Review

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# Introduction and Advancements in Room Temperature Ferromagnetic Metal Oxide Semiconductors for Enhanced Photocatalytic Performance

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*Review*

# Introduction and Advancements in Room Temperature Ferromagnetic Metal Oxide Semiconductors for Enhanced Photocatalytic Performance

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**Abstract:** Recent developments in the field of room temperature ferromagnetic metal oxide semiconductors (RTFMOS) have shown promising potential for improved photocatalytic performance. This review focuses on the combined study of photocatalytic and ferromagnetic properties at room temperature, with a particular emphasis on metal oxides, such as $TiO_2$, which have emerged as a key area of interest in the domains of magnetism and environmental remediation. Despite extensive research over the years, the precise mechanism behind the interplay of ferromagnetism and photocatalysis in these materials remains incompletely understood. Several critical factors contributing to magnetism have been hinted at, including oxygen vacancies and various metal doping. Numerous reports have demonstrated that these factors play a primary role in room temperature ferromagnetism and photocatalysis in wide-band-gap metal oxides. However, establishing a direct correlation between magnetism, oxygen vacancies, dopant concentration, and photocatalysis has proven challenging. This review aims to provide a comprehensive overview of the recent progress in understanding the magnetism and photocatalytic behaviour of metal oxides. By examining the latest findings, this study sheds light on the potential of RTFMOS as effective photocatalysts, thereby contributing to advancements in environmental remediation and related applications.

**Keywords:** metal oxide semiconductors; photocatalytic performance; environmental remediation; oxygen vacancy

## 1. Introduction

In recent years, the quest for sustainable and environmentally friendly technologies has intensified, driving significant research efforts towards the development of advanced materials with multifunctional properties. Among these materials, room temperature ferromagnetic metal oxide semiconductors (RTFMOS) have emerged as a promising class of materials with potential applications in both magnetic and photocatalytic fields [1–4].

The intriguing fusion of ferromagnetism and photocatalysis within metal oxide semiconductors (MOS) has captured significant interest owing to its promising capacity to tackle pressing environmental concerns, especially in the arena of environmental restoration [5]. The process of photocatalysis, leveraging light energy to propel catalytic transformations, presents an environmentally conscious avenue for the disintegration of contaminants in both water and air. Concurrently, the manifestation of room-temperature ferromagnetism introduces a spectrum of potential technological utilities, encompassing spintronics and magnetic storage devices [6–8].

***Moreover:***

- The amalgamation of these attributes not only extends the functionality of MOS but also stimulates innovative avenues in multifunctional material design.
- The intersection of ferromagnetic and photocatalytic properties in MOS necessitates sophisticated characterization techniques to unravel the underlying mechanisms and interactions, fostering deeper insights for optimized applications.
- MOS exhibiting dual ferromagnetism and photocatalysis broaden the horizons of pollutant removal strategies, enabling simultaneous catalytic activity and pollutant adsorption for enhanced purification efficiency [9].
- The intricate interplay between ferromagnetism and photocatalysis in MOS can be harnessed for advanced water treatment systems, where contaminants can be effectively removed while exploiting the material's magnetic responsiveness for facile separation and recovery.
- Further research into the fundamental principles governing the coexistence of these phenomena could pave the way for tailored MOS hybrids with tunable functionalities, offering versatile solutions across fields spanning environmental science to electronics [10].This comprehensive review delves into the recent advancements made in the domain of RTFMOS and their implications for enhanced photocatalytic performance [11]. With a primary focus on metal oxides like Titanium dioxide ($TiO_2$), which stand at the forefront of this exciting field, the review aims to shed light on the intriguing interplay between magnetism and photocatalysis in these materials.

Despite decades of research, the exact mechanisms governing the coexistence of ferromagnetism and photocatalytic properties in metal oxides remain partially understood [12]. Several key factors, such as oxygen vacancies and metal doping, have been identified as crucial contributors to the observed room temperature ferromagnetism and photocatalytic behaviour [13]. However, a clear and direct correlation between these factors and the enhancement of photocatalytic performance has yet to be fully established.

Throughout this review, we will delve into the latest findings and key insights that have driven advancements in understanding the magnetism and photocatalytic attributes of MOS, particularly under visible light illumination. By comprehensively analyzing the existing body of knowledge, this review aims to provide valuable insights into the potential applications of RTFMOS for environmental remediation and other relevant fields.

The synergistic investigation of photocatalytic and ferromagnetic properties at room temperature presents a compelling avenue of research with promising implications across multiple fields. This combined study involves the exploration of materials possessing both photocatalytic capabilities and ferromagnetic behavior without the need for extreme conditions, thus enabling practical applications. The photocatalytic prowess of such materials allows for efficient light-driven catalysis, promoting environmentally friendly energy conversion and pollutant degradation. Concurrently, their ferromagnetic attributes open doors to spintronic applications, including data storage and sensing. The interplay between these two distinct yet interconnected properties holds the potential to revolutionize fields like sustainable energy, environmental remediation, and information technology, paving the way for innovative technologies and a more sustainable future.

In the subsequent sections, we will explore the mechanisms that underlie the interplay of ferromagnetism and photocatalysis, highlight the role of oxygen vacancies and metal doping, and discuss the challenges and opportunities in harnessing these materials for enhanced photocatalytic performance. Ultimately, this review seeks to contribute to the ongoing efforts in developing cutting-edge technologies that foster a cleaner and more sustainable future.

## 2. Advancements in Metal Oxide-Based Semiconductor Manipulation

Recent years have witnessed remarkable advancements in the manipulation of oxide-based semiconductors, leading to a transformative era in electronics and materials science [14]. Oxide-based semiconductors, with their diverse electronic, optical, and magnetic properties, have gained prominence as crucial components in various applications [15].Through precise engineering at the atomic level, researchers have achieved unprecedented control over the properties of these materials, tailoring their bandgap, conductivity, and even catalytic activity. The emergence of techniques such as epitaxial growth, strain engineering, and doping strategies has enabled the creation of designer interfaces and heterostructures, leading to novel functionalities and enhanced performance [16]. Moreover, the integration of oxide-based semiconductors into flexible and transparent devices has expanded their applications into wearable electronics and displays. As these advancements continue, the boundaries of what is achievable with oxide-based semiconductors are continuously pushed, promising breakthroughs in fields ranging from energy harvesting and storage to quantum computing and beyond [17].

### *2.1. Tunability of Wide Bandgap MOS Properties through Defect Engineering*

The intriguing convergence of ferromagnetism and photocatalysis within metal oxide semiconductors (MOS) has ignited widespread interest due to their potential in addressing environmental challenges and enabling advanced technologies. Notably: *Defect Engineering for Tuning Properties:* The manipulation of defect concentrations offers a versatile means to tailor MOS properties. By controlling defect levels, researchers can exert a profound influence on various aspects such as photon absorption, emission energies, and even intrinsic magnetism within MOS compounds [2]. This level of control provides a dynamic platform for customizing material behaviours to suit specific applications, spanning from photocatalysis to magnetics.

*Defect-Related Absorption Spectra Tuning:* The intricate interplay between defects and the electronic band structure gives rise to defect-related absorption spectra tuning. This phenomenon becomes a cornerstone for innovative applications, including the design of light-emitting diodes (LEDs), opto-magnetic devices, and even tuneable oxide-based materials [3,18]. The ability to engineer defect-induced absorption features empowers researchers to craft materials with tailored optical and magnetic functionalities.

*Versatility of $d^0$-Magnetism:* A distinguishing characteristic of these MOS materials is their $d^0$-magnetism, wherein their lack of partially filled d orbitals challenges conventional magnetic models [19]. This unique property enhances their versatility across different applications, ranging from catalysis and sensors to spintronic and optoelectronic devices [20]. The discovery of $d^0$-magnetism has unveiled a new paradigm in materials science and widened the scope of possible applications for these intriguing materials.

*Significance of n-type and p-type MOS Models:* Recent research has underscored the significance of n-type and p-type MOS models in various applications [21]. The distinct electronic characteristics of these models offer diverse avenues for tailoring material responses. N-type MOS materials, rich in electrons, are promising candidates for enhanced photocatalytic activity and charge transport, while p-type MOS materials, with electron deficiencies, offer intriguing possibilities for novel magnetic behaviours and spintronic applications. Exploring the capabilities of both models enriches our understanding of their potential roles in the technological landscape [4,22].

*Prospects for Advanced Technological Innovations:* The capacity to engineer wide bandgap MOS properties through defect engineering is a frontier with vast potential for innovative technological advancements. As researchers delve deeper into the intricate mechanisms that link defects to material behaviours, new avenues for functional materials emerge [23]. The ability to fine-tune electronic, optical, and magnetic properties opens up exciting possibilities for applications spanning energy conversion, environmental remediation, data storage, and beyond. These prospects not only fuel the curiosity of scientific exploration but also inspire the development of transformative technologies that can reshape industries and impact society on a global scale.

The convergence of defect engineering, ferromagnetism, and photocatalysis within wide bandgap MOS materials presents a captivating arena for exploration and innovation. By harnessing the power of defects to tailor material properties, researchers are poised to unlock a plethora of applications that harness the unique electronic and magnetic behaviours of these materials. This dynamic interplay between defects and properties serves as a catalyst for advanced technological innovations, shaping a future where materials are designed with precision to meet the demands of a rapidly evolving world.

### *2.2. Harnessing MOS Nanoparticles for Unique Properties*

MOS nanoparticles (NPs) present a captivating platform for harnessing exceptional properties that span various applications and industries. These nanoparticles, with their distinct characteristics, offer a diverse range of possibilities:

*Versatile Property Manipulation:* Metal oxide semiconductor NPs allow for the precise tuning of properties, ranging from bandgap to surface chemistry and charge carrier dynamics. This tunability empowers researchers to craft materials that precisely match specific needs, making them invaluable in tailoring materials for desired functionalities across domains [24].

*Enhanced Optical Properties:* The size and composition-dependent optical behaviours exhibited by metal oxide semiconductor NPs open doors to applications in sensors, displays, and optoelectronics [25]. Through meticulous control of their dimensions, these NPs can be engineered to emit, absorb, or scatter light in unique ways, enabling advancements in technologies such as light-emitting diodes, photodetectors, and optical sensors [26].

*Efficient Catalysis:* Leveraging their high surface area and tailored reactivity, metal oxide semiconductor NPs emerge as exceptional catalysts. They facilitate a broad spectrum of chemical reactions, from environmental clean-up and pollution mitigation to fuel cell efficiency enhancement. The ability to accelerate reactions at the nanoscale makes these NPs crucial components in addressing global sustainability challenges [27].

*Advanced Energy Technologies:* Metal oxide semiconductors NPs are instrumental in improving energy storage and conversion devices. Their integration into batteries, supercapacitors, and solar cells enhances overall performance and efficiency. By optimizing charge transport and recombination dynamics, these NPs contribute to the development of more sustainable and powerful energy solutions [28].

*Biomaterials and Medicine:* Surface engineering of metal oxide semiconductor NPs enables their seamless integration into biomedical applications. They find roles in drug delivery systems, targeted therapies, non-invasive imaging, and diagnostics. Their biocompatibility and tuneable properties open doors to innovative solutions in healthcare and medical technologies [29].

*Nanoelectronics:* Metal oxide semiconductor NPs Bridge the gap between traditional semiconductors and the nanoscale realm. This convergence facilitates innovations in nanoelectronics, enabling the development of novel electronic devices, memory technologies, and quantum computing components [30].

*Environmental Remediation:* One of the standout features of metal oxide semiconductor NPs is their photocatalytic prowess. These NPs can harness solar energy to drive pollutant degradation processes, offering a sustainable solution for eco-friendly water and air purification. This capability is poised to transform how we approach environmental remediation and tackle pollution challenges [31].

The manipulation of metal oxide semiconductor NPs unlocks a treasure trove of unique properties with immense potential across industries. Their adaptability, coupled with continuous research, promises transformative breakthroughs in technology, energy, healthcare, and sustainability. As our understanding of their behaviour deepens and our engineering capabilities

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expand, the applications of these nanoparticles are poised to shape the trajectory of technological advancement in the years to come.

2.2.1. MOS Nanoparticles and their Multifaceted Attributes

MOS nanoparticles (NPs), encompassing materials like $TiO_2$, ZnO, and $SnO_2$, have garnered significant attention for their intriguing blend of magnetic and charge transport properties [7]. Notably:

*$TiO_2$'s Special Significance:* Among MOS NPs, titanium dioxide ($TiO_2$) holds a distinctive position due to its solid photocatalytic behaviour and a plethora of advantages. These include affordability, exceptional chemical stability, and a high refractive index. The remarkable photocatalytic activity of $TiO_2$ has led to its widespread use in environmental remediation and self-cleaning surfaces.

*Addressing UV Limitations:* A significant challenge associated with $TiO_2$ is its reliance on ultraviolet (UV) light for photoexcitation, limiting its effectiveness under visible light. To overcome this limitation, researchers have devised strategies such as doping, co-doping, and surface grafting to enhance $TiO_2$'s photo-absorption capability. These modifications extend the photocatalytic activity of $TiO_2$ to the visible light spectrum, unlocking new possibilities for solar-driven applications [7–9,32].

*Structural Diversity:* The versatility of MOS composite nanomaterial structures adds a new dimension to their properties and applications. Configurations like core-shell, matrix-dispersed, Janus, and shell-core-shell arrangements (Figure 1) provide opportunities for enhancing specific attributes. These engineered structures enable fine-tuning of properties such as charge separation efficiency, catalytic activity, and even magnetic behaviour [12–15,32]. This diversity in structure offers a playground for tailoring materials to meet specific requirements, driving innovation across multiple disciplines.

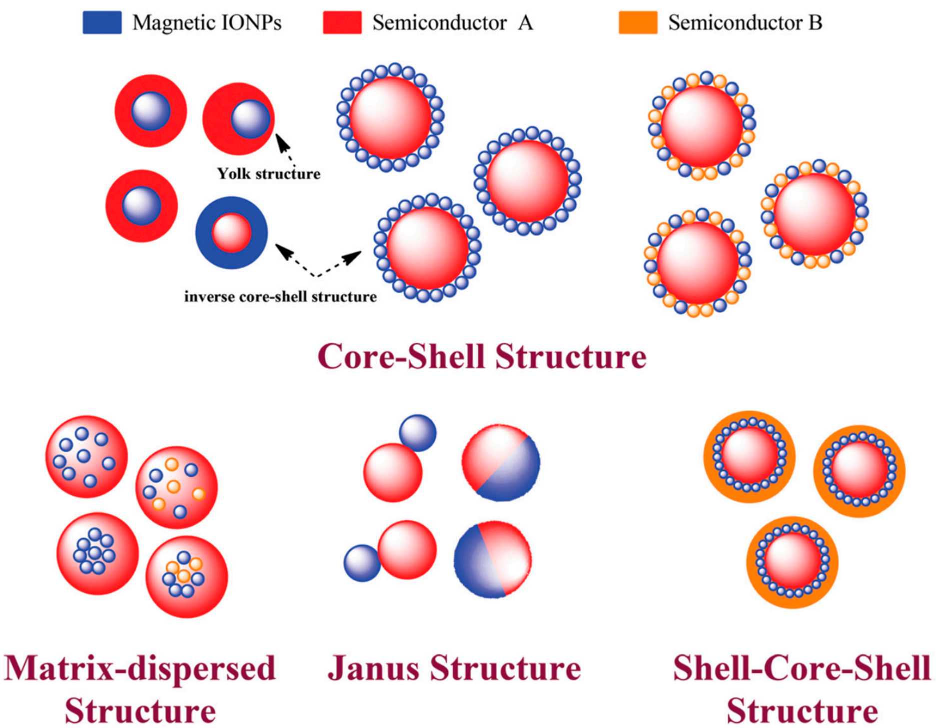


**Figure 1.** vividly illustrates the diverse architectures of magnetic MOS composite materials, highlighting the presence of magnetic MOS NPs (blue spheres) embedded within non-magnetic matrices and secondary materials [6].

*Exploring Magnetic-Transport Interplay:* The amalgamation of magnetic and charge transport properties within MOS NPs fuels novel scientific inquiries and applications. This interplay paves the way for multifunctional materials that can simultaneously respond to external stimuli, exhibit unique magnetic behaviours, and partake in energy conversion processes. The convergence of these attributes opens up innovative avenues for energy-efficient technologies, catalysis, and sensing.

*Beyond Photocatalysis:* While photocatalysis is a prominent domain of application for MOS NPs, their magnetic and electronic attributes extend their utility to diverse realms. These nanoparticles hold promise in spintronics, magnetic sensors, data storage, and even as building blocks for quantum technologies. The ability to manipulate both charge and magnetic properties introduces a level of versatility that widens their scope far beyond their traditional roles.

*Future Frontiers:* As the field of MOS nanoparticles advances, researchers continue to explore uncharted territories. The multifaceted attributes of these nanoparticles create a rich landscape for interdisciplinary research, driving collaborations between materials scientists, chemists, physicists, and engineers. The ongoing exploration of novel structures, enhanced properties, and multifunctional applications ensures that the journey of MOS nanoparticles remains a captivating and transformative one.

### 2.2.2. Impact of Sn Doping on MOS Properties

*Bandgap Modification through Doping:* The introduction of metal dopants into $TiO_2$ nanoparticles can exert a profound impact on their electronic properties. Sn doping, in particular, offers a means to modify the bandgap of $TiO_2$, leading to enhanced charge migration and shifts in photo-absorption spectra. This bandgap engineering opens up pathways for improved photocatalytic performance and increased efficiency in energy conversion processes.

*$SnO_2$-$TiO_2$ Hybrid System:* The hybridization of $TiO_2$ with another metal oxide, such as SnO2, presents an intriguing avenue for enhancing photocatalytic activity. In the case of [$Sn_xTi_{1-x}O_2$] hybrid nanocomposites, the synergistic interaction between $SnO_2$ and $TiO_2$ creates a platform where charge separation and catalytic processes are optimized. This enhancement can result in improved solar energy utilization and more efficient degradation of pollutants [33].

*Synthesis Challenges and Influences:* The successful synthesis of $SnO_2$-$TiO_2$ nanocomposites hinges on precise control over experimental parameters. Hydrothermal methods are often employed to fabricate these nanocomposites; however, challenges arise in preventing the formation of undesirable secondary phases. Achieving a well-defined $SnO_2$-$TiO_2$ hybrid structure requires careful manipulation of precursor concentrations, reaction temperatures, and growth times [34,35]. The synthesis intricacies underscore the importance of mastering materials engineering for tailoring desired properties.

*Applications of Sn-Doped $TiO_2$ NPs:* Sn-doped $TiO_2$ nanoparticles have exhibited improvements across diverse applications, solidifying their role as versatile materials. In the realm of photocatalysis, their enhanced charge carrier dynamics and modified band structures contribute to more efficient pollutant degradation and hydrogen generation [36,37]. Additionally, Sn-doped $TiO_2$ NPs find utility in energy storage technologies, including batteries and supercapacitors, where their improved charge transport properties enhance overall performance [38,39]. Furthermore, their application extends to solar cells, where the modified bandgap facilitates better light absorption and electron-hole separation, leading to enhanced photovoltaic efficiency [40,41].

*Unveiling New Horizons:* The impact of Sn doping on MOS properties extends beyond a mere modification of electronic structure. This deliberate introduction of Sn into $TiO_2$ nanocomposites opens doors to multifunctionality and tailored performance. As researchers continue to delve into the intricacies of Sn-doped systems, opportunities arise for optimizing synthetic approaches, elucidating fundamental mechanisms, and discovering novel applications. These nanocomposites exemplify the marriage of material design and functional outcomes, propelling the exploration of advanced materials with unprecedented attributes.

## *2.3. Unlocking Dual Properties: Ferromagnetism and Photocatalysis*

The intriguing convergence of ferromagnetism and photocatalysis within metal oxide materials offers a captivating avenue for multifaceted applications, merging magnetic responsiveness and light-driven catalysis. This dualistic interplay presents compelling opportunities across various fields:

*Synergistic Potential:* The coexistence of ferromagnetic and photocatalytic properties bestows materials with the capacity to serve diverse functions simultaneously. This transcendence of conventional capabilities opens doors to innovative solutions that harness the strengths of both properties in synergy [42].

*Advanced Functionalities:* The fusion of ferromagnetism and photocatalysis creates materials with enhanced functionalities that extend beyond traditional single-domain materials. This convergence fosters innovation in domains ranging from environmental remediation and energy conversion to advanced sensing and information storage technologies [42].

*Environmental Remediation:* Magnetic photocatalysts emerge as promising candidates for tackling water and air pollution challenges. These materials harness sunlight-driven reactions for pollutant degradation while also allowing for efficient magnetic separation. This dual approach offers an eco-friendly and effective solution for cleaning up environmental contaminants [43].

*Energy Conversion:* The intrinsic magnetic properties of these materials introduce new dimensions to energy conversion and storage applications. The coupling of magnetic behavior with photocatalysis holds potential for advancements in renewable energy technologies, such as solar-driven hydrogen production and efficient energy storage [44].

*Magnetic Manipulation:* The presence of ferromagnetism in these materials adds a novel layer of functionality—magnetic manipulation. External magnetic fields can be harnessed to control and modulate material behaviour, enabling applications like remote switching and controlled release in drug delivery systems [45].

*Tailored Synergy:* The interaction between ferromagnetism and photocatalysis can be finely tuned to achieve tailored synergies. By adjusting the material composition, structure, and magnetic properties, researchers can amplify performance in specific applications. This customization empowers materials to address targeted challenges with heightened efficiency [46].

The integration of ferromagnetism and photocatalysis in metal oxide materials marks a pioneering step towards versatile materials capable of addressing multifaceted challenges and pioneering novel technological frontiers. This convergence sparks curiosity and collaboration across scientific disciplines, driving researchers to explore uncharted territories and redefine the possibilities of materials with dual functionalities. The journey of harnessing the interplay between ferromagnetism and photocatalysis holds the promise of transformative impacts on technology, industry, and our efforts to build a sustainable future.

#### 2.3.1. Novel Synthesis Approach for Enhanced Nanocrystals

A novel synthesis approach has yielded remarkable results in the fabrication of Sn-$TiO_2$ nanocrystals, demonstrating the synergy of ferromagnetism and outstanding photocatalytic activity [47,48]. This hydrothermal method introduces controlled oxygen vacancies into the nanocrystal structure, inducing ferromagnetic behavior while retaining their photocatalytic prowess.

*Optical Shift in Sn-Doped $TiO_2$:* A noteworthy observation in Sn-doped and Sn-Fe co-doped $TiO_2$ systems is the optical absorption spectrum red-shift. This phenomenon results from the incorporation of Sn and Fe dopants, altering the electronic band structure of the nanocrystals. This shift holds the potential to enhance the efficiency of light absorption, enabling applications that require extended photo-response in the visible light spectrum [49]. This optical modification broadens the utility of these materials in light-driven technologies.

Multifunctional Potential: The tunability of metal oxide semiconductor nanoparticles, particularly through Sn doping, presents a gateway to enhancing both magnetic and photocatalytic properties. This multifunctional potential holds promise for advancing scientific understanding and technological applications across a diverse range of fields. From environmental remediation and energy conversion to information technology and biomedicine, the ability to tailor MOS nanoparticles with specific functionalities opens doors to innovative solutions that can reshape industries and improve quality of life [50–58].

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Harnessing this novel synthesis approach not only contributes to our understanding of materials' behaviour at the nanoscale but also paves the way for pioneering applications. The ability to engineer nanocrystals with tailored magnetic and a photocatalytic property broadens the scope of what these materials can achieve. As researchers continue to explore and refine these fabrication techniques, the world of nanotechnology stands poised to witness transformative advancements with far-reaching implications.

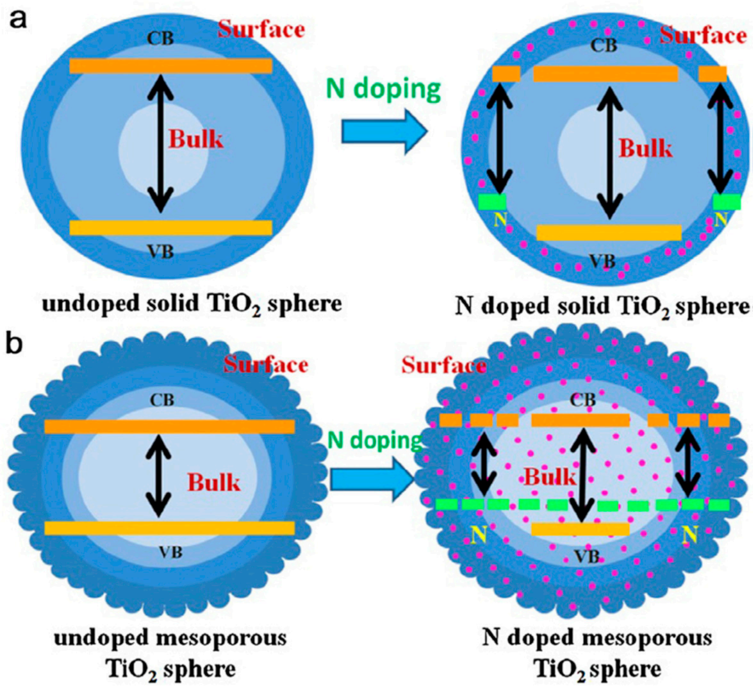


**Figure 2.** presents schematic diagrams elucidating the band structures of solid and mesoporous $TiO_2$, showcasing the effects of nitrogen doping [59,60].

*2.4. Elevating Visible-Light Activity via Co-Doping of MOS*

Co-doping of MOS emerges as a powerful strategy to significantly amplify their visible-light activity, ushering in a new era of enhanced photocatalytic performance and versatile applications:

*Synergistic Effects:* Co-doping involves introducing multiple dopants that work in synergy to manipulate electronic structures and bandgaps, enhancing light absorption and utilization.

*Expanded Photo-responsive Range:* By tuning co-doping ratios and combinations, MOS can effectively extend their light absorption spectrum into the visible range, unlocking previously untapped energy sources.

*Efficient Charge Separation:* Co-doping creates unique energy levels, facilitating the separation of photo-generated electron-hole pairs and thus elevating catalytic efficiency.

*Reduction of Bandgap:* Non-metal co-dopants introduce additional valence bands, while non-transition metal co-dopants introduce charge carrier traps, collectively narrowing the bandgap for visible-light utilization.

*Enhanced Catalytic Performance:* The improved charge carrier mobility and suppressed recombination rate achieved through co-doping lead to superior photocatalytic activity.

*Versatile Applications:* Co-doped MOS find applications in diverse fields, from environmental remediation to solar energy conversion, where efficient visible-light photocatalysis is crucial.

*Tailored Designs:* The flexibility of co-doping allows for tailoring MOS properties according to specific requirements, leading to advancements in materials engineering [51–54].

The co-doping of MOS emerges as a ground breaking avenue to unlock their untapped potential, revolutionizing their role in harnessing visible light for various sustainable applications and paving the way for a greener and more energy-efficient future.

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#### 2.4.1. Synergistic Effects of Non-Metal and Non-Transition Metal Co-Doping

*Boosting Photo-Electron Separation:* Co-doping of non-metals and non-transition metals enhances separation of electron-hole pairs, broadening photo-absorption limits [55,56].

*Potential of Nitrogen Doping:* Nitrogen doping, particularly effective, modifies charge transport properties and induces oxygen-defect sites, improving photocatalytic performance [57,58].

*Influence of Nitrogen Doping:* Nitrogen atoms substitution in the $TiO_2$ lattice reduces bandgap width, leading to promising visible-light photocatalysis [59].

#### 2.4.2. Unlocking Nitrogen Doping Potential

*Challenges of Bulk Nitrogen Doping:* Nitrogen doping in solid $TiO_2$ structures is hindered due to compact packing [60].

*Advantages of Mesoporous Nitrogen Doping:* Mesoporous $TiO_2$ with nitrogen doping showcases uniform energy levels, enhancing visible-light photocatalytic activity [60].

#### 2.4.3. Advancements in Sn and N Co-Doping

*Sol-Gel Preparation:* The integration of Sn and N co-doping into $TiO_2$ photocatalysts has demonstrated remarkable advancements in performance, particularly under visible light or simulated solar light irradiation [61]. The sol-gel preparation method has proven to be effective in introducing these dopants into the $TiO_2$ lattice, leading to enhanced photocatalytic activity through improved light absorption and charge separation.

*Remaining Frontiers:* While significant progress has been made in harnessing Sn and N co-doping for enhanced photocatalysis, there remain frontiers to be explored. Comprehensive research is needed to unravel the full extent of doping effects on the physical, chemical, and catalytic properties of co-doped microspheres. Understanding the intricate interplay between dopants, defects, and material behaviours is crucial for optimizing the design and fabrication of these advanced materials [62].

The strategic manipulation of oxide-based semiconductor properties through defect engineering, co-doping, and novel synthesis techniques holds immense promise across a wide spectrum of scientific and technological advancements. From the remediation of environmental pollutants to the creation of multifunctional materials with tailored properties, these approaches have the potential to reshape industries and drive innovation. Within this dynamic realm of materials engineering, the exploration of Sn and N co-doping emerges as a noteworthy avenue for achieving enhanced photocatalytic performance and expanding the applications of oxide-based nanocomposites. As research continues to progress, these advancements will contribute to a more sustainable and technologically advanced future.

## 3. Unveiling Diluted Magnetic Semiconductors

Diluted Magnetic Semiconductors (DMS) have emerged as a captivating class of materials that resonates with the pursuit of unconventional material functionalities. In recent years, the intersection of magnetic and semiconducting properties within DMS has sparked significant interest. DMS materials ingeniously integrate magnetic impurities—typically transition metal ions—into semiconductor matrices. This deliberate infusion of magnetic dopants within semiconductors engenders localized magnetic moments, effectually transforming otherwise non-magnetic semiconductor lattices. This intriguing synergy of magnetism and semi conductivity opens pathways to innovative applications spanning diverse scientific fields and technologies. As such, DMS materials stand as a testament to the boundless potential that arises from synergistically marrying distinct material attributes.

Recent strides in the realm of DMS have unveiled captivating phenomena and promising avenues that unfold across scientific disciplines and technological horizons. Within this evolving landscape, several distinct facets beckon exploration:

### 3.1. Exploring Spintronics Potential

*A Glimpse into Spintronics:* The realm of spintronics, propelled by the intriguing spin degree of freedom in electrons, has ignited significant interest due to its promise of revolutionary advances in electronics. Unlike traditional electronics that rely solely on the charge of electrons, spintronics harnesses the intrinsic spin property of electrons, opening up new horizons for efficient information storage, processing, and transmission. [63] This burgeoning field is characterized by its potential to revolutionize computing, memory, and sensor technologies by offering enhanced speed, lower power consumption, and increased data storage density.

DMS materials are emerging as critical players in spintronics, enabling precise control and manipulation of electron spins through external magnetic fields or electrical triggers. DMS are semiconductor materials doped with magnetic elements, introducing localized magnetic moments in the semiconductor lattice. This controlled introduction of magnetism into a semiconducting host material lays the foundation for creating spin-polarized currents and enabling efficient spin manipulation. The integration of DMS materials into spintronic devices introduces the exciting possibility of designing components that can simultaneously process and store information based on the spin state of electrons [64].

*Pioneering Spintronic Devices:* DMS materials hold the potential to underpin the development of various spintronic devices, thereby adding momentum to the spin-based information storage and manipulation arena. Spintronic devices, such as spin valves and magnetic tunnel junctions, leverage the ability to manipulate electron spins to encode and retrieve information. These devices are promising candidates for next-generation memory technologies, offering non-volatile storage with high speed and energy efficiency. Furthermore, the utilization of DMS materials in spintronic devices could potentially lead to the creation of more compact and power-efficient devices, revolutionizing not only the information technology sector but also advancing fields like quantum computing and advanced sensors [65].

The synergy between DMS materials and spintronics presents an exciting frontier in materials science and electronics. As researchers delve deeper into understanding the intricate interactions of electron spins within these materials, the realization of novel spintronic devices with unprecedented capabilities draws ever closer. The fusion of materials innovation, theoretical exploration, and device engineering in this domain is poised to reshape the technological landscape and fuel a new era of transformative electronics.

### 3.2. Augmenting Properties through Innovative Synthesis

*Engineering Magnetic-Semiconductor Synergy:* The pursuit of enhancing the synergistic interplay between magnetic and semiconductor properties within DMS materials has propelled the exploration of innovative synthesis methodologies and composite formations. These endeavours are rooted in the understanding that the manipulation of material composition, crystalline structure, and doping profiles can intricately modulate the magnetic and electronic characteristics of DMS materials. By engineering these factors, researchers aim to achieve enhanced control over spin interactions and electronic band structure, paving the way for novel functionalities in spintronic and electronic devices [66].

*Tailored DMS Compounds:* At the heart of this pursuit lies the discovery and design of tailored DMS compounds, where meticulous tuning of material properties holds the potential to unlock entirely new avenues for technological applications. The deliberate manipulation of DMS materials at the atomic and nano-structural scales allows for the creation of customized materials with properties optimized for specific tasks. This tailored approach enables the exploration of previously inaccessible parameter spaces, facilitating the emergence of unprecedented DMS materials with precisely engineered magnetic and electronic attributes. Such advancements carry profound implications for the development of cutting-edge magnetic sensors, spin-based logic devices, and energy-efficient memory technologies [67,68].

Unveiling new DMS compounds with precisely tailored properties has emerged as a beacon of progress in the field, signifying prospects for the realization of innovative magnetic and electronic devices. These endeavours not only deepen our fundamental understanding of the intricate interplay between magnetism and semi conductivity but also invigorate the exploration of uncharted territories within materials design. The fusion of innovative synthesis strategies with precise property tailoring promises to reshape the landscape of materials science, thrusting DMS materials to the forefront of next-generation electronics and spintronic technologies [69]. As researchers delve further into these transformative approaches, they open doors to a realm of possibilities where the boundaries of traditional materials limitations are redefined, ushering in a new era of functional materials and advanced device architectures.

### *3.3. Unveiling Magneto-Optical Frontiers*

*Magneto-Optical Enigma:* The recent strides in materials research have unveiled a realm of unique magneto-optical effects within DMS materials, heralding a new era of exploration and innovation. [70] These intriguing phenomena have transformed DMS materials into a fertile ground for the convergence of magnetism and optics, with profound implications for the development of next-generation optoelectronic devices. Through the interaction between external magnetic fields and light, researchers have uncovered fascinating magneto-optical properties that can be harnessed for a variety of applications.

*A Nexus of Light and Magnetism:* The marriage of magneto-optical attributes with the inherent properties of DMS materials offers a tantalizing glimpse into the creation of novel optoelectronic devices. The ability to modulate light properties, such as polarization, reflectance, and transmission, through the manipulation of magnetic characteristics presents unprecedented opportunities. By controlling the interaction between photons and spin-polarized carriers, DMS materials hold the potential to revolutionize fields such as magneto-optical data storage, quantum information processing, and advanced sensing technologies [71].

*Tunable Magnetic and Optical Functionalities:* The allure of DMS materials lies in their inherent tunability—allowing for the manipulation of both magnetic and optical properties through external stimuli. This tunability opens pathways for the creation of dynamic and adaptive devices where magnetic and optical functionalities can be tailored in real time. From magneto-optical modulators to spintronic-based light sources, the synergistic integration of magneto-optical effects within DMS materials empowers engineers and researchers to envisage and fabricate devices that harness the full spectrum of light-matter interactions [72].

As magneto-optical research continues to unravel the complex interplay between magnetic ordering and optical behaviour within DMS materials, the stage is set for a vibrant and transformative chapter in optoelectronics. The magneto-optical enigma, once shrouded in mystery, is now being harnessed to drive innovation, pushing the boundaries of what is achievable in the realm of light manipulation and magnetic control. This evolving landscape not only deepens our understanding of fundamental physics but also enriches the potential for breakthrough technologies that will shape the future of information processing, communication, and sensing.

### *3.4. Surmounting Challenges*

*Room-Temperature Ferromagnetism:* Despite significant progress, achieving robust and stable ferromagnetic order at room temperature within DMS materials remains a formidable challenge. The susceptibility of magnetic properties to temperature fluctuations necessitates innovative strategies to enhance and maintain ferromagnetic behaviour. Researchers are actively exploring avenues such as precise doping profiles, defect engineering, and nano-structuring to surmount these challenges and enable consistent ferromagnetic properties at practical operating temperatures [73].

*Efficient Spin Manipulation:* The efficacy of spin injection, transport, and detection is a cornerstone of successful DMS research, directly influencing the viability of spintronic applications [74]. Maximizing the efficiency of spin-related functionalities requires intricate control over spin polarization, carrier lifetimes, and spin relaxation mechanisms. Scientists are delving into techniques like spin injection from ferromagnetic electrodes, as well as tailoring interfaces between DMS and

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non-magnetic materials, to optimize the interaction between spins and carriers, with the aim of creating highly efficient spintronic devices [75].

*The Evolving Landscape of DMS:* The dynamic evolution of DMS research has opened up vistas that extend toward the realm of next-generation spintronic and magneto-optical devices. As we navigate these uncharted territories, the marriage of magnetic and semiconductor properties are within DMS materials presents an unprecedented opportunity to craft advanced functionalities. With continued research and development, DMS materials are poised to leave an indelible mark on modern technology, shaping the contours of magnetic and semiconductor domains alike. This trajectory promises to unleash transformative devices that harness the unique interplay of spins and charge carriers, bridging the gap between conventional electronics and the future of spin-based technologies. As the boundaries of what is possible with DMS materials expand, they are poised to reshape the technological landscape and catalyze the emergence of a new era of multifunctional, high-performance devices [76].

### *3.5. Exploring Ferromagnetism in DMS Intricacies of Ferromagnetism: Diluted*

Magnetic Semiconductors, often dubbed "semi-magnetic semiconductors," have incited rigorous exploration due to their unique blend of semiconductor properties and ferromagnetic behaviour. The intricate interplay between electron charge and spin has captured the attention of researchers, driving them to delve deeper into the fascinating world of DMS materials [77].

*Unravelling the Phenomenon:* The coexistence of semiconductor and ferromagnetic properties within DMS materials presents a complex puzzle that scientists are striving to solve. The controlled introduction of magnetic ions into a semiconductor matrix creates a system where the interaction between localized magnetic moments and mobile charge carriers gives rise to novel physics and functionalities [78]. Understanding the mechanisms that govern the emergence and manipulation of ferromagnetism in these materials is essential for harnessing their potential in various applications.

*Ferromagnetic Fascination:* The tantalizing prospect of achieving room temperature ferromagnetism in DMS, especially in oxide-based variants, has ignited a wave of excitement within the scientific community. The ability to achieve and control ferromagnetism at temperatures that are practical for everyday applications opens up a plethora of possibilities.

*Cross-Disciplinary Applications:* The allure of DMS materials with ferromagnetic properties extends far beyond the realm of fundamental research. The integration of these materials into practical technologies holds promise for numerous fields. For instance, the development of magnetic fluids using DMS could revolutionize industries ranging from transportation to robotics by enabling efficient and controllable fluid manipulation through external magnetic fields [79].

*Biomedical Innovations:* The intersection of DMS and biomedicine showcases another facet of the potential impact. The magnetic properties of DMS could be harnessed to develop targeted drug delivery systems, where externally applied magnetic fields guide drug-loaded DMS particles to specific locations within the body. This precision could minimize side effects and enhance the efficacy of therapeutic treatments [79].

*Catalysis and Environmental Remediation:* DMS materials with ferromagnetic behaviour have shown promise in catalytic applications and environmental remediation efforts. These materials could be employed as catalysts in various chemical reactions, and their magnetic properties might facilitate separation and recovery processes, reducing waste and improving the efficiency of resource utilization [79].

The journey to unravel the mysteries of ferromagnetism in DMS continues to captivate researchers. As our understanding of the underlying physics deepens and our ability to engineer these materials advances, we stand on the cusp of transformative breakthroughs across multiple scientific disciplines and industries [78,79].

### *3.6. Novel Synthesis Unveils Potential*

*Synthesis's Impressive Yield:* The journey of synthesizing DMS materials has been marked by remarkable breakthroughs, each contributing to the expansion of our understanding and capabilities.

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One exemplary feat in this realm comes from the work of Wang *et al.*, who devised an ingenious method to synthesize ZnO crystals enriched with Zn vacancies. This novel approach not only resulted in materials with unique properties but also opened up exciting avenues for applications across various domains [80].

*Beyond Conventional Boundaries:* The synthesis methods used to engineer DMS materials have evolved significantly, breaking away from conventional strategies and venturing into innovative territories. Wang et al.'s approach exemplifies this trend, where the intentional introduction of Zn vacancies within ZnO crystals led to the emergence of unexpected characteristics. These advancements highlight the power of unconventional thinking in materials synthesis, enabling the tailoring of properties that were previously considered elusive [81].

*Pioneering Photo-Induced Ferromagnetism:* A captivating advancement in the field of DMS synthesis revolves around photo-induced ferromagnetism in transition metal-doped $TiO_2$ nanoparticles. This pioneering discovery challenges conventional notions of temperature-dependent ferromagnetism by demonstrating that controlled defect creation induced by light can lead to ferromagnetic ordering even at room temperature [22]. This phenomenon introduces a new dimension to our understanding of magnetism and lays the groundwork for innovative approaches to engineering magnetic materials.

*Unravelling the Mystery:* While the emergence of room-temperature ferromagnetism in transition metal-doped $TiO_2$ nanoparticles is a significant stride, the precise mechanisms underlying this phenomenon continue to intrigue researchers. The role of transition metals in inducing ferromagnetic ordering within $TiO_2$ remains an enigma that scientists are diligently working to solve. Unravelling this mystery holds the potential to not only deepen our fundamental understanding of magnetism but also pave the way for tailored synthesis strategies to harness this unique behaviour [82].

*Synergy of Synthesis and Exploration:* The evolving landscape of DMS synthesis exemplifies the symbiotic relationship between materials engineering and scientific exploration. As researchers push the boundaries of what is possible in synthesis techniques, they simultaneously unravel new properties and behaviours in DMS materials. This synergy underscores the dynamic nature of scientific progress, where advancements in synthesis methodologies continually inform and guide our quest to understand and harness the potential of novel materials.

The impressive achievements in DMS synthesis, as exemplified by the innovative work of Wang et al. [81] and the ground-breaking photo-induced ferromagnetism in transition metal-doped $TiO_2$ nanoparticles, reflect the relentless pursuit of scientific discovery and technological innovation. These strides not only contribute to the expansion of our knowledge but also inspire novel applications that could reshape industries and enhance our daily lives.

### *3.7. Unlocking Magnetic-Photocatalyst Synergy*

*Magnetic-Photocatalyst Nexus:* The pursuit of merging the seemingly disparate realms of ferromagnetism and photocatalytic activity within wide-band-gap metal oxide-based nanocomposites has catalyzed the development of innovative models and approaches [47]. Researchers recognize that the intersection of these two properties holds immense promise for applications spanning environmental remediation, energy generation, and beyond. Central to these investigations is the exploration of how surface oxygen vacancies and heightened charge carrier concentration synergistically influence both magnetism and photocatalytic performance [83].

*Harnessing Synergistic Effects:* The convergence of room-temperature ferromagnetism and enhanced photocatalytic efficiency in nanocomposites has unveiled a remarkable synergy. These materials exhibit the capacity to harness visible light irradiation, a crucial aspect for practical applications, and convert it into efficient photocatalytic processes. This ability to simultaneously manipulate charge carriers for magnetic responses and facilitate photocatalytic reactions highlights the power of engineered nanomaterials in achieving multifunctional capabilities [84].

*A New Era in Photocatalysis:* The emergence of magnetic photocatalysts signifies a paradigm shift in the field of photocatalysis. Traditional diamagnetic photocatalysts often face limitations in efficiently utilizing visible light due to their band structures. The introduction of room-temperature ferromagnetism not only extends the spectral range for photocatalysis but also provides an avenue for fine-tuning catalytic properties through magnetic manipulation [85]. This breakthrough is particularly significant in the quest for sustainable energy solutions and pollution mitigation.

*Doping and Co-Doping Strategies:* The development of magnetic photocatalysts underscores the pivotal role of controlled doping and co-doping in semiconductor nanocomposites. By judiciously introducing magnetic ions into the semiconductor matrix, researchers can tailor the electronic band structure and modulate charge carrier dynamics [86].

This strategic manipulation empowers materials to exhibit both ferromagnetic behaviour and enhanced photocatalytic performance simultaneously [87,88]. Such insights into the synergy between doping strategies and multifunctionality hold promise for the design of next-generation functional materials.

*Innovation at the Interface:* The convergence of magnetism and photocatalysis at the nanoscale interface exemplifies the power of interdisciplinary research. This fusion necessitates expertise in materials science, solid-state physics, chemistry, and engineering, highlighting the collaborative nature of scientific advancements. As researchers continue to unravel the intricate mechanisms governing magnetic-photocatalyst synergy, they pave the way for transformative technologies with applications that extend from clean energy production to pollutant degradation [85–88].

The magnetic-photocatalyst synergy exemplifies how harnessing multiple functionalities within a single nanocomposite can lead to ground-breaking advancements. This emergent field not only expands our fundamental understanding of materials but also presents innovative solutions to pressing global challenges. The journey to unlock the full potential of magnetic-photocatalyst nanocomposites is a testament to human ingenuity and the limitless possibilities that interdisciplinary research can unfold.

### *3.8. DMS for Technological Evolution*

*DMS's Technological Relevance:* The advent of DMS materials exhibiting room temperature ferromagnetism has ignited a technological revolution with profound implications. These materials have rapidly transitioned from theoretical curiosities to pivotal players in various technological domains. Their unique combination of semiconductor behaviour and ferromagnetic properties holds immense promise for innovations in spintronics, optoelectronics, and memory devices, paving the way for a new era of electronic technologies [89,90].

*Reshaping Electronics:* DMS materials are poised to revolutionize the landscape of electronics by enabling the development of spin-based field-effect transistors (spin-FETs) and spin-based light-emitting diodes (spin-LEDs). These advancements are underpinned by the ability to manipulate and control the spin of charge carriers, offering potential for low-power, high-speed devices that can surpass the limitations of conventional transistor technology [91,92]. The marriage of ferromagnetism with electronic functionality brings about a fundamental shift in the design and operation of electronic components.

*Exploring Multiferroics:* Beyond their standalone ferromagnetic behaviour, the exploration of DMS materials extends into the realm of multiferroics. The integration of magnetic ordering with other ferroic ordering parameters, such as ferroelasticity or ferroelectricity, holds great promise for the development of novel spintronics and magneto-optic devices. These multifunctional materials could pave the way for new paradigms in data storage, sensor technology, and even quantum computing [93].

*Lightweight Doping for Enhanced Properties:* Researchers are continually pushing the boundaries of DMS materials by exploring the impact of lightweight doping elements such as carbon (C), nitrogen (N), and lithium (Li) in metal oxide matrices. These doping strategies have been found to bolster ferromagnetic behaviour, thus expanding the range of materials that can exhibit this unique property. The marriage of theoretical modeling and experimental investigations is shedding light on the intricate mechanisms that govern these enhancements, with potential implications for both fundamental physics and practical applications [94].

*Innovation's Horizon:* As the technological landscape continues to evolve, DMS materials stand at the forefront of innovation. Their capacity to bridge the gap between semiconductors and ferromagnets has opened up new possibilities that were once deemed unattainable. From advancing information storage and processing to revolutionizing data communication, the journey of DMS materials promises to reshape industries and influence our daily lives in ways that were once the realm of science fiction.

The emergence of DMS materials as technological enablers exemplifies the rapid pace of scientific advancement. These materials are not only rewriting the rules of electronics but also inspiring a new wave of interdisciplinary research that blurs the boundaries between distinct fields. As DMS materials continue to unveil their potential, they usher in a future where the fusion of semiconductors and ferromagnetism gives rise to transformative technologies.

### *3.9. Harnessing Defect Engineering for Enhanced Performance*

*Defect Engineering's Impact:* The strategic incorporation of defects into the matrices of transition metal-doped metal oxide semiconductors has emerged as a powerful avenue for tailoring material properties. This innovative technique, often achieved through controlled ion beam irradiation, offers a transformative approach to manipulating the behaviour of materials on the nanoscale. Notably, the synergy between defects and magnetic properties has gained attention, particularly in the context of enhancing the ferromagnetic behaviour of materials like ZnO nanoparticles [95–97].

*Unleashing Structural Complexity:* Ion beam irradiation represents a sophisticated method for introducing controlled defects into materials. By irradiating ZnO nanoparticles with low-energy ions, researchers have managed to induce structural complexity that goes beyond conventional doping approaches. This structural manipulation serves multiple purposes—eliminating unwanted secondary impurity phases, fine-tuning lattice arrangements, and inducing localized distortions. The resulting materials exhibit enhanced ferromagnetic properties that are pivotal for diverse applications [98].

*Balancing Defects and Functionalities:* One of the key challenges in defect engineering is striking a delicate balance between introducing defects and preserving desired functional properties. Low-energy ion beam irradiation, particularly with inert gases, emerges as an ideal strategy in this regard. This technique enables the controlled induction of defects while simultaneously managing intrinsic structural imperfections. Additionally, it mitigates the risk of segregation of doped transition metal clusters that could hinder desired material properties [99]. This approach aligns with the overarching goal of developing cost-effective, high-efficiency materials for multifunctional applications.

*Towards Enhanced Nanocomposites:* The marriage of defect engineering with DMS materials holds immense promise in the realm of advanced nanocomposites. The integration of controlled defects not only enhances ferromagnetic properties but also synergistically influences other functionalities, such as photocatalytic activity. This dual enhancement is particularly relevant in the context of materials like $TiO_2$, where defect engineering could unlock the full potential of ferromagnetic and photocatalytic $TiO_2$ nanocomposites [99].

*Beyond Empirical Exploration:* Defect engineering offers more than just empirical enhancements; it provides a pathway for rational design and optimization. Through computational simulations and theoretical modeling, researchers are gaining insights into the intricate mechanisms that govern defect-induced changes in material properties. This deeper understanding enables targeted defect engineering strategies, reducing the need for trial-and-error approaches and accelerating the development of tailored materials [98].

*Future Prospects:* Harnessing defect engineering to optimize material properties transcends the realm of DMS materials. It underscores the versatility of this approach in enhancing a wide range of functional materials, from semiconductors to catalysts and beyond. As our ability to engineer and characterize defects advances, the potential for creating materials with unprecedented combinations of properties grows, opening up new frontiers in technology and innovation.

The art of defect engineering is revolutionizing our approach to materials design. The strategic manipulation of defects through techniques like ion beam irradiation is enabling us to craft materials

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with enhanced and multifunctional properties. This approach, exemplified in the context of DMS materials, promises to reshape industries and drive innovations that address some of society's most pressing challenges. As we continue to delve into the intricacies of defect-engineered materials, we step closer to a future where materials are tailored to our needs with unprecedented precision.

### 3.10. A Rich Portfolio of Achievements

*Past Endeavors, Ongoing Explorations:* Previous research reports have chronicled the photocatalytic and magnetic prowess of various $TiO_2$-based photocatalysts, spanning metal oxide coupled $TiO_2$ to hierarchical Sn and N co-doped $TiO_2$ [47–49,100–103].

*Towards Enhanced Functionalities:* These studies collectively deepen the understanding of $TiO_2$ nanocomposites, enhancing their photocatalytic and magnetic functions, and charting pathways towards diverse applications in materials science and technology.

*Discerning Magnetic Realms:* Figure 3(A) artfully captures the potential magnetic species and their distribution, hinting at intriguing interactions [104].

*Magnetism in Action:* Figure 3(B) delves into the magnetic world, illustrating M-H curves of pristine and Fe-doped $TiO_2$, evoking the magnetic transitions at play [104].

*Peering into Fe-Doped $TiO_2$:* Figure 3(A) casts light on the magnetic landscape of Fe-doped $TiO_2$ NPs under vacuum annealing, highlighting magnetic polarons and their alliances [104].

*Mapping Magnetization:* Figure 3(B) charts the journey of magnetization, capturing its trajectory in vacuum-annealed pristine and Fe-doped $TiO_2$ NPs, each curve telling a magnetic tale [104].

*Oxygen Vacancies' Role:* The magnetic ordering in Fe-doped $TiO_2$ NPs toggles between paramagnetism and ferromagnetism *via* oxygen vacancies [104].

*Defect-Induced Ferromagnetism:* The interplay of defects and Fe doping emerges as a potent mechanism, triggering ferromagnetic exchange coupling [104].

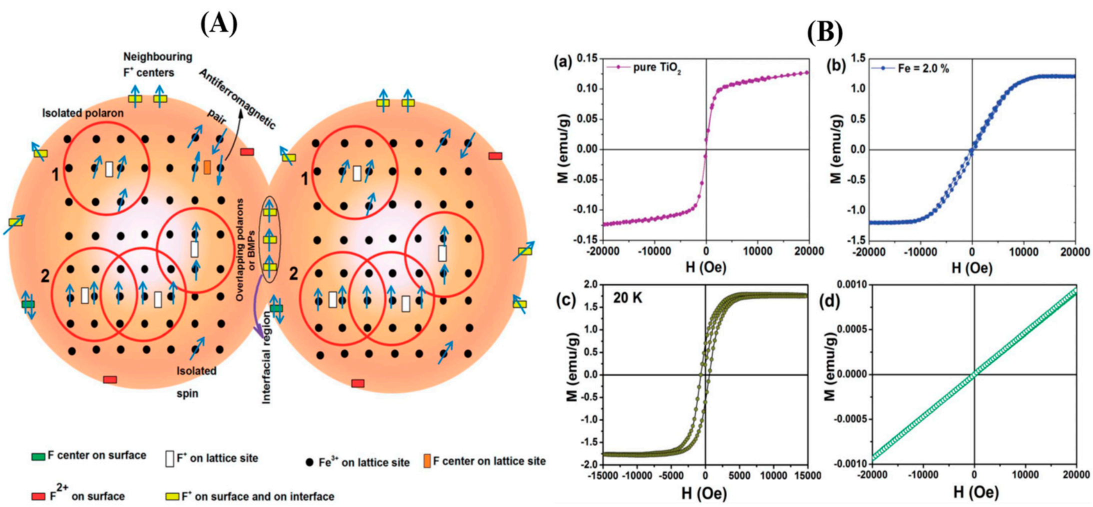


**Figure 3. A)** illustrates various possible magnetic species, their distribution, and potential interactions [96]. **Figure 3(B)** shows the M-H curves of vacuum-annealed NPs for (a) pristine $TiO_2$ and (b) 2% Fe-doped $TiO_2$ at room temperature, (c) 2% Fe-doped $TiO_2$ at 20 K, and (d) the paramagnetic M-H curve of vacuum-annealed 2% Fe-doped $TiO_2$ after reheating in air at 450 °C [96].

### 3.11. Role of Ion Beam Irradiation in Defect Engineering

*Defect Engineering Unveiled:* Ion beam irradiation stands as a masterful technique to incorporate defects and elevate ferromagnetic properties [105–107].

*A Careful Approach:* Low-energy ion beam irradiation with inert gases strikes a balance, enhancing defects without complicating the material's chemistry [106].

*Photocatalysis at the Nexus:* Photocatalytic performance hinges on electrical, optical, and structural attributes, where defects play a decisive role [103].

*Charting the Trajectory:* DMS, alongside defect engineering, charts the course for advancements across materials science and technology.

*Magnifying Magnetic Species:* Figure 3(A) paints a visual of magnetic species, their distribution, and potential interactions, elucidating the delicate dance of magnetism within Fe-doped $TiO_2$ NPs [104].

*Magnetization Under the Lens:* Figure 3(B) encapsulates magnetization's narrative through M-H curves, unfolding the magnetic journey in Fe-doped $TiO_2$ NPs [104].

In the dynamic realm of DMS, each discovery uncovers new dimensions, bolstering the quest for unparalleled functionalities. As research fervor persists, DMS materials stand poised to revolutionize technology, scripting a captivating saga in the ever-evolving narratives of magnetic and semiconductor domains.

## 4. Harnessing Visible Light for Photocatalysis: Progress and Prospects

Recent breakthroughs in the realm of visible light photocatalysis have illuminated a pathway towards harnessing solar energy for diverse applications. Visible light-responsive photocatalysts hold the key to addressing global challenges, spanning environmental remediation, energy conversion, and storage. The ability to efficiently convert sunlight into usable energy has garnered significant attention due to its potential to mitigate the environmental impact of traditional energy sources and reduce our carbon footprint. As researchers continue to unveil innovative strategies for enhancing the efficiency and selectivity of visible light photocatalysts, the prospect of realizing sustainable and eco-friendly technologies becomes increasingly attainable. These advancements not only underscore the power of interdisciplinary collaboration but also inspire a future where sunlight acts as a driving force for positive change on a global scale.

### *4.1. Advancements in Photocatalyst Design*

*Innovations in Material Choices:* Researchers have spearheaded advances in visible light photocatalysts, crafting novel solutions from metal oxides, carbon-based materials, and hybrid nanocomposites [108,109]. These materials exhibit heightened light absorption and improved charge separation efficiency, unlocking the potential to capture a broader solar spectrum.

*Defects and Dopants:* Harnessing the power of defects and dopants, studies showcase enhanced photocatalytic activity for organic pollutant degradation and clean fuel generation, such as hydrogen. The incorporation of various dopants and defects amplifies the photocatalytic prowess of these materials.

*Unraveling Mechanistic Insights:* Researchers delve into the mechanics that underpin visible light photocatalysis, delving into the intricacies of bandgap engineering, energy level alignment, and charge carrier dynamics [110–112]. These insights illuminate the avenues for optimizing the performance of photocatalytic materials.

*Beyond Conventional Approaches:* Innovative strategies, like plasmonic nanoparticle integration, co-catalyst deposition, and heterostructure formation, are poised to elevate visible light photocatalytic efficiency. These innovative pathways hold promise for crafting efficient and stable photocatalysts for large-scale environmental and energy applications.

### *4.2. Wide-Reaching and Challenging Applications*

*Expanding Horizons:* The potential of visible light photocatalysts isn't confined to a single domain. These advancements extend to water splitting, $CO_2$ reduction, and pollutant remediation, making headway in addressing global energy and environmental challenges in a sustainable manner. Water splitting, driven by visible light-responsive photocatalysts, offers a pathway to produce clean hydrogen fuel from water, presenting a promising alternative to conventional fossil fuels. Moreover, $CO_2$ reduction using these materials provides a tantalizing solution to counteracting greenhouse gas emissions by converting $CO_2$ into valuable fuels and feedstocks. In the realm of pollutant remediation, visible light photocatalysts are poised to revolutionize water and air purification technologies, paving the way for cleaner and healthier environments [113].

*Pioneering Challenges:* While significant strides have been made in the realm of visible light photocatalysis, challenges persist on the path to widespread implementation. The quest to enhance quantum efficiency, maximize photocatalyst stability, and mitigate the detrimental effects of photo-corrosion remains a focal point of research efforts. The intricate interplay between material properties, such as band structure, surface morphology, and defect concentration, and their ultimate impact on photocatalytic performance requires further elucidation. Addressing these challenges demands a multidisciplinary approach that combines materials science, chemistry, engineering, and theoretical modelling [114].

*Tackling Efficiency:* One of the central challenges in visible light photocatalysis is improving the quantum efficiency of the process ensuring that a higher percentage of absorbed light is effectively utilized for the desired photocatalytic reactions. Strategies such as bandgap engineering, surface modification and co-catalyst incorporation are being explored to enhance light absorption, charge separation, and reaction kinetics, thereby optimizing the overall efficiency of the process.

*Stability and Durability:* The long-term stability and durability of visible light photocatalysts are critical factors for their practical implementation. Photocatalyst degradation due to photo-corrosion, surface fouling, and other degradation mechanisms can hinder their performance over time. Researchers are delving into the development of novel materials and protective coatings that can mitigate these degradation pathways and extend the operational lifespan of photocatalysts.

*Unveiling Mechanistic Insights:* Understanding the intricate mechanisms that govern the interactions between photons, charge carriers, and reactants on the photocatalyst surface is paramount for designing more efficient materials [115]. This involves unravelling complex surface reaction pathways, quantifying charge transfer processes, and deciphering the role of defects in catalytic performance. Advanced characterization techniques and theoretical simulations play a pivotal role in providing insights into these fundamental processes.

*A Future of Possibilities:* Despite these challenges, the future of visible light photocatalysis is brimming with possibilities. As researchers continue to uncover the fundamental principles governing photocatalytic processes and explore innovative materials and strategies, the potential for scalable, sustainable, and economically viable solutions becomes increasingly evident. The convergence of scientific understanding, technological innovation, and global demand for clean energy and environmental solutions paves the way for a future where visible light photocatalysts play a pivotal role in shaping a more sustainable world.

### *4.3. A Vision for a Transformed Landscape*

*Transformative Potential:* The progress in harnessing the power of visible light photocatalysts resonates with the exciting advancements made. These strides not only hold the potential to tap into solar energy but also to revolutionize how we address pressing environmental and energy-related concerns. As we stand at the intersection of scientific innovation and real-world applications, the landscape of visible light photocatalysis holds the promise of reshaping industries and redefining the way we harness and utilize energy.

*A Landscape of Promise:* The journey of visible light photocatalysts is characterized by relentless exploration, innovation, and collaboration across diverse scientific disciplines. With ongoing research and development, the trajectory of visible light photocatalysts is poised to reshape the renewable energy and sustainable technology arena, propelling us toward a cleaner and more efficient future [116]. From powering remote communities with solar-derived hydrogen to mitigating air and water pollution on a global scale, the potential of visible light photocatalysis is far-reaching and transformative.

*Sustainable Synergy:* The transformative potential of visible light photocatalysts extends beyond individual applications. The synergy between these materials and other emerging technologies, such as energy storage systems and smart grids, presents the opportunity for holistic and sustainable energy solutions. This interconnected approach has the power to usher in an era where our energy sources are not only clean but also intelligently integrated, ensuring stability and reliability in our energy infrastructure.

*A Collaborative Journey:* The vision of a transformed landscape driven by visible light photocatalysis is a collective endeavour. Researchers, engineers, policymakers, and industry leaders collaborate to bridge the gap between fundamental scientific breakthroughs and practical applications. This journey is underscored by the recognition that tackling global challenges requires a multidimensional approach—one that seamlessly integrates scientific excellence with technological innovation and societal engagement.

*Fostering a Resilient Future:* As we envisage a landscape transformed by visible light photocatalysis, we glimpse a future marked by energy independence, environmental responsibility, and sustainable prosperity. The ability to tap into the abundant and renewable energy of the sun, combined with the creativity of the scientific community, empowers us to build a more resilient and equitable world for future generations. With each new advancement, we move closer to realizing this vision and embracing the potential of a transformed tomorrow.

### *4.4. Advancing Energy Conversion with $TiO_2$-Based Materials*

In the pursuit of efficient energy conversion, $TiO_2$-based materials have emerged as pivotal players, propelling the realm of solar power-based energy conversion and wastewater treatment into new frontiers [117–119]. These materials stand at the forefront of harnessing solar-based light energy to drive chemical reactions and generate vital electrical power. Advancing energy conversion through the utilization of $TiO_2$-based materials stands at the forefront of innovative research in sustainable technology. $TiO_2$, a versatile metal oxide semiconductor, has emerged as a cornerstone for efficient energy conversion due to its exceptional photocatalytic properties. These materials possess the remarkable ability to harness sunlight and initiate catalytic reactions, such as water splitting and pollutant degradation, with remarkable efficiency [120]. This capability not only contributes to clean energy generation and environmental remediation but also holds promise for advancing the realms of hydrogen production and solar fuel synthesis [121]. Additionally, $TiO_2$-based materials have found application in dye-sensitized solar cells, where they efficiently convert solar energy into electricity [122]. As researchers delve deeper into the design and engineering of $TiO_2$-based materials at the nano- and microscale, novel strategies are being developed to enhance light absorption, charge separation, and overall conversion efficiency. Through synergistic efforts in material science, chemistry, and engineering, the integration of $TiO_2$-based materials into energy conversion technologies is poised to revolutionize our approach to sustainable energy solutions, forging a cleaner and more resourceful energy landscape.

### *4.5. Pursuit of Efficiency: Noble Metal Doping*

The pursuit of efficiency in materials science has led researchers to explore the strategy of noble metal doping in metal oxides, uncovering a pathway to enhance catalytic and electronic properties [123]. Noble metals, known for their exceptional catalytic activity and stability, are introduced as dopants into metal oxide matrices to create hybrid materials with synergistic functionalities. By strategically incorporating elements like gold, platinum, or palladium into metal oxide structures, catalytic processes such as oxygen reduction reactions in fuel cells or $CO_2$ conversion are accelerated, owing to the unique electronic and surface properties of these metals [124,125]. Furthermore, noble metal doping can modulate the electronic band structure of metal oxides, resulting in improved charge carrier mobility and enhanced photocatalytic efficiency [126]. This approach not only tackles the challenge of limited intrinsic catalytic activity in metal oxides but also opens doors to tailor-made materials for various applications in energy conversion, environmental remediation, and beyond [127]. The pursuit of efficiency through noble metal doping underscores the innovative nature of materials design, as researchers endeavor to unlock new avenues for sustainable technologies with higher performance and versatility. To amplify the efficiency of $TiO_2$-based photocatalysis, noble metal doping and modification strategies have garnered significant interest. This approach seeks to unlock enhanced photocatalytic performance through tailored modifications. The incorporation of

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silver (Ag) into $TiO_2$, particularly in various forms such as Ag cluster-incorporated AgBr NPs and Ag/AgCl in $TiO_2$ photocatalysts, showcases a promising avenue for efficiency enhancement [119,128].

### 4.6. Leveraging Hierarchical Assembly for Superior Performance

*Strategic Nanomaterial Assembly:* The concept of hierarchical heterostructures, formed through the strategic assembly of nanoscale building blocks, holds the promise of elevating photocatalytic performance by harnessing tunable dimensionality and structural complexity [129].

*Multi-Functional Materials:* Hierarchical heterostructures offer not only enhanced performance but also a versatile platform with applications spanning various domains, making strides towards meeting multifaceted energy and environmental challenges [130]. The journey of energy conversion through $TiO_2$-based materials stands as a testament to human innovation and the limitless potential of harnessing the sun's energy for a sustainable and greener future.

*Efficient Energy Conversion:* Contemporary research endeavors shine light on solar power-based energy conversion and wastewater treatment, stirring considerable interest [101–103].

*Photon-Powered Chemical Reactions:* Photocatalytic and photovoltaic solar cells, the vanguards of solar-based light energy conversion, fuel chemical reactions and generate electrical power.

*$TiO_2$'s Crucial Role:* $TiO_2$'s versatile properties find applications in diverse environmental and energy realms, including photocatalysis, photovoltaics, artificial photosynthesis, and spintronics [131].

*Nanocrystals to Unleash Potential:* To enhance $TiO_2$'s photocatalytic activity with visible light, noble metal (Pt, Pd, Rh, Au) doped and modified $TiO_2$ photocatalysts have garnered attention for efficiency enhancement [132].

*Ag-Loaded $TiO_2$ Marvel:* The integration of Ag into $TiO_2$, such as Ag cluster-incorporated AgBr NPs, Ag NPs, CuO nanoclusters, and Ag/AgCl in $TiO_2$ photocatalysts, emerges as a promising avenue [113,114].

*Harnessing Heterojunctions:* Interfacial heterojunctions between $TiO_2$ and $SnO_2$ create a synergy that elevates photoactivity [133].

*Hierarchical Heterostructures:* The strategic assembly of nanoscale building blocks offers an avenue to enhance photocatalytic performance by tuning dimensionality and structural complexity [134].

*Multi-Functionality Unleashed:* Hierarchical heterostructures unlock ultrahigh specific surface areas and interconnected networks, facilitating improved performance across applications [135].

### 4.7. Exploring Fe-Doped $TiO_2$ Mechanics

Exploring the mechanics of Fe-doped $TiO_2$ unveils a fascinating realm at the intersection of material science and energy conversion. Fe-doped $TiO_2$, a distinguished member of the $TiO_2$-based materials family, has emerged as a compelling candidate for advancing photocatalytic and energy-related applications. By introducing Fe(III) ions into the $TiO_2$ lattice, researchers have successfully bridged the gap between visible light absorption and efficient charge carrier transfer [136]. This strategic doping not only enhances the material's photocatalytic activity but also brings forth its potential as a co-catalyst for multi-electron reduction reactions. The synergy between surface-grafted and bulk-doped Fe(III) ions holds the key to effective charge carrier transportation, enabling the material to excel in decomposing organic compounds. Through a blend of material engineering and in-depth understanding of charge carrier dynamics, Fe-doped $TiO_2$ demonstrates the intricate interplay between material properties and photocatalytic performance [137]. This exploration propels us closer to unlocking the untapped potential of Fe-doped $TiO_2$, offering a deeper understanding of the mechanisms that underlie its remarkable capabilities in advancing energy conversion and environmental remediation.

*Reimagining $TiO_2$ with Fe(III):* The intricacies of the Fe(III)-$Fe_xTi_{1-x}O_2$ system illuminate the potential of surface grafting and bulk doping for visible-light absorption in Figure 4 [31].

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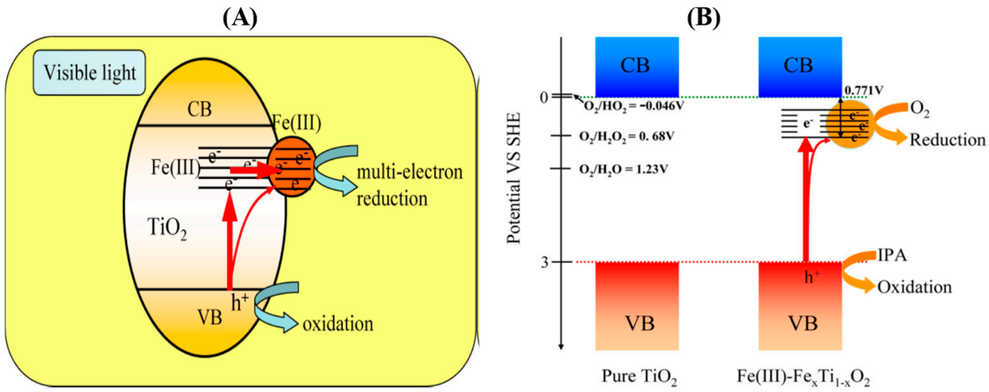


**Figure 4.** Illustrates the proposed photocatalysis process (A) and the change in bandgap and photoactivity due to Fe doping (B) [33].

*Balancing Efficiency:* The creation of an interface junction between surface-grafted and bulk-doped Fe(III) ions is essential for efficient charge carrier transfer.

*Unlocking Photocatalytic Potential:* Effective charge carrier transfer to the surface of Fe(III) doped $TiO_2$ leads to efficient co-catalyst functionality for multi-electron reduction reactions [31].

*Efficient Decomposition:* The unique property of Fe(III) doped $TiO_2$ allows deep-level valence band holes to decompose organic compounds, resulting in high photocatalytic activity.

### *4.8. Charting the Future: AgCl-Loaded Sn-Doped $TiO_2$*

The alliance between AgCl NPs and Sn-doped $TiO_2$ microspheres stands as a compelling approach to amplify visible-light activity, leaving a prominent mark on photocatalytic and photovoltaic applications [138,139]. The journey of visible light photocatalysis is both fascinating and transformative, as researchers forge pathways to tap into solar energy's abundance, inspiring innovations that promise to reshape the energy and environmental landscape. Charting the future, the integration of AgCl-loaded Sn-doped $TiO_2$ emerges as a promising frontier in advanced materials research. This innovative hybrid material combines the exceptional properties of tin-doped $TiO_2$ with the unique attributes of AgCl, paving the way for multifunctional applications. Sn-doped $TiO_2$, already known for its enhanced charge carrier mobility and extended visible-light absorption, synergistically merges with AgCl's exceptional visible light photocatalytic capabilities and antibacterial properties [140]. This novel composite holds immense potential in fields ranging from sustainable energy production and water purification to medical devices. Its ability to harness sunlight efficiently for catalytic reactions while concurrently acting as an antimicrobial agent positions it at the crossroads of various technological advancements. By charting this unexplored territory, researchers strive to shape a future where tailored materials exhibit unprecedented multifaceted functionalities, propelling us towards sustainable solutions and novel scientific horizons [141].

## 5. Recent Advances in Magnetic $TiO_2$: Expanding Horizons for Ferromagnetic Photocatalysis

This review delves into the intricate interplay between magnetism and photocatalytic activity within $TiO_2$, unveiling a realm of opportunities across diverse applications such as environmental remediation, solar energy conversion, and advanced catalysis. By strategically incorporating magnetic elements like Fe, Mn, or Co into $TiO_2$ structures, researchers have forged a path towards magnetic $TiO_2$ materials that exhibit both ferromagnetic behavior and exceptional photocatalytic efficiency. The article meticulously examines the spectrum of applications that magnetic $TiO_2$ offers, including its pivotal role in purifying the environment, treating wastewater, and degrading organic pollutants under both visible and UV light [142].As this dynamic field progresses, the review article underscores the challenges in precisely controlling magnetic properties, comprehending the

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underlying mechanisms governing this dual behavior, and scaling up production for practical applications. Ultimately, the review accentuates the immense potential of magnetic $TiO_2$ as a driver for sustainable technologies and clean energy solutions, pointing towards a future shaped by innovative $TiO_2$-based materials with remarkable multi-functionality [143,144].

### *5.1. Combining Magnetism and Photocatalysis: Unleashing $TiO_2$'s Potential*

The convergence of magnetic and photocatalytic properties within $TiO_2$ offers a realm of possibilities across environmental remediation, solar energy conversion, and advanced catalysis [145]. While traditional $TiO_2$ boasts exceptional photocatalytic traits, the introduction of magnetic elements like Fe, Mn, or Co into $TiO_2$ paves the way for magnetic $TiO_2$. This novel breed exhibits both ferromagnetic behavior and photocatalytic capabilities, yielding exciting applications across various domains.

*Exploring Applications and Opportunities*

Magnetic $TiO_2$'s impact spans far and wide, from cleaning up the environment to treating wastewater and purifying air. It proficiently dismantles organic pollutants under both UV and visible light, making it pivotal for sustainable solutions. Notably, it finds its footing in solar energy conversion systems and advanced catalytic processes. Amid ongoing research, the journey is focused on enhancing both photocatalytic efficiency and magnetic properties, which is crucial for scalability and practical implementation [146].

### *5.2. Delving into Sn-Doped $TiO_2$: Amplifying Performance and Potential*

*Tailoring Sn-Doped $TiO_2$:* Through an exploration of diverse Sn doping concentrations, our previous studies [57,102,108,135] have shed light on augmenting the structural, electronic, magnetic, and photocatalytic attributes of $TiO_2$ NPs. A notable highlight emerges in the form of Sn-doped $TiO_2$ NPs' room temperature photocatalytic and ferromagnetic prowess, particularly in the realm of environmental remediation. By integrating varying $SnCl_4$ concentrations into $Ti(NO_3)_4$ aqueous solutions, we harnessed a facile hydrothermal technique to synthesize $TiO_2$ NPs featuring anatase, anatase-rutile mix, and rutile phases with embedded Sn atoms.

*Probing Photocatalytic Behavior:* To assess the prowess of synthesized Sn-$TiO_2$ NPs, we turned to methyl orange (MO) and RPhOH (where PhOH represents a phenol group and R is 3-$NH_2$, H, or 4-Cl) as model pollutants, both under visible and UV light. Illumination unearthed a compelling connection between RPhOH's Hammett substitution constant ($\sigma$) and the degradation efficiency of Sn-$TiO_2$ NPs. The concentration of Sn doping played a pivotal role, wielding influence over structural, electronic, magnetic, and photocatalytic traits of the $TiO_2$ NPs. Amidst extensive research, the enigma of combined ferromagnetism and photocatalytic behavior prevails, underpinned by factors like oxygen vacancies, phase transitions, and doping levels. Our current pursuit aims to unravel the role of $Sn^{4+}$ ions in shaping these properties of $TiO_2$ NPs.

### *5.3. Hierarchical SNT Microspheres: Pioneering Enhanced Photocatalysis and Ferromagnetism*

*Co-Doping for Enhanced Performance:* Our exploration continued in the synthesis arena, wherein we employed a hydrothermal route followed by nitriding treatment using flowing ammonia gas to craft hierarchical Sn and nitrogen co-doped $TiO_2$ (SNT) microspheres [45,87]. This innovation heralded improved photocatalytic efficacy and room temperature ferromagnetism through simultaneous incorporation of Sn and N atoms. These co-doped microspheres emerged as a breakthrough, outshining both pristine and Sn-doped $TiO_2$ NPs. The co-doped microspheres demonstrated remarkable visible light absorption, resulting in elevated photocatalytic activity and highlighting their potential for efficient solar-driven applications. While these microspheres exhibited resilience in the face of Rhodamine B (RhB) degradation under visible light, their magnetic behaviour remained uncharted territory, intriguing us with the possibility of room temperature ferromagnetism stemming from trapped electrons in oxygen vacancies ($V_O$) or structural anomalies. This multifaceted study not only enriches our understanding of visible light photocatalysis and room temperature ferromagnetism but also sets new trajectories for $TiO_2$-based materials, potentially shaping their role in diverse applications, including photovoltaics.

*Unveiling Novel Hierarchical Structure:* The synthesis of hierarchical SNT microspheres with co-doping introduces a novel structural dimension that goes beyond traditional $TiO_2$ photocatalysts. The hierarchical arrangement not only enhances light trapping and charge separation but also offers increased surface area for catalytic interactions. The integration of vanadium oxide as a co-dopant introduces additional complexity to the system, potentially leading to new electronic and magnetic phenomena. Understanding the interplay between the hierarchical structure, co-doping, and resulting properties opens the door to tailoring materials for specific applications that demand both enhanced photocatalytic activity and magnetic behaviour [147].

*Ferromagnetism and Trapped Electrons:* The intriguing possibility of room temperature ferromagnetism in the SNT microspheres sparks curiosity about its origins. Trapped electrons in the $V_O$ co-dopant or structural defects could potentially contribute to this magnetic behaviour. Unravelling the mechanisms behind the observed ferromagnetic properties would shed light on the potential of harnessing defect engineering to achieve multi-functionality in $TiO_2$-based materials. Furthermore, this insight could pave the way for the development of novel magnetic photocatalysts with broader implications for energy conversion and storage.

*Charting New Trajectories:* This study marks a significant advancement in the field of $TiO_2$-based materials and their applications. The co-doped SNT microspheres not only showcase enhanced photocatalytic performance but also introduce the element of ferromagnetism, adding to the growing pool of multifunctional materials. The implications span various domains, including photocatalysis, magnetics, and potentially photovoltaics. By charting these new trajectories, this research exemplifies the iterative nature of scientific progress, where each discovery opens up unforeseen opportunities for innovation and exploration.

*Innovative Insights and Future Directions:* The synthesis and characterization of hierarchical SNT microspheres with co-doping provide innovative insights into the intricate relationship between structure, composition, and properties. As we delve deeper into understanding the origins of ferromagnetic behaviour and its synergy with photocatalytic activity, new avenues for tailored materials and applications come to light. The co-doped SNT microspheres serve as a testament to the potential of materials design and engineering, offering glimpses into a future where multifunctional materials play a pivotal role in addressing complex technological challenges.

### *5.4. Advancing Photocatalysis through Hierarchical AgCl in Sn-$TiO_2$ Microspheres*

A novel synthesis methodology emerged [102,148], culminating in the creation of hierarchical AgCl in Sn-$TiO_2$ (AST) microspheres through diverse post-calcination treatments. The central aim lay in enhancing photocatalytic potency by loading AgCl NPs onto Sn-doped $TiO_2$. These AST microspheres outperformed Sn-$TiO_2$, AgCl, Ag/AgCl, and commercial Degussa P25 photocatalysts, flaunting superior visible light absorption. Under visible light, these hierarchical AST microspheres showcased heightened degradation rates for model systems like RhB and 3-nitrophenol aqueous solutions. A thorough exploration of varying AgCl concentrations in the AST microspheres emerged as an essential next step. Furthermore, this study pioneers the facile synthesis route, elevated visible-light photocatalysis within hierarchical AST microspheres, and uncovers the magnetic attributes through the Sn Mössbauer method. This revelation ushers in a new class of semiconductor materials, opening exciting avenues for $TiO_2$-based innovations.

### *5.5. Correlation between Magnetic and Photocatalytic Properties*

The simultaneous increase in ferromagnetic character and photocatalytic efficiency for metal oxide semiconductors can be attributed to specific material properties and interactions. However, it's important to note that such a correlation is not always straightforward and depends on various factors. Here's a general explanation for why this could occur:

*Crystal Structure and Defects:* Both ferromagnetism and photocatalytic efficiency are influenced by the crystal structure and defects within metal oxide semiconductors [149]. Certain crystal structures can support both ferromagnetic ordering of electron spins and efficient charge carrier generation for photocatalysis. Defects, such as oxygen vacancies or dopants, can enhance both magnetic properties and photocatalytic performance by creating additional electronic states for carriers to populate [150].

*Electronic Band Structure:* The electronic band structure of a material plays a crucial role in determining its magnetic and photocatalytic properties [151,152]. If the material's band structure allows for the existence of partially filled d or f orbitals, this can lead to ferromagnetism. Simultaneously, the same band structure can enable efficient charge separation and mobility necessary for effective photocatalysis.

*Synergistic Charge Carrier Behaviour:* Efficient photocatalysis relies on the effective separation and migration of photo-generated charge carriers (electrons and holes) [153,154]. In some cases, the same processes that lead to ferromagnetic behaviour, such as exchange interactions between electron spins, can also facilitate the movement of charge carriers, enhancing photocatalytic efficiency.

*Surface and Interface Effects:* The surface and interface properties of metal oxide semiconductors are critical in determining their catalytic and magnetic behaviors. Surface defects and exposed facets can provide active sites for photocatalysis, while also influencing magnetic interactions in the vicinity of the surface [155,156].

*Doping and Elemental Composition:* Controlled doping of metal oxide semiconductors can tune both their magnetic and photocatalytic properties [157]. Certain dopants can introduce magnetic moments and enhance photocatalytic activity simultaneously, making it possible to design multifunctional materials [158].

*Spintronic Effects:* The coupling of spin and charge in ferromagnetic materials can lead to spin-dependent charge transport phenomena. These effects can enhance the efficiency of charge separation and transport in photocatalytic processes [159,160].

*Complex Interplay:* The relationship between magnetic character and photocatalytic efficiency is complex and not always linear. It's possible for these properties to be enhanced in tandem due to shared underlying mechanisms, but they can also exhibit opposing behaviours depending on factors such as material composition, crystal structure, and external conditions [161–163]

The increase in ferromagnetic character and photocatalytic efficiency for metal oxide semiconductors can arise from shared material properties, such as electronic band structure, defects, and charge carrier behaviour [164–167]. However, it's important to evaluate each material system individually, as the correlation between these properties can vary based on specific conditions and material characteristics.

## 6. Advances in Mössbauer Spectroscopy and Ferromagnetic Photocatalytic Studies of Sn and Fe Doped $TiO_2$ Nanocomposites

The rapid emergence of $TiO_2$-based nanocomposites has stirred significant interest, driven by their exceptional photocatalytic properties and potential applications spanning environmental remediation, solar energy conversion, and advanced catalysis. Delving into the realm of enhancement, the incorporation of dopants like Sn and Fe has been meticulously explored, unlocking a realm of structural, electronic, and magnetic augmentations within $TiO_2$ [168]. Anchored at the atomic level, Mössbauer spectroscopy emerges as a pivotal tool to scrutinize the intricate interplay of these doped nanocomposites' structural and magnetic attributes [169].

Unveiling Dopant Influence: The intentional introduction of dopants like Sn and Fe into $TiO_2$ matrices marks a paradigm shift in materials engineering. These dopants, carefully selected for their electronic and magnetic properties, engender complex alterations in the host material's structure and behaviour. Understanding the nuanced effects of dopants on both lattice structure and electronic states is crucial for tailoring materials with desired properties. Mössbauer spectroscopy, a precise and sensitive technique, plays a transformative role in unravelling the intricacies of these dopant-induced modifications at the atomic scale.

*Probing Local Environments:* One of the distinguishing features of Mössbauer spectroscopy is its ability to probe the local atomic environment with unparalleled precision [170].

By harnessing the Mössbauer effect—a quantum mechanical phenomenon involving gamma-ray absorption and emission—researchers gain insights into the oxidation state, coordination geometry, and magnetic interactions of specific atomic species, even in the presence of complex materials [171]. In the context of Sn and Fe doped $TiO_2$ nanocomposites, Mössbauer spectroscopy unveils the local environments surrounding these dopants, shedding light on their integration into the host lattice and their role in governing the resulting properties [172].

*Deciphering Magnetic Phenomena:* The introduction of dopants like Fe introduces the potential for magnetic behaviour within $TiO_2$, transforming it into a ferromagnetic material. Mössbauer spectroscopy is uniquely positioned to decipher the magnetic properties of these doped nanocomposites. By characterizing hyperfine interactions and magnetic hyperfine splitting patterns, researchers can elucidate the nature of magnetic ordering, the presence of magnetic clusters, and the mechanisms that underpin room temperature ferromagnetism [173,174].

This knowledge not only enriches our fundamental understanding of the material's behavior but also offers critical insights for the development of magnetic photocatalysts and related applications [175].

*Mapping Ferromagnetic Photocatalysis:* The convergence of Mössbauer spectroscopy with ferromagnetic photocatalytic studies creates a synergistic approach that bridges structural and magnetic analyses with functional performance. This integrated methodology allows researchers to correlate magnetic phenomena, such as room temperature ferromagnetism, with enhanced photocatalytic activity. By mapping the intricate relationship between magnetic behaviour and photocatalytic efficiency, this approach guides the design and optimization of materials with multifunctional properties, propelling advancements in solar energy utilization and environmental remediation.

*Future Prospects:* The union of Mössbauer spectroscopy and ferromagnetic photocatalytic studies ushers in a new era of materials characterization and engineering. As nanocomposites continue to evolve and find applications in diverse fields, this combined approach holds promise for uncovering hidden correlations between structure, magnetism, and functionality [176]. By leveraging the atomic-level insights provided by Mössbauer spectroscopy, researchers are poised to accelerate the development of tailored materials that redefine technological possibilities and contribute to a more sustainable future.

Further, an in-depth exploration of Sn and Fe-doped $TiO_2$ nanocomposites is presented through the lens of Mössbauer spectroscopy. This meticulous analysis unravels the structural and magnetic intricacies, contributing to the fundamental understanding of how dopants, structural anomalies, and photocatalytic activity intertwine. Such insights are pivotal for designing durable and efficient photocatalytic materials. Peering into the heart of nanocomposites, Mössbauer spectroscopy emerges as an invaluable tool, unveiling a wealth of structural and magnetic insights. As nanocomposites revolutionize materials engineering, the complex interactions between distinct components demand meticulous characterization. Mössbauer spectroscopy, with its ability to provide detailed information about the oxidation state, local environment, and magnetic behavior of atoms, offers a unique window into these intricate systems. By probing the hyperfine interactions between atomic nuclei and their surroundings, this technique facilitates the understanding of nanoscale phase distribution, chemical bonding, and magnetic coupling within composite materials. From catalytic nanoparticles on support matrices to magnetic oxide-polymer hybrids, the application of Mössbauer spectroscopy unveils hidden correlations, guiding the design and optimization of tailored nanocomposites with enhanced performance. Its role in illuminating the inner workings of these innovative materials reinforces its status as an indispensable analytical tool, enabling researchers to sculpt the future of advanced materials with precision and insight.

## 7. A Glimpse into the Future: Potential and Prospects

Offering a glimpse into the future, this review article not only presents a cutting-edge overview of the advancements in Mössbauer spectroscopy and ferromagnetic photocatalytic studies of Sn and Fe doped $TiO_2$ nanocomposites but also extends its horizon towards the potential and prospects that

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lie ahead. By weaving together these two intricate fields of study, the article not only sheds light on the present state of research but also envisions novel avenues of comprehension and application for these materials in the realms of environmental remediation and renewable energy technologies. This integrative approach, fusing the analytical precision of Mössbauer spectroscopy with magnetic and photocatalytic investigations, constructs a comprehensive roadmap to unlock the full potential of these nanocomposites. This endeavor is poised to propel the advancement of high-performance, sustainable photocatalytic materials, capable of addressing pressing environmental challenges and powering future energy solutions. Drawing inspiration from the reservoir of insights gleaned from prior studies, this review not only encapsulates the multifaceted journey of exploration, understanding, and application but also serves as a foundation for ushering in an era characterized by the emergence of innovative $TiO_2$-based materials with far-reaching implications. As researchers traverse this dynamic landscape, they are poised to shape the trajectory of scientific discovery and technological innovation, forging a transformative path towards a cleaner and more sustainable future.

## 8. Conclusions

This review underscores the paramount importance of broadening the scope of wide bandgap metal oxide nanoparticles (NPs) in the realm of photocatalysis. A prominent spotlight has been cast upon the advancement of room-temperature ferromagnetic $TiO_2$, a captivating photocatalyst adept at harnessing visible light from the solar spectrum with utmost efficiency. Nonetheless, pristine $TiO_2$ NPs harbor limitations such as accelerated recombination of photo-generated charges and a reliance on UV light for catalytic prowess. In pursuit of fully harnessing the potential of $TiO_2$-based photocatalysts, a diverse array of strategies has been meticulously explored. Within the purview of this review, two potent pathways have been dissected and expounded. The first avenue involves the strategic infusion of metallic or non-metallic dopants into $TiO_2$, a transformation that tweaks its band structure, extends the photo-response into the visible spectrum, and crucially, enhances the separation of charge carriers. Additionally, grafting $TiO_2$ NPs with either anionic or cationic elements emerges as a transformative maneuver to finetune surface properties, foster interfacial charge transfer, and amplify photocatalytic efficacy under the illumination of visible light. Complementary to this trajectory, the review sheds light on another compelling journey: the amalgamation of $TiO_2$ NPs with other semiconductor counterparts. The resultant heterojunctions manifest a heightened efficiency in separating electron-hole pairs, presenting an innovative avenue to expand the photo-response spectrum and enhance the overall photocatalytic performance. Gazing into the horizon, the pathway ahead necessitates comprehensive explorations to unearth the true potential of novel ferromagnetic metal oxide-based photocatalysts, especially in the context of large-scale applications. As the continuum of photocatalysis journeys forward, the quest for efficient, enduring, and environmentally benign photocatalytic materials resonates more than ever. The imperative to combat water contamination, air pollution, and foster renewable energy conversion spurs us to harness the expansive potential harbored by wide bandgap metal oxide NPs, most notably room-temperature ferromagnetic $TiO_2$. Ingenious doping and coupling strategies wield the key to unlocking novel vistas, emboldening sustainable and pragmatic photocatalytic technologies. This voyage calls for a harmonious alliance of researchers across diverse domains, orchestrated to usher in large-scale applications of these trailblazing ferromagnetic metal oxide-based photocatalysts, propelling us towards a cleaner, more sustainable future.

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