Chapter

Effects of Gamma Radiation on the Structural, Optical, and Photocatalytic Properties of TiO_2 Thin Films and Nanostructures for Photovoltaic Applications

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Abstract

In this chapter, we delve into a comprehensive discussion of the complex impact of gamma rays on materials of titanium dioxide (TiO_2) and their practical use in photovoltaic contexts. Our goal is to gain a better grasp of the dynamic interplay between gamma irradiation and the performance of TiO_2 for better utilization in photocatalysis. We aim to explore how the employment of gamma-treated TiO_2 in photovoltaic applications can lead to amplified solar cell effectiveness and endurance. As we strive to enhance sustainable energy initiatives and extend the range of innovative prospects for TiO_2 materials, we also scrutinize the fundamental processes that drive these developments. Additionally, we contemplate prospective avenues for research such as identifying optimal gamma-ray parameters, assessing the durability of treated TiO_2, and studying the synergistic influence of combining gamma radiation with other treatments. Scientists and industrialists seeking to enrich the performance of TiO_2 materials in solar energy endeavors can benefit from this chapter as a valuable reference.

Keywords: gamma radiation, TiO_2 thin films, TiO_2 nanostructures, structural modifications, optical properties, photocatalytic activity, photovoltaic devices

1. Introduction

Different fields are interested in titanium dioxide (TiO_2) due to its exceptional traits that make it a versatile material and crucial area of research [1, 2]. With a high surface-to-volume ratio, TiO_2 thin films are able to enhance properties and therefore receive significant attention [3]. The fabrication of TiO_2 thin films has been accomplished through different synthesis techniques that include sol-gel, chemical vapor deposition, and physical vapor deposition [4–6]. Nevertheless, post-treatments like ionizing radiation [7] can enhance these thin films.

Ionizing radiation in the form of gamma rays has been used to modify the chemical and physical characteristics of diverse materials, such as thin films of TiO_2. Induction of defects and oxygen vacancies in TiO_2 through gamma radiation has been found to change its structural, optical, and photocatalytic properties [8]. Still, the methods responsible for these adjustments are currently under investigation.

This chapter seeks to offer a thorough examination of how gamma radiation exposure affects the physical properties of both TiO_2 thin films and nanostructures, emphasizing its applications in photovoltaic technology. An overview of how gamma radiation interacts with matter is provided in our discussion about the mechanism of TiO_2 materials under this effect. This is given in our first section. In this section, we delve into how gamma radiation specifically impacts both the structural and electronic traits of TiO_2. This includes examining how it creates defects and impurities within the material.

The third section thoroughly examines the optical effects of gamma radiation on titanium dioxide materials, which can lead to the creation of defects and alterations in electronic structure. These changes can result in improved visible light absorption and an overall enhancement of the material's photocatalytic properties.

In the fourth section, we investigate the impacts of gamma ray exposure on TiO_2 photocatalytic characteristics. Our goal is to comprehend the intricate correlation between gamma radiation and TiO_2 efficiency in various photocatalysis domains. Through exploring the underlying mechanisms, we can enhance TiO_2 applications, realize more effective photocatalysts, and accomplish eco-friendly solutions, ultimately resulting in increasing possibilities for innovation and utilization of TiO_2 materials.

In section five, we explore the prospects of utilizing gamma-treated TiO_2 materials for photovoltaic purposes. The study concentrates on comprehending the consequences of gamma radiation exposure on TiO_2 material's efficiency, stability, and endurance concerning solar cells. Through scrutinizing the fundamental mechanisms, our goal is to refine TiO_2 implementation, design more potent photovoltaic apparatuses, and promote sustainable energy alternatives.

In the sixth section, we outline the future research directions for TiO_2 materials in photovoltaic applications, which involve gamma rays treatment. Our primary focus is on finding the optimal gamma-ray treatment parameters and assessing the long-term stability of treated TiO_2. Additionally, we investigate the possible synergistic benefits of combining gamma radiation with other treatments like doping and annealing.

In summary, this chapter provides a thorough examination of the impact of gamma radiation on thin films and nanostructures of TiO_2, emphasizing its potential applications in photovoltaics. By exploring the underlying mechanisms that drive these effects, the latest advancements in this field, and the associated challenges and merits of gamma radiation treatment, this chapter aims to provide invaluable insights into utilizing this tool for optimizing the properties of TiO_2-based devices.

2. Gamma radiation-induced structural changes in TiO_2 materials

Significant alterations in the structural characteristics of TiO_2 materials can result from exposure to gamma radiation. The crystalline composition may undergo changes such as transitioning from the anatase stage to the rutile phase or the emergence of faults in the crystal lattice. For instance, a study noted that a dose of 10 kGy (1 Mra) of gamma irradiation could raise the anatase to rutile transformation temperature from T_1 = 773 K to T_2 = 873 K, indicating that the thermal stability of the TiO_2 phase can be influenced by gamma radiation [9]. Furthermore, the ability of TiO_2 nanoparticles to perform optimally in procedures such as gas sensing and photocatalysis can be impacted by exposure to gamma radiation because it lowers the surface area and porosity of the particles. By way of example, another study found that the specific surface area of TiO_2 nanoparticles declined from 233.2 to 107.9 m^2/g subsequent to being exposed to 300 kGy of gamma radiation [10]. The reduction in surface area was determined to be due to the particles agglomerating and their porous structure collapsing.

Significant impacts on the properties and performance of TiO_2 materials can result from structural changes induced by gamma radiation. The material's optoelectronics and photocatalytic characteristics may be altered due to changes occurring in both its crystal structure and morphology [11]. In addition to its effects on other properties, such as morphology and gamma radiation-induced structural changes in titanium dioxide (TiO_2), nanomaterials can reduce both surface area and porosity. Such alterations could potentially hinder optimal functioning for gas sensing or photocatalytic applications [10].

The investigation of gamma radiation effects on TiO_2 materials can involve various techniques such as X-ray diffraction, Raman spectroscopy, transmission electron microscopy, and positron annihilation spectroscopy [12]. A high anisotropy in stretched thermal and electrical conductivity of TiO_2 nanostructures was demonstrated by one study through DFT calculations [9]. Various studies have investigated the effects of gamma radiation on organic matter composed of one or more constituents and determined that the radiation caused significant alterations to their electronic and structural properties [13].

It is important to comprehend the alterations in the structures of TiO_2 nanomaterials and thin films caused by gamma radiation, as it can enhance their properties for numerous applications, such as photocatalysis, gas sensing, and electronics. For instance, research indicates that gamma radiation ameliorates the photocatalytic performance of TiO_2 nanoparticles in eliminating pollutants [14]. Furthermore, a separate examination employing ceramography notes the influence of gamma radiation on the electronic properties of TiO_2 thick film, displaying that the method has potential in electronic device production [15].

It can be concluded that TiO_2 material properties and performance can be greatly impacted by structural changes induced by gamma radiation. Therefore, it is crucial to utilize multiple techniques to study the impact of gamma radiation on TiO_2 materials in order to gain a better understanding of the underlying mechanism and enhance their effectiveness for diverse applications.

3. Gamma rays-induced optical effects in titanium dioxide materials

Gamma rays, as a form of high-energy electromagnetic radiation, can cause substantial changes in the optical properties of titanium dioxide (TiO_2) materials, which serve as a highly adaptable and commonly employed semiconductor [4]. Interaction between titanium dioxide (TiO_2) materials with gamma rays has been known to elevate photocatalytic properties, amend electronic structures, and lead to the formation of defects [5]. This section will analyze the different optical impacts caused by gamma rays in TiO_2 materials, cite examples, and debate prior experimental findings.

In their study, Bouregui et al. [16] explored the effect of gamma irradiation on TiO_2 thin films' optical properties. By examining how different doses of gamma radiation affected these properties, they found that the absorption edge shifted toward lower energies, indicating a decrease in bandgap energy. This change could be due to defects produced by gamma irradiation, which increase the number of defect states and enhance visible light absorption. Along with an increase in photocatalytic efficiency, Bouregui et al. [16] suggest that gamma irradiation may be a valuable technique for tailoring TiO_2 thin films' optical properties to meet specific application needs.

The TiO_2 lattice can experience defects and oxygen vacancies when gamma rays disrupt the Ti-O bonds [16]. This, in turn, leads to an increased degree of defect states, decreased amount of energy in the bandgap, and a subsequent reinforcement of visible light usage [4]. This process can significantly amplify the photocatalytic efficiency of the TiO_2 materials. Wang and colleagues [17] found that by diminishing the energy in the bandgap of gamma-irradiated TiO_2 from 3.2 to 2.9 eV, there was a higher degree of photocatalytic activity for the breakdown of organic pollutants.

Several other investigations have reported related findings, supporting the influence of gamma rays on the optical properties of TiO_2. In one study by Zuo et al. [18], gamma-irradiated TiO_2 nanoparticles were perceived to demonstrate amplified photocatalytic activity in the degradation of organic pollutant under visible light. The enhancement was credited to a reduction in the bandgap and an escalation in oxygen vacancies induced by gamma irradiation. Furthermore, another study by Kumar et al. [19] observed a decline in the bandgap energy and improved photocatalytic activity of TiO_2 nanoparticles following exposure to gamma rays, which they attributed to the creation of oxygen vacancies and other defects.

Furthermore, along with photocatalytic applications, gamma-irradiated TiO_2 materials seem to have the potential for solar energy conversion. TiO_2-based solar cells can benefit from the reduced bandgap energy and increased visible light absorption. A good example is the improvement in photovoltaic performance shown by gamma-irradiated TiO_2 nanotubes as reported by Choi et al. [20], which was due to the increase in visible light absorption and the gamma ray-induced modification of electronic structures.

In summary, TiO_2 materials can undergo significant alterations in their optical properties, which can improve visible light absorption and photocatalytic efficiency when exposed to gamma rays. Numerous studies have highlighted the potential of gamma-irradiated TiO_2 in areas like environmental remediation and solar energy conversion [16]. This is possible since the interaction between gamma rays and TiO_2 can produce defects, modify the electronic structures, and improve the photocatalytic properties. Subsequently, researchers should focus on refining the gamma irradiation protocol to achieve the optimal optical properties to enhance the applications of TiO_2 [14]. Hybrid materials are also an area of interest. Through the use of semiconductors or metal nanoparticles in conjunction with TiO_2, researchers can enhance the separation of photogenerated charge carriers, resulting in improved photocatalytic performance [21]. In hybrid systems, gamma-irradiated TiO_2 can be beneficial owing to the changes in optical properties resulting from gamma rays.

Research on gamma rays-generated optical outcomes in titanium dioxide materials has unraveled multiple remarkable phenomena that could be utilized to boost the efficiency of TiO_2 in diverse roles. Through comprehending the processes that underpin these outcomes and refining the gamma irradiation procedure, experts can forge fresh methods to engineer sublime TiO_2 materials boasting specific optical traits.

This research domain is ripe with prospects for novel inventions and the generation of eco-friendly and better-performing resolutions in environmental revitalization, photovoltaic transformation, and other domains.

4. The influence of gamma radiation on titanium dioxide photocatalysis

Titanium dioxide (TiO_2), a widely-employed photocatalyst, boasts reactive properties, commendable stability, cost-effectiveness, and biocompatibility. TiO_2 nanoparticles, of exceptional interest as photocatalysts, exhibit sterling photocatalytic activity since their nanometric size and high surface area promote such reactivity. Photocatalytic activity of TiO_2 materials has been linked to a number of variables, gamma radiation among them. The effect of gamma rays on the photocatalytic activity of TiO_2 nanoparticles has been investigated using a multitude of samples.

A research study by Bouregui et al. [16] examined the impact of gamma radiation on the photocatalytic performance of controlled atmosphere TiO_2 nanoparticles. The nanoparticles underwent gamma irradiation at varying doses for investigation into their optical, structural, and photocatalytic attributes. According to the results, gamma radiation exerted favorable effects on the optic and structural properties of the TiO_2 nanoparticles. Further, there was a rise in nanoparticle crystallinity while their bandgap energy decreased due to increased gamma radiation dosages. The photocatalytic activity of the nanoparticles also improved with gamma radiation dosages by enhancing their surface area and creating oxygen vacancies. Such vacancies served as recombination centers for electron-hole pairs, elevating the charge separation efficacy and photocatalytic activity of the nanoparticles.

The impact of gamma radiation on the photocatalytic features of TiO_2 thin films was investigated in other studies conducted by Semalti et al. [22] and Haldar et al. [23]. Semalti et al. found that photocatalytic activity was amplified by gamma radiation, particularly at higher doses, due to the accumulation of oxygen vacancies and the development of Ti^{3+} ions, which boosted carrier separation. In contrast, Haldar et al. found that TiO_2 nanoparticle photocatalytic activity decreased with gamma radiation exposure due to defects and impurities formed in the crystal lattice, leading to reduced efficiency of charge separation and decreased photocatalytic activity.

A report published by Sajjadi et al. [24] shared that TiO_2 nanoparticles' photocatalytic activity reduced after gamma irradiation. Their research showed that as gamma radiation dose increased, the degradation rate of methylene blue dye under UV light irradiation also reduced. This is due to the reduction of oxygen vacancies and hydroxyl radicals. Xue et al. [25], on the other hand, discovered a rise in photocatalytic activity of TiO_2 nanoparticles at higher doses of gamma radiation. However, they associated the decrease in activity at low doses to the formation of recombination centers for electron-hole pairs and oxygen vacancies, but the high concentration of Ti^{3+} ions enhanced the carriers' separation.

We may reconcile these two studies by considering that oxygen vacancies and Ti^{3+} ions may impact TiO_2 nanoparticle photocatalysis. Low gamma radiation may increase oxygen vacancies, limiting photocatalytic activity, but at higher doses Ti^{3+} ions may dominate oxygen vacancies, boosting photocatalytic activity.

Ti^{3+} ions may impact the photocatalytic activity of TiO_2 nanoparticles [26], which can also be influenced by nanoparticle size, shape, contaminants, dopants, and irradiation conditions. Gamma radiation is known to affect the electronic structure and surface area of TiO_2 crystals, potentially altering the generation and recombination of electron-hole pairs vital to photocatalytic activity. The degree and type of defects formed by gamma radiation are dependent on a range of variables such as radiation dose, nanoparticle type, and environmental factors.

TiO_2 materials remains an encouraging option for environmental use cases like purifying water and controlling air pollution despite contradictory findings. Using TiO_2-based photocatalysis in solar photocatalysis has proven to effectively decontaminate and disinfect water [27]. The utilization of sunlight activates the photocatalytic reaction in this technology, without requiring any external energy sources or chemicals. Moreover, nanotechnologies based on TiO_2 have been created to purify and recycle water [28]. Their performance under visible light irradiation [29] is enhanced by combining TiO_2 nanoparticles with other materials like graphene.

Photocatalytic performance of TiO_2 materials can be enhanced by altering its surface properties. TiO_2 nanoparticles that have high-energy {001} facets exhibit improved photocatalytic activity due to increased adsorption of reactant molecules and facilitated separation of charge carriers. This phenomenon has been previously established by researchers [30]. The photocatalytic activity of TiO_2 nanoparticles can be enhanced by modifying their surface with metals or nonmetals, which improves their electron transfer and surface plasmon resonance properties.

Machine learning methods were utilized to examine the photocatalytic mechanism of semiconducting materials like TiO_2. Photocatalytic processes involve various intricate steps such as adsorption-reaction mechanisms for reactants' generation-separation mechanisms for charged particles role played by defects impurities; all these procedures can be investigated with these techniques. To explore the photocatalytic mechanism of TiO_2 nanoparticles under UV and visible light irradiation, Wu et al. [31] used machine learning algorithms. This study revealed that nanoparticles' photocatalytic activity was most significantly influenced by its surface structure and defects. Additionally, other important factors include its adsorption energy of reactant molecules and its energy barrier for electron transfer.

To summarize, the influence of gamma radiation on the photocatalytic operation of TiO_2 nanoparticles is still being questioned. Although some studies observed an improvement in photocatalytic performance, others noted a decrease. The inconsistent findings could be ascribed to the different experimental parameters and TiO_2 nanoparticles employed in each analysis. Additional investigation is necessary to fully comprehend the fundamental mechanisms and optimize the conditions for employing gamma-irradiated TiO_2 nanoparticles in photocatalytic applications. TiO_2 remains a hopeful photocatalyst for environmental implementations, and its photocatalytic efficiency may be boosted by combining it with other substances or altering its surface attributes. Learning algorithms may provide useful understandings into the intricate techniques implicated in photocatalysis and lead the way in designing more dependable photocatalysts.

5. Potential uses of gamma-treated TiO_2 materials in photovoltaics

The employment of gamma-examined TiO_2 materials in photovoltaic devices has demonstrated various benefits over unexamined TiO_2 materials. Gamma radiation handling alters the surface qualities of TiO_2, ensuring in enhanced light absorption, charge separation, and charge transit characteristics [16]. This may ultimately lead to amplified potency in solar cells, as well as enhanced resilience and durability.

Dye-sensitized solar cells (DSSCs) could benefit greatly from using gamma-treated TiO_2 materials in photovoltaics. Their affordability, lightweight, and flexibility make DSSCs an attractive alternative to the conventional silicon-based solar cells [32]. Enhancement of the surface area, crystallinity, and charge transfer properties [33, 34] of TiO_2 materials is achieved through gamma radiation treatment, thereby improving their performance in DSSCs. Additionally, this therapy can be a hopeful method to boost the effectiveness of DSSCs. TiO_2 nanotubes treated with gamma radiation demonstrated higher DSSC efficiency compared with untreated ones, as discovered by Kim et al. [35], while Mahmoud et al. [36] found that using gamma radiation-treated TiO_2 nanoparticles also increased DSSC efficiency.

Perovskite solar cells have displayed potential in photovoltaic applications due to their proficient power conversion efficiency and economical manufacturing expenses. Gamma radiation-treated TiO_2 materials have been studied as electron transport layers in perovskite solar cells, with arousing outcomes. Liu et al. [37] noted a substantial progress in the conductivity and crystallinity of gamma radiation-treated TiO_2 films. This led to a better charge transfer performance and a consequential elevation in the efficiency of the perovskite solar cells.

The study of organic solar cells, which use organic materials rather than inorganic semiconductors, has revealed promising results for use in photovoltaics. Gamma-treated TiO_2 materials have been shown to improve power conversion efficiency by improving light absorption, charge separation, and mobility of charges properties [38].

Photovoltaic device performance may be enhanced by gamma radiation treatment. Likewise, it can contribute toward enhancing the stability and endurance of TiO_2 components that play a crucial role in their long-term deployment within solar panels. Gamma treatment applied on TiO_2 materials enhances their surface area and crystallinity, which leads to reduced recombination speed and increased lifespan of electrons. This eventually promotes greater stability [35, 36]. TiO_2 materials treated with gamma radiation have shown increased ability in resisting various forms of environmental stressors, among them being high temperature and humidity. Also, this can reinforce the resilience of solar panels [33].

In general, the utilization of gamma-treated TiO_2 substances in the photovoltaic industry presents a hopeful pathway for creating effective, enduring, and stable solar cells. Further examination is necessary to investigate the complete potential of gamma radiation therapy on TiO_2 materials and how it affects different photovoltaic devices. Solar energy's adoption as a renewable resource can be boosted with improvements in this field. Additionally, their involvement can lead to the progression of a more eco-conscious future.

6. Gamma rays treatment of titanium dioxide materials for photovoltaic applications: Future research directions

Further investigations are needed to find the optimum parameters for gamma-ray treatment of TiO_2 materials, which would result in desirable properties for photovoltaic applications [10]. The dose and the dose rate of gamma radiation are critical considerations in controlling the physical and chemical properties of the material. Gamma radiation can affect the crystal structure, morphology, and electrical features of TiO_2 materials in different ways, thus making it a promising research avenue to determine the optimal protocol for photovoltaic usage.

Combining gamma radiation with other treatments, such as doping and annealing, may further enhance the performances of titanium dioxide thin films and nanostructures used in photovoltaic applications. Doping with transition metal ions or non-metals can improve titanium dioxide material's photocatalytic activity and electronic properties [11], while annealing can enhance its conductivity and optical absorption properties by reducing defects and enhancing crystal quality [12]. Novel strategies for improving of titanium dioxide thin films and nanostructures properties for photovoltaic applications can be explored by mixing gamma radiation with such treatments.

It is essential to study the long-term stability of TiO_2 materials that have been exposed to gamma radiation [13], as gamma radiation has been shown to gradually diminish the properties of materials. Thus, it is crucial to identify the degradation processes and investigate the durability of TiO_2 materials after extended exposure to gamma rays. This knowledge is essential for ensuring the long-term performance and durability of photovoltaic applications that involve TiO_2 materials.

Future research should focus on enhancing the durability of irradiated TiO_2 materials, refining gamma radiation treatment settings, and exploring the use of gamma radiation in conjunction with other therapies. These strategies will help advance the comprehension of photovoltaics by utilizing more efficient and resilient TiO_2 materials.

7. Conclusion

Titanium dioxide thin films and nanostructures exposed to gamma radiation exhibit significant modifications in their structural, optical, and photocatalytic properties, rendering them promising candidates for various applications. Gamma irradiation of TiO_2 is being explored for its potential use as an electron transport layer in perovskite solar cells and as a photoanode in dye-sensitized solar cells. Experiments have confirmed long-term increases in power conversion efficiency and reliability, offering hope for practical usage of these materials in PV systems.

Future research avenues may include refining the gamma radiation treatment settings to achieve greater performance and investigating the compatibility of these materials with other photovoltaic systems such as organic photovoltaics and multi-junction solar cells. Comprehensive research must be conducted to ensure the safety of these materials in real-world applications.

In summary, gamma radiation treatment of TiO_2 is a promising technique for customizing the material's properties for use in photovoltaic cells. Gamma radiation-induced changes in the crystal structure, morphology, electronic properties, and photocatalytic activity of TiO_2 contribute to enhancements in photoanode and electron transport layer performance in solar cells. However, further studies are needed to determine the viability of gamma radiation-treated TiO_2 in practical applications.

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