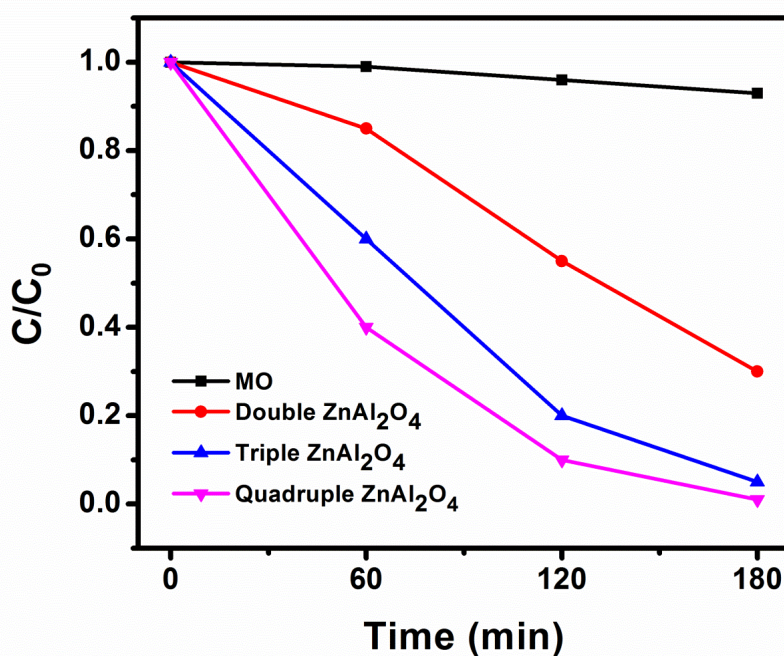


Figure 6.8. Photodegradation of MO by Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄.

Table 6.6. Kinetic parameters for photocatalytic activities of ZnO/ZnAl₂O₄ double, triple and quadruple co-centric nanotubes.

	MO	Double	Triple	Quadruple
k_a (min ⁻¹)	0.00035	0.0067	0.0167	0.0253
R^2	0.9538	0.9113	0.9436	0.9386

Figure 6.9 shows the different kinetic linear curves. The photodegradation reactions follow a Langmuir–Hinshelwood first-order kinetics model. The explanation is described as follows [31]:

$$r = dC/dt = kKC/1+KC \quad (\text{Equation 4})$$

Where r is the degradation rate of MO (mg (L min)^{-1}), C is the concentration of the MO solution (mg l^{-1}), t is the irradiation time, k is the reaction rate constant (mg (L min)^{-1}), and K is the adsorption coefficient of MO (mg L^{-1}). Since the initial concentrations ($C_0 = 10 \text{ mg L}^{-1}$) of the MO solutions are very low in the present experiments, the relationship between $\ln(C_0/C)$ and reaction time t shows that the decomposition of MO with different photocatalysts accords with a pseudo first order kinetic [31]:

$$\ln (C_0/C) = kKt = k_a t \quad (\text{Equation 5})$$

Where k_a is the apparent first-order rate constant (min^{-1}) and C is the concentration at time t . k_a obtained from the linear dependence between $\ln (C_0/C)$ and time are reported in Table 6.6. The increasing order of the rate constants in the samples is: ZnO/ZnAl₂O₄ quadruple > ZnO/ZnAl₂O₄ triple > ZnO/ZnAl₂O₄ double > MO. The rate constant exhibits a maximum of 0.0253 min^{-1} for ZnO/ZnAl₂O₄ quadruple co-centric nanotube, which is 3.7 and 1.5 times higher than that of ZnO/ZnAl₂O₄ double and ZnO/ZnAl₂O₄ triple co-centric nanotubes, respectively. Thus, compared with other samples, the ZnO/ZnAl₂O₄ quadruple co-centric nanotubes show higher photocatalytic activity under UV light, which is represented by larger value of k_a . All these results indicate that compared with single phase ZnO material reported in previous studies (MO photodegradation: 28%) [9], the coupling effect between ZnO and ZnAl₂O₄ increases the life time of charge carriers which leads to the enhancement of its photocatalytic activity.

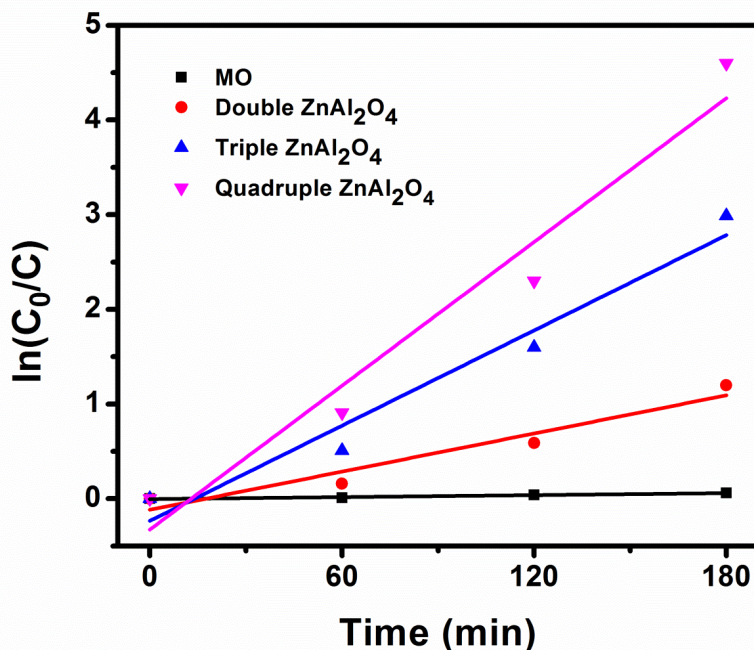


Figure 6.9. Kinetics of Methyl orange degradation by Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄.

The re-use of catalysts is very important. However to our knowledge, there is no study concerning the long term stability of ZnO/ZnAl₂O₄. Therefore, we performed for the first time the photocatalytic repeatability test of each catalyst. Repetitive degradation of MO by Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ under UV light irradiation was conducted to study their long-term stability and the results are shown in Figure 6.10. After each cycle, the catalyst was separated from the solution by centrifugation. From Table 6.7, it can be seen that after 180 min of UV light irradiation and in the presence of the same ZnO/ZnAl₂O₄ samples, MO has been degraded in four repeated cycles. The loss of efficiency was only 6% after the fourth cycle, which can be attributed to the loss of catalyst during centrifugation after each cycle. In addition, the used nanotubes show the same off-white color as the newly prepared catalyst. These results suggest that the multi co-centric nanotubes of ZnO/ZnAl₂O₄ have higher photodegradation efficiency in repeated and long-term applications compared to the pure ZnO which has very low long-term photocatalytic stability [32].

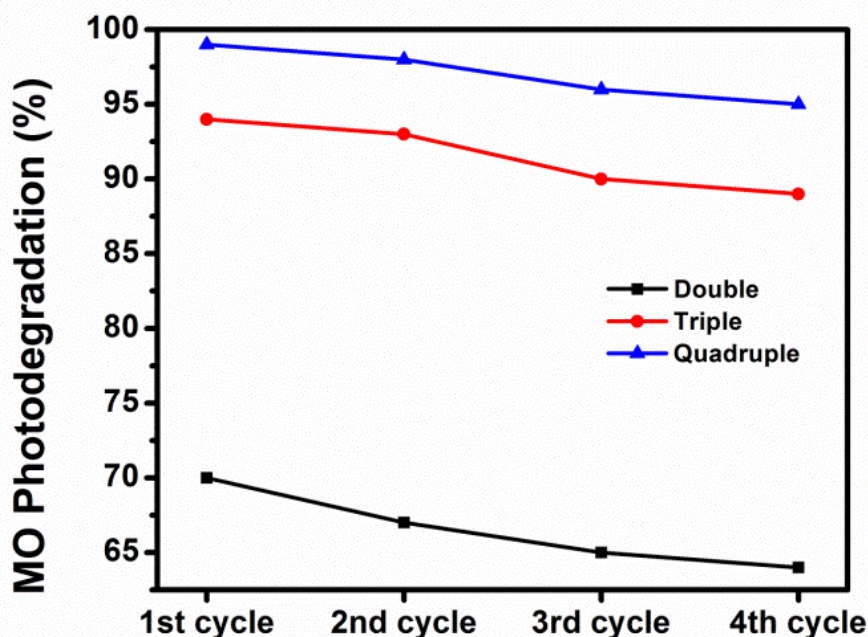


Figure 6.10. Long-term catalytic stability of Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ in four repeated cycles of MO degradation under UV irradiation.

Table 6.7. MO photodegradation percentages by Double, Triple and Quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ in four repeated cycles.

	Double	Triple	Quadruple
First cycle	70%	94%	99%
Second cycle	67%	93%	98%
Third cycle	65%	90%	96%
Fourth cycle	64%	89%	95%

5. Conclusion

In summary, novel multi co-centric nanotubes of ZnO/ZnAl₂O₄ have been fabricated by combining the two techniques of Electrospinning and Atomic Layer Deposition (ALD). The photocatalytic activity of the resultant nanotubes has been investigated in details. All the samples were annealed at 900°C in air for 12 hours. The new morphology of double, triple and quadruple co-centric nanotubes of

ZnO/ZnAl₂O₄ was shown by SEM images. The successful synthesis of ZnO/ZnAl₂O₄ multi co-centric nanotubes and ALD was confirmed by EDX, XRD and Raman results. The UV-Vis analysis showed the band gap energy of the different samples. Photocatalysis results confirmed that the coupling of the band gap structure in the novel ZnO/ZnAl₂O₄ nanotubes ensured the efficient separation of the photogenerated e⁻ and h⁺ pairs, which leads to a high photocatalytic performance for the degradation of MO (99% and 94%) and a long-term photocatalytic stability compared to the pure ZnO. The fact of combining the two techniques, Electrospinning and ALD might open a new route for new design and controlled fabrication of semiconductor nanocomposites in the development of future photocatalysts.

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General Conclusion

The strategies to improve the photocatalytic activity of the semiconductors under UV and visible light for wastewater treatment are still remaining the interest of researchers for future studies in energy and environmental field. In this work, we succeeded to enhance the photocatalytic efficiency of TiO₂ under UV and visible light by metal and non metal doping. Also, we improved the photocatalytic stability of ZnO by designing novel nanostructures using atomic layer deposition and electrospinning techniques. The morphological, structural and optical properties of the prepared samples were analyzed using several characterizations techniques. In order to modify the properties of TiO₂ and ZnO, different strategies have been investigated and reported as follow:

- (1) Reduced GO/TiO₂ composite nanofibers with different GO nanosheets amounts were successfully prepared by electrospinning. The GO was reduced under a heat treatment at 500°C in N₂ atmosphere for 6 hours. The band gap energy of TiO₂ NFs was decreased from 3.2 eV to 2.9 eV due to the presence of rGO sheets. The incorporation of rGO with an amount of (2 wt %)/TiO₂ significantly increases the visible light photo-response and improves the separation of the photo-induced electron-hole pairs of TiO₂. The photocatalytic degradation of methyl orange under visible light was 6 times higher than that of commercial TiO₂-P25. Thus, incorporating rGO into TiO₂ NFs is an efficient and simple way for enhancing the visible-light photocatalytic activity.

- (2) Elaboration of BN/TiO₂ composite nanofibers with different BN nanosheets amounts was performed using electrospinning technique. The successful incorporation of boron nitride in TiO₂ nanofibers was confirmed by SEM, EDX, Raman and FTIR. An increase of crystal sizes and specific surface area of BN (10wt. %)/TiO₂ compared to the pure TiO₂ nanofibers was found. A blue shift of the band gap energy from 3.2 eV to 3.62 eV due to the presence of BN sheets was confirmed by UV-VIS analysis. XRD and photoluminescence spectra confirmed that BN incorporation increases the lattice strain in the TiO₂ cell. As result, BN sheets can promote the migration of h⁺ from the bulk of TiO₂ to its surface due to the electrostatic interaction and consequently improve the photocatalytic activity of TiO₂ under UV light due to efficient charge separation. The photocatalytic degradation of methyl orange under UV light was 5 and 3.8 times higher than that of commercial TiO₂-P25 and TiO₂ nanofibers, respectively.

- (3) To develop an effective material having photocatalytic properties for both organic compound degradation and bacterial removal, we report on the elaboration of Ag/TiO₂ and BN-Ag/TiO₂ composite nanofibers with controlled amounts of BN nanosheets and Ag. The photocatalytic tests using methylene blue under visible light, in repeated and long term applications, showed that the photodegradation efficiency of BN(5 wt %)-Ag (3 wt %)/TiO₂ was 17.2 and 2.3 times higher than that of pure TiO₂ nanofibers and Ag (3 wt %)/TiO₂ respectively. This higher activity is due to the efficient electron transfer from photo-excited Ag/TiO₂ to BN nanosheets to retard the charge recombination. Antibacterial tests against gram-negative *Escherichia coli* indicate that BN (5 wt %)-Ag (3 wt %)/TiO₂ resulted in a total removal of cultivable bacteria within a short time. The prepared samples can be nominated as multifunctional materials for photodegradation and antibacterial applications.

- (4) Al₂O₃ doped ZnO nanotubes with controlled doping ratio of Al₂O₃ were designed by combining the two techniques of atomic layer deposition and electrospinning. The effects of Al₂O₃ doping on optical and structural properties of Al₂O₃ doped ZnO nanotubes were discussed and the photocatalytic activity of these materials under UV light was studied by the photodegradation of methyl orange as model pollutant. As a result, the Al₂O₃ doping increases the disorder (defects and oxygen vacancies formation) in the ZnO nanostructure which improves the separation efficiency of electron-hole pairs. Therefore, the photocatalytic degradation of methyl orange by Al₂O₃/ZnO (20 wt%) was 5 times higher than that of ZnO nanotubes.

- (5) Novel double, triple and quadruple co-centric nanotubes of ZnO/ZnAl₂O₄ have been successfully designed by combining the two techniques of atomic layer deposition and electrospinning. After a heat treatment at 900°C under air, morphological, structural and optical analysis confirmed the elaboration of multi co-centric nanotubes of ZnO/ZnAl₂O₄ based on Kirkendall effect. Photoluminescence results showed that the coupling of the band gap structure in the novel ZnO/ZnAl₂O₄ nanotubes ensured the efficient separation of the photogenerated e⁻ and h⁺ pairs and leads therefore, to a high photocatalytic performance for the degradation of methyl orange (99% and 94%) and a long-term photocatalytic stability compared to the pure ZnO.

The results presented in this work are hoped to contribute to the development of the green photocatalysis for wastewater treatment in the near future. The prepared photocatalysts could be used for other photocatalytic applications such as the hydrogen production, water disinfection, degradation of heavy metals and pharmaceutical products. Even though great progresses have been achieved in the photocatalysis under visible light at a laboratory scale, future research should be devoted to further improve the efficiency of these photocatalysts for large scale applications (industrial use). In addition, the photocatalyst must be removed after treatment. A post treatment will therefore be necessary; it consists of a solid-liquid separation step. Thus, future studies should be focused in this area.

Scientific Contributions

Publications

1. **Maryline Nasr**, Adib Abou Chaaya, Nadine Abboud, Mikhael Bechelany, Roman Viter, Cynthia Eid, Antonio Khoury, Philippe Miele, Photoluminescence: A very sensitive tool to detect the presence of anatase in rutile phase electrospun TiO₂ nanofibers, Superlattices and Microstructures 77 (2015) 18–24.

DOI: [10.1016/j.spmi.2014.10.034](https://doi.org/10.1016/j.spmi.2014.10.034)

2. **Maryline Nasr**, Sébastien Balme, Cynthia Eid, Roland Habchi, Philippe Miele, Mikhael Bechelany, Enhanced Visible-Light Photocatalytic Performance of Electrospun rGO/TiO₂ Composite Nanofibers, J. Phys. Chem. C 2017, 121, 261–269.

DOI: [10.1021/acs.jpcc.6b08840](https://doi.org/10.1021/acs.jpcc.6b08840)

3. **Maryline Nasr**, Roman Viter, Cynthia Eid, Roland Habchi, Philippe Mielea, Mikhael Bechelany, Enhanced photocatalytic performance of novel electrospun BN/TiO₂ composite nanofibers, NewJ.Chem., 2017, 41, 81.

DOI: [10.1039/c6nj03088b](https://doi.org/10.1039/c6nj03088b)

4. **Maryline Nasr**, Roman Viter, Cynthia Eid, Fabienne Warmont, Roland Habchi, Philippe Mielea, Mikhael Bechelany, Synthesis of novel ZnO/ZnAl₂O₄ multi co-centric nanotubes and their long-term stability in photocatalytic application, RSC Adv., 2016, 6, 103692.

DOI: [10.1039/c6ra22623j](https://doi.org/10.1039/c6ra22623j)

5. **Maryline Nasr**, Roman Viter, Cynthia Eid, Roland Habchi, Philippe Miele, Mikhael Bechelany, Optical and structural properties of Al₂O₃ doped ZnO nanotubes by ALD and their photocatalytic application, Applied Materials & Interfaces, 2017.

Submitted (Manuscript ID: am-2017-07712b).

6. **Maryline Nasr**, Laurence Soussan, Roman Viter, Cynthia Eid, Roland Habchi, Philippe Miele, Mikhael Bechelany, High photocatalytic and antibacterial activity of BN-Ag/TiO₂ composite nanofibers under visible light, The Journal of Physical Chemistry C, 2017.

Submitted (Manuscript ID: jp-2017-05976g).

7. **Maryline Nasr**, Cynthia Eid, Roland Habchi, Philippe Miele, Mikhael Bechelany, Recent progress in enhancing visible light photocatalytic activity of TiO₂: Review (In progress).

8. Amr A. Nada, **Maryline Nasr**, Mikhael Bechelany, Stéphanie Roualdes, Enhancing the photocatalytic properties of mesoporous TiO₂@ZnFe₂O₄ nanofiber via PECVD (In progress).

Conferences

➤ Oral Communcations

1. **Maryline Nasr**, Cynthia Eid, Philipe Miele, Roland Habchi, Mikhael Bechelany, Oxides membranes by electrospinning for photocatalytic applications, 3rd International Conference on Bioinspired and Biobased Chemistry & Materials, October 16-19, 2016 Nice, France.

2. **Maryline Nasr**, Roman Viter, Cynthia Eid, Philipe Miele, Roland Habchi, Mikhael Bechelany, Synthesis of novel ZnO/ZnAl₂O₄ multi co-centric nanotubes and their long-term stability in photocatalytic application, E-MRS Spring Meeting, May 21-26, 2017 Strasbourg, France.

3. **Maryline Nasr**, Roman Viter, Cynthia Eid, Philipe Miele, Roland Habchi, Mikhael Bechelany, Enhanced photocatalytic performance of novel electrospun BN/TiO₂ composite nanofibers, E-MRS Spring Meeting, May 21-26, 2017 Strasbourg, France.

4. **Maryline Nasr**, Sébastien Balme, Cynthia Eid, Roland Habchi, Philippe Miele, Mikhael Bechelany, Enhanced Visible-Light Photocatalytic Performance of Electrospun rGO/TiO₂ Composite Nanofibers, Le 5ème Forum Doctoral, le 18 et 19 Mai 2016. Ecole Doctorale en Sciences et Technologie (EDST), Unversite Libanaise, Liban.

➤ Posters

1. **Maryline Nasr**, Sébastien Balme, Cynthia Eid, Roland Habchi, Philippe Miele, Mikhael Bechelany, Synthèse des nanofibres de TiO₂ dopées avec des monofeuillets de GO pour des applications photocatalytiques, la 22ème Conférence Scientifique Internationale (LAAS22), les 14 et 15 Avril 2016 - USEK campus Kaslik – Liban.

2. **Maryline Nasr**, Adib Abou Chaaya, Nadine Abboud, Mikhael Bechelany, Roman Viter, Cynthia Eid, Antonio Khoury, Philippe Miele, Elaboration des membranes d'oxydes par

electrospinning pour des applications photocatalytiques, Troisièmes Journées Franco-Libanaises JFL3, le 29 et 30 octobre 2015. Ecole Doctorale en Sciences et Technologie (EDST) et la Faculté des Sciences, Université Libanaise, Liban.

3. **Maryline Nasr**, Sébastien Balme, Cynthia Eid, Roland Habchi, Philippe Miele, Mikhael Bechelany, Enhanced Visible-Light Photocatalytic Performance of Electrospun rGO/TiO₂ Composite Nanofibers, les 12^{ème} Journées de l'Ecole Doctorale, les 5 et 6 décembre 2016 - Institut Botanique, Montpellier – France.

Annex

Photoluminescence: a very sensitive tool to detect the presence of anatase in rutile phase electrospun TiO₂ nanofiber

1. Abstract

This paper reports on the synthesis and the characterization of titanium dioxide (TiO₂) nanofiber prepared by electrospinning. The samples were annealed at various temperatures in air for 4h. The as-spun and annealed TiO₂/PVP composite nanofibers were characterized by scanning electron microscopy (SEM), Energy-dispersive X-ray spectroscopy analysis (EDX), X-ray diffraction (XRD), Raman spectroscopy and photoluminescence (PL). The results show that the heat treatment has an effect on the crystallization process. Even if the XRD data shows a complete anatase-to-rutile transition in the TiO₂ nanofibers at 900°C, photoluminescence shows a small portion of anatase in rutile sample. This observation proved that photoluminescence is a very sensitive tool to detect the presence of anatase in rutile phase TiO₂ nanostructures.

2. Introduction

In the last decade, the attention of researchers is paid to design new nanoscale materials such one-dimensional nanostructures [1-6]. Different methods have been used to produce one-dimensional nanomaterials such as thermal evaporation,[7] freeze-drying method,[8] physical vapor deposition,[9] and chemical vapor deposition.[10] Among these methods, the simplest technique to design nanofibers is the electrospinning. This method was first introduced by Formhals [11]. It is a versatile and cost-effective technique for the production of multi-functional nanofibers from various polymers, polymer blends, composites, sol-gels, and ceramics [12]. The fibers are rather uniform in diameter ranging from tens of nanometers to several micrometers [13, 14]. The basic principle of this technique is based on generating the direct movement of charged molecules by applying a high voltage. The droplets coming from the polymer solution, through the spinneret, would then be ejected in the form of a liquid jet forming the nanofibers on the collector.

Among the different types of oxide semiconductors produced by this method, Titanium oxide (TiO₂) is one of the most extensively studied materials because of its remarkable optical and electronic properties along with its chemical and thermal stability [15]. Due to

these outstanding properties, TiO₂ has been used in wide range of applications such as chemical sensors,[16, 17] catalytic filters,[18, 19]and solar cells [20, 21]. TiO₂ has three crystalline phases: anatase, rutile, and brookite. Rutile is a stable phase at high temperature, where anatase and brookite would transform to rutile when treated at high temperatures.

In addition, TiO₂ nanostructures demonstrate room temperature photoluminescence in visible (440-570 nm) and IR (800-860 nm) intervals of the wavelength spectrum, in particular for anatase and rutile phases respectively [22-25]. The emission of anatase nanostructures has usually two bands, related to self-trapped excitons luminescence (440-510 nm) and deep levels formed by oxygen vacancies (515-560 nm) [26-28]. Photoluminescence in rutile phase concerns deep levels, related to Ti³⁺ states [15, 25]. It was mentioned that photoluminescence in TiO₂ is sensitive to ambient conditions and thermal treatment [24, 25]. PL in TiO₂ nanostructures is ruled by the surface charge and could be changed by the adsorption of gas and biomolecules on TiO₂ surface [29, 30], what makes an impact on some application if the TiO₂ is used in optical sensors or biosensors for instance.

In the present paper we report the fabrication of TiO₂ nanofibers by electrospinning method and detailed optical and structural characterization of the obtained nanostructures. The structural and optical changes induced by high temperature annealing will be discussed. The high sensitivity of the photoluminescence technique for detecting anatase trace in rutile phase will be also highlighted.

3. Experimental section

3.1. Materials

In this study titanium tetraisopropoxide [Ti(O*i*Pr)₄; 97%,], PVP (Mw = 1 300 000), ethanol (98%) and acetic acid (100%) were purchased from Sigma–Aldrich.

3.2. Preparation of TiO₂ nanofibers

Fabrication of the TiO₂ nanofibers was achieved by electrospinning. The TiO₂ sol was prepared by hydrolyzing 3 ml of titanium tetraisopropoxide with a mixture of 2 mL of ethanol and 2 mL of acetic acid. 0.3g of PVP was separately dissolved in 3 mL of ethanol and then added to the TiO₂ sol solution. The precursor mixture was stirred for 2h at room temperature to obtain sufficient viscosity required for electrospinning. The electrospinning

solution was placed into a 22 ml syringe with a 25 gauge stainless steel needle at the tip. The syringe was placed on a syringe pump which was adjusted to 0.4 ml/h of feeding rate. Then the electric voltage of 25 kV was applied between the needle and the collector. The distance between the tip of the syringe needle and the collector (Al plate) was fixed to 10 cm. The as-spun nanofibers were left overnight in air to fully hydrolyze. To remove the polymer and achieve crystallinity, the composite fibers were then treated in air at different temperatures 500°C, 700°C and 900°C for 4h with a heating rate of 5°C/min.

3.3. Structural characterizations

The microstructures, the phase and the crystal structure of the synthesized nanofibers were investigated using scanning electron microscopy (SEM, Hitachi S-4800), X-ray diffraction (PANalytical Xpert-PRO diffractometer equipped with a X'celerator detector using Ni-filtered Cu-radiation), Raman (Horiba xplora, 532 nm) and Energy-dispersive X-ray spectroscopy analysis (Ametek, EDX). Photoluminescence of TiO₂ nanostructures was measured at room temperature using the experimental setup, described elsewhere by Abou Chaaya *et al.*[31] The PL was excited by solid state laser (355 nm) and the emission spectra were recorded in the range 360-800 nm.

4. Results and discussion

The morphology of the nanofibers was examined by scanning electron microscopy (SEM). Figure 1a shows the SEM images of the fibers before annealing. The average diameter of the fibers is 300 nm. The composite nanofibers were then treated in air at different temperatures 500°C (Figure 1b), 700°C (Figure 1c) and 900°C (Figure 1d). As shown in the Figure 1b and Figure 1c the nanofibers have uniform surfaces with an average diameter of 170 nm and 140 nm, respectively, smaller than the as-spun nanofibers because of the loss of PVP and the decomposition of titanium tetraisopropoxide. After calcination at 900°C (Figure 1d), the average diameter (190 nm) increased and this can be explained by the process of crystallization. The average diameter of TiO₂ nanofibers increases with the increasing of crystallinity therefore with the increasing of calcination temperature [28]. The EDX data (Table 1) confirms the removal of polymer and show the formation of stoichiometric TiO₂ nanofibers.

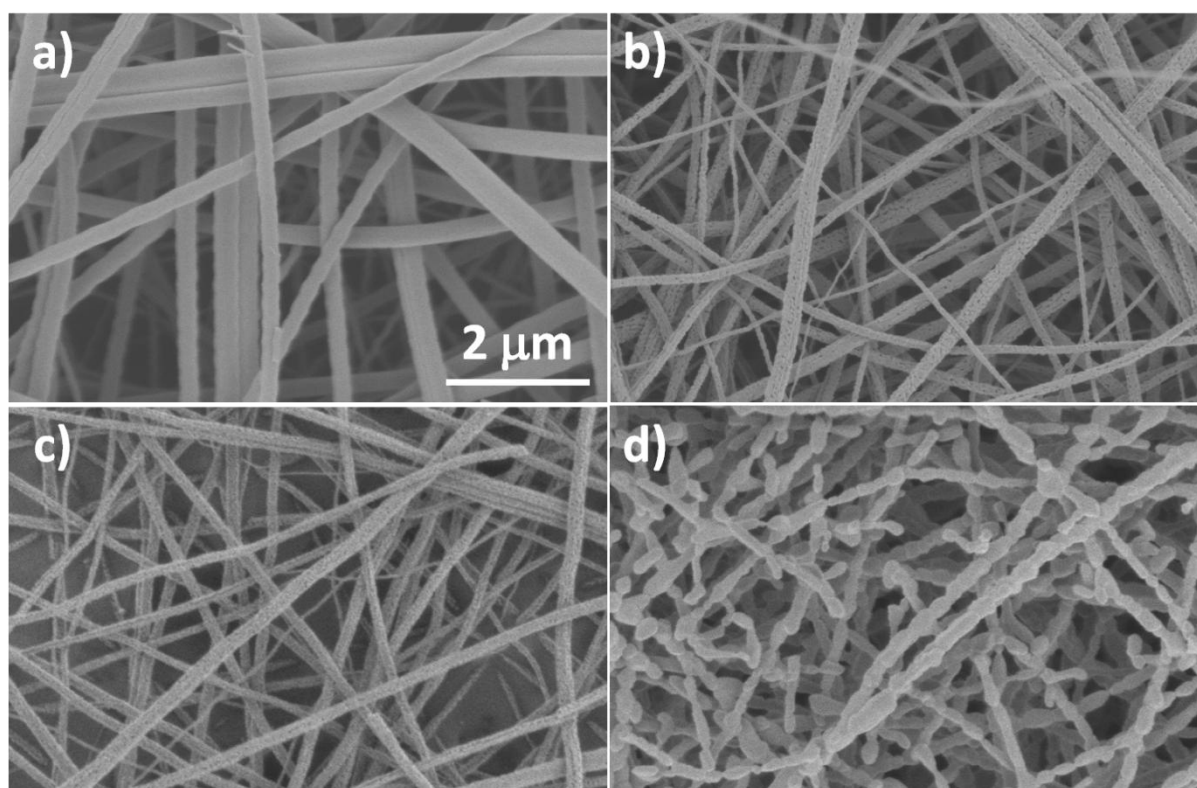


Figure 1. Scanning electron microscope images of the (a) as-spun TiO_2 -PVP composite nanofibers and TiO_2 nanofibers annealed in air at various temperatures for 4h: (b) 500°C , (c) 700°C , and (d) 900°C .

Table 1. EDX data showing the composition of TiO_2 nanofibers annealed at 500°C , 700°C and 900°C

Element	Atomic percentage		
	500°C	700°C	900°C
Ti	31.76	37.75	33.11
O	68.24	62.25	66.89

The XRD analysis (Figure 2) confirms the change of the crystalline structures when the annealing temperature increases. At 500°C, five peaks appear at $2\theta = 25.5^\circ$, 38.2° , 48.2° , 54.1° and 55.3° which correspond to (101), (004), (200), (105), (211) respectively of the crystallized anatase-structured TiO_2 . The Debye-Scherrer equation was used to calculate the crystal size of TiO_2 nanofibers. The grain size obtained at 500°C is 16 nm. At 700°C, the rutile phase is observed with the two diffraction peaks at $2\theta = 27.7^\circ$ and 35.8° that correspond to (110) and (101) respectively. An increasing of the average grain size to 30 nm is also observed. With the increasing of annealing temperature to 900°C, we have an increasing of the grain size to 45 nm and the anatase phase disappears and pure rutile-structured TiO_2 is observed with the diffraction peaks at $2\theta = 27.7^\circ$, 35.8° , 38.9° , 54.1° and 56.4° which correspond to (110), (101), (111), (210), (211) respectively.[26] The XRD results show a clear evolution of TiO_2 anatase-to-rutile when the temperature rises as well as an improvement in the crystalline structures.

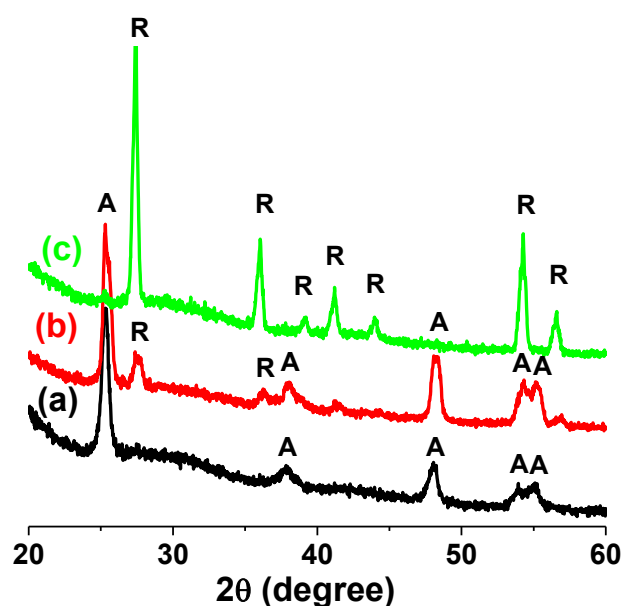


Figure 2. X-ray diffraction patterns of TiO_2 nanofibers treated at (a) 500, (b) 700, and (c) 900°C in air for 4h (A: anatase, R: rutile)

The formation of TiO_2 nanofibers and the anatase -to- rutile phase transition was confirmed by Raman spectroscopy because the two phases have two different spectra. The

spectra were taken at room temperature using a 532 nm laser line as the excitation source. Figure 3 shows Raman spectra of the TiO₂/PVP composite nanofibers calcined at 500°C, 700°C, and 900°C. We identify that anatase has six Raman active modes at 144 cm⁻¹ (E_g), 197 cm⁻¹ (E_g), 399 cm⁻¹ (B_{1g}), 513 cm⁻¹ (A_{1g}), 519 cm⁻¹ (B_{1g}) and 639 cm⁻¹ (E_g). [27] The Raman spectra of anatase phase were observed in the nanofibers treated at 500°C. At 700°C the very small peak at around 449 cm⁻¹ which is E_g mode of the rutile phase indicates the presence of rutile phase. Rutile has four Raman active modes detected at 244 cm⁻¹ (B_{1g}), 447 cm⁻¹ (E_g), 612 cm⁻¹ (A_{1g}) and 826 cm⁻¹ (B_{2g}). [32] After treated at 900°C the intensity of the peaks at around 449 cm⁻¹ (E_g) and at around 612 cm⁻¹ (A_{1g}) increased relative to the anatase peaks at around 400 cm⁻¹ (B_{1g}) and 639 cm⁻¹ (E_g), respectively, which confirm the anatase-to-rutile transformation. A small peak corresponding to E_g (144 cm⁻¹) which indicate the presence of anatase phase in the rutile sample even after annealing at 900°C is still observed.

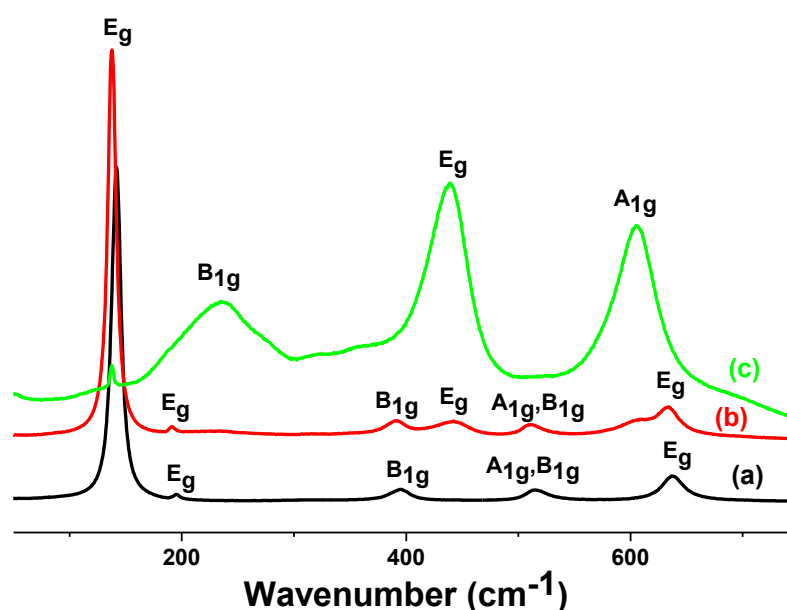


Figure 3. Raman spectra of TiO₂ nanofibers annealed at (a) 500, (b) 700, (c) 900°C

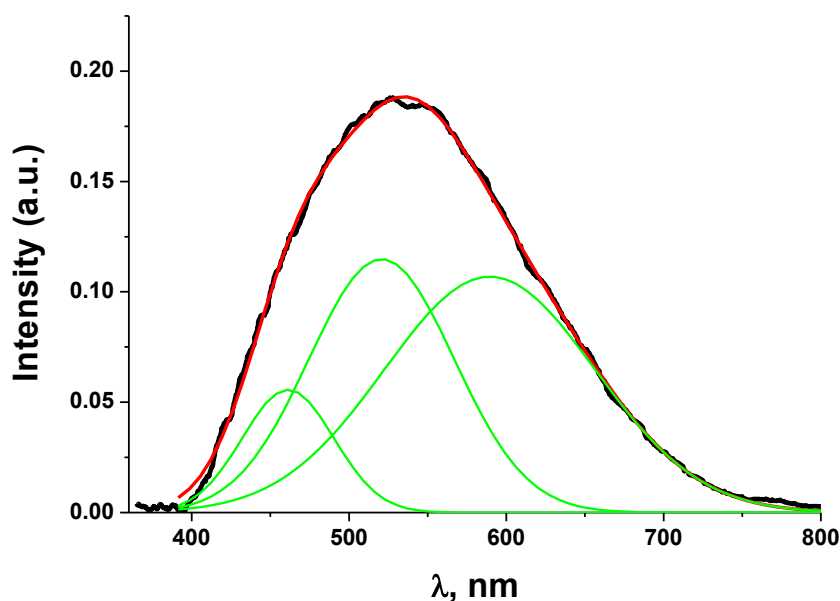


Figure4. Photoluminescence of TiO₂ nanofibers annealed at 500°C

The photoluminescence spectrum of TiO₂ nanofibers, annealed at 500°C is shown in Figure 4. The analysis of the spectrum was performed with Gaussian function fitting in Origin 7.5. Three emission bands were found: peak at 461 nm (related to self-trapped excitons)[24], peak at 520 nm (related to oxygen vacancies)[24] and peak at 589 nm. Room temperature emission at 580 nm was observed for TiO₂ nanofibers by J. Liu *et al.* [33], however no explanation of the peak was proposed. Knorr *et al.*[34] proposed that in anatase nanostructures two types of luminescence centers (traps) are possible: oxygen vacancies (hole traps) and electron traps (structural defects: Ti³⁺, Ti³⁺ interstitials, undercoordinated Ti atoms).[25, 35] According to Knorr *et al.*[34], the emission assisted by oxygen vacancies was blue shifted in comparison to the emission, assisted by electron traps. Candy Mercado *et al.*[36] generalized visible photoluminescence (~530 nm) in TiO₂ as recombination of free electrons with trapped holes and red emission (600 nm) as recombination of free holes with trapped electrons. Wang *et al.* [15] proposed donor-acceptor mechanism of photoluminescence in TiO₂ nanostructures. According to Wang *et al.*[15], singly ionized oxygen vacancies capture photogenerated electrons whereas the surface hydroxyl groups capture generated holes. The formed donor-acceptor couple induces electron-hole recombination with energy lower than free hole-donor recombination. As the samples were treated at high temperatures in air, the hydroxyl groups were removed or transformed to

molecular surface oxygen. Therefore, emission mechanisms proposed by Mercado *et al.*[36] are more possible.

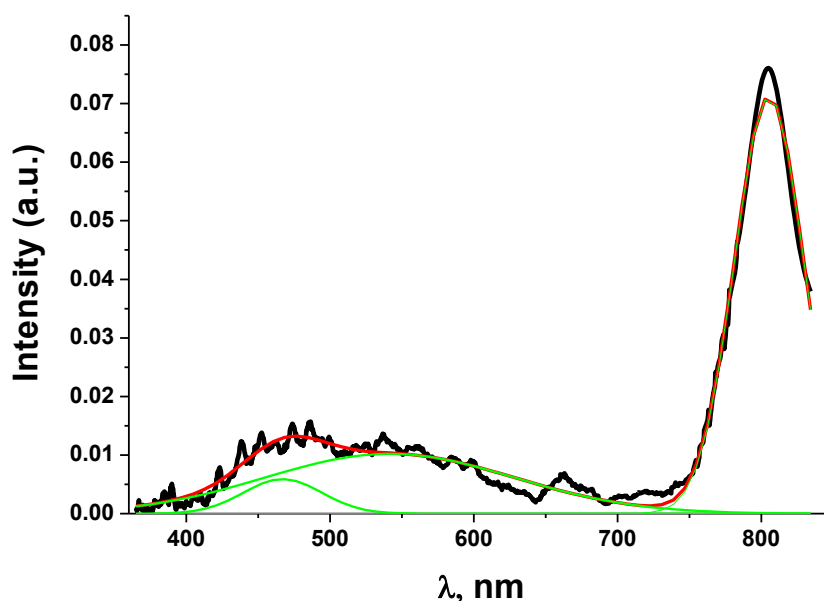


Figure 5. Photoluminescence of TiO₂ nanofibers, annealed at 900°C

The photoluminescence spectrum of TiO₂ nanofibers, annealed at 900°C is shown in Figure 5. The analysis of the spectrum with Gaussian function fitting showed 3 peaks: at 467 nm, 541 nm and 805 nm. It was found that PL emission of rutile phase of TiO₂ is located in IR range of the wavelengths.[25, 34, 36] It is associated with Ti³⁺ states and can be shown as recombination of free holes with trapped electrons.[25, 34, 36] According to XRD data, no anatase peaks were observed. Therefore, peak centered at 805 nm is attributed with Ti³⁺ states in TiO₂ rutile nanofibers. However, two weak peaks were observed at 467 and 541 nm. These peaks are well fit with anatase phase of TiO₂. The red shift is associated with annealing induced grain growth. Although XRD did not show the presence of anatase, Raman spectroscopy showed weak peak, corresponding to E_g (144 cm⁻¹). The small portion of anatase in rutile sample can explain the presence of anatase related PL peaks on emission spectrum of TiO₂ nanofibers, annealed at 900°C.

5. Conclusion

In conclusion, TiO₂ nanofibers with uniform diameters have been fabricated via electrospinning followed by calcination at different temperature in air for 4h. The SEM measurements indicate that the average diameter of nanofibers calcined at 500°C and 700°C is smaller than the as-spun nanofibers. At 900°C, the average diameter increases relative to 500°C and 700°C due to the increasing of the domain size of the crystal structure which is confirmed by XRD analysis. The Raman spectra and the XRD analysis show clearly the anatase phase at 500°C, the anatase-rutile mixed phase at 700°C and the complete anatase-to-rutile transformation at 900°C. Even if the XRD data shows a complete anatase-to-rutile transition in the TiO₂ nanofibers at 900°C, photoluminescence shows a small portion of anatase in rutile sample. This observation proved that photoluminescence could be a very sensitive tool to detect the presence of anatase in rutile phase TiO₂ nanostructures.

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