CHALCOGENIDE-BASED NANOMATERIALS AS PHOTOCATALYSTS

Edited by

Mohammad Mansoob Khan

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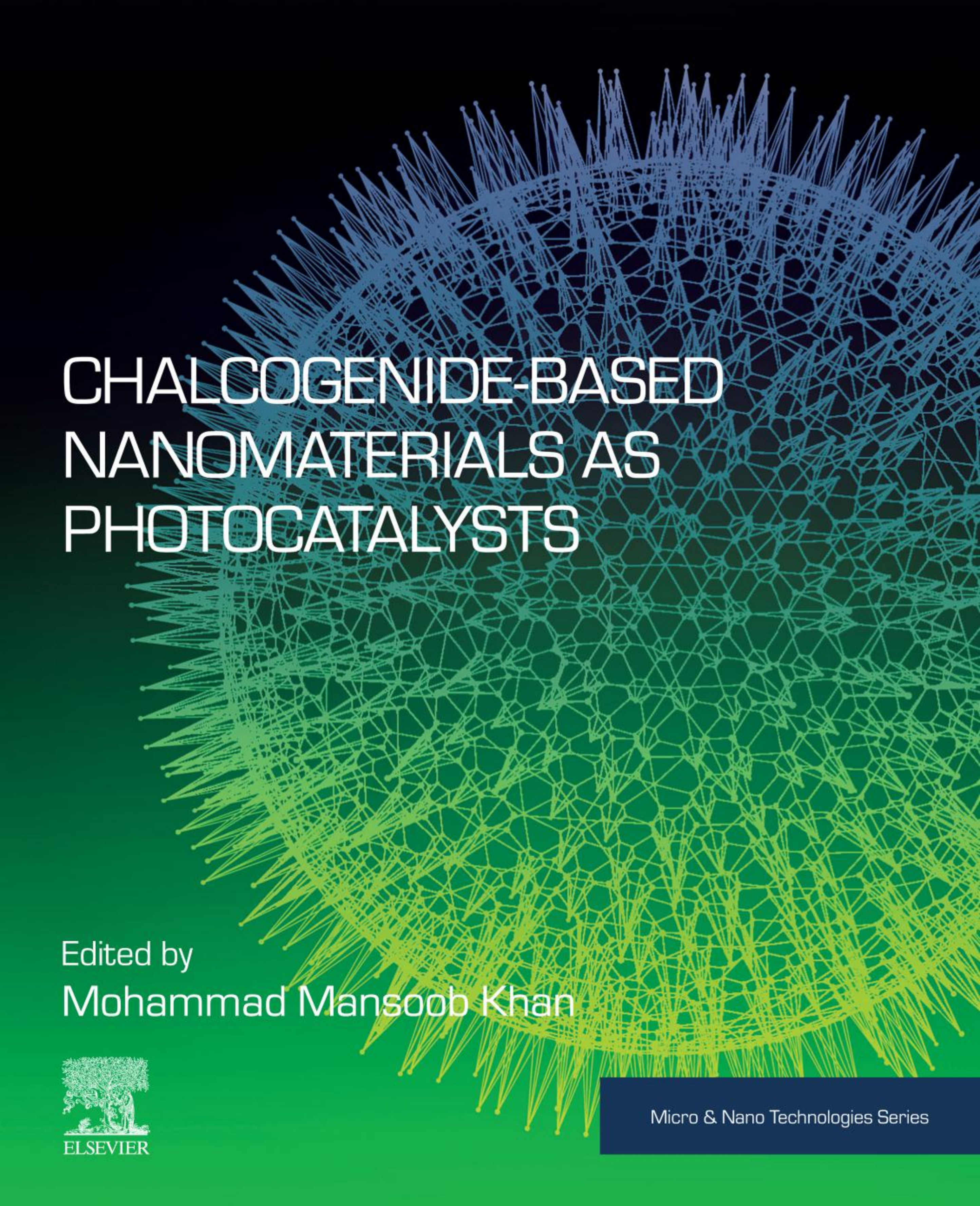

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Short biography

Dr. Mohammad Mansoob Khan is working as an Associate Professor in Chemical Sciences, Faculty of Science, Universiti Brunei Darussalam, Brunei Darussalam. He earned his PhD from Aligarh Muslim University, Aligarh, India, in 2002. Afterward he has worked as researcher, academician, lecturer, and Professor in different countries (India, Ethiopia, Oman, and South Korea), taught various courses at undergraduate and postgraduate levels and has demonstrated excellence in teaching and research. His main research interests are in the field of nanosciences, nanotechnology, nanomaterials, materials science, and band gap engineering, especially in the green syntheses of metal nanoparticles, metal oxides, chalcogenides, inorganic nanohybrid, and nanocomposite materials. He is also working on synthesis of graphene, graphene-based nanocomposites, graphitic carbon nitride (g-C_3N_4), and g-C_3N_4-based nanocomposites for various novel applications in the field of energy, environment, and biological applications such as catalysis, photocatalysis, photoelectrodes, optoelectronic devices, hydrogen production, sensing, and selected biological applications.

Preface

This book **Chalcogenide-Based Nanomaterials as Photocatalysts** provides a comprehensive and updated review of major innovations in the field of chalcogenide-based nanomaterials for photocatalysis-related applications. This book encompasses synthesis, properties, and applications of chalcogenides and chalcogenide-based nanomaterials from different sources and strategies on the efficacy and major challenges associated with successful scale-up of fabrication. The chapters provide up-to-date and cutting-edge research findings on the use of chalcogenides and chalcogenide-based nanomaterials for energy and environmental applications. It also describes materials characteristics and significant enhancements in physical, chemical, catalytic, and photocatalytic properties.

This book is an essential reference book for present and future research in photocatalysis based on chalcogenides and chalcogenide-based nanomaterials for recyclable, sustainable, and ecofriendly methods for highly innovative and applied nanomaterials.

This book contains 14 chapters that deal with several types of chalcogenides and chalcogenide-based nanomaterials and their applications as photocatalysts in various photocatalytic reactions and applications:

Chapter 1. Introduction and fundamentals of chalcogenides and chalcogenides-based nanomaterials. This chapter covers the fundamentals and classifications of chalcogenide and chalcogenide-based nanomaterials.

Chapter 2. Advances in chalcogenides and chalcogenides-based nanomaterials such as sulfides, selenides, and tellurides. This chapter focuses on chalcogenides-based nanomaterials such as sulfur, selenium, and tellurium which is combined with other elements to form binary, ternary, and quaternary materials.

Chapter 3. Chalcogenides as well as chalcogenides-based nanomaterials and its importance in photocatalysis. This chapter provides a summary of the usefulness of chalcogens and their nanomaterials for photocatalysis as a future guidance for researchers working in the field of chalcogen based photocatalysis with promising future directions.

Chapter 4. Basic principles, fundamentals, and mechanisms of chalcogenide-based nanomaterials in photocatalytic reactions. This chapter discusses the unique properties, significance of chalcogenide-based nanomaterials, principles and fundamentals of photocatalysts.

Chapter 5. Synthesis methods for chalcogenides and chalcogenides-based nanomaterials for photocatalysis. In this chapter, the synthesis strategies of chalcogenide-based nanomaterials in order to obtain desired properties for photocatalytic applications have been discussed.

Chapter 6. Band gap engineered chalcogenide nanomaterials for visible light-induced photocatalysis. In this chapter the strategies for band gap engineered chalcogenide nanomaterials for visible light-induced photocatalysis have been discussed.

Chapter 7. Chalcogenide-based nanomaterials as photocatalysts for water splitting and hydrogen production. This chapter discusses about chalcogenide-based nanomaterials as photocatalysts for water splitting and hydrogen production.

Chapter 8. Chalcogenides-based nanomaterials for solar cells and dye sensitized solar cells. In this chapter chalcogenides-based nanomaterials for solar cells and dye sensitized solar cells have been discussed.

Chapter 9. Chalcogenides-based nanomaterials for artificial photosynthesis. This chapter mainly deals about the chalcogenides based nanomaterials in the applications of artificial photosynthesis.

Chapter 10. Use of chalcogenides-based nanomaterials for wastewater treatment including bacterial disinfection and organic contaminants degradation. This chapter discusses different strategies for the use of chalcogenides-based nanomaterials for wastewater treatment including bacterial disinfection and organic contaminants degradation.

Chapter 11. Use of chalcogenides-based nanomaterials for photocatalytic heavy metal reduction and ions removal. In this chapter use of chalcogenides-based nanomaterials for photocatalytic heavy metal reduction and ions removal have been discussed.

Chapter 12. Photocatalytic N_2 fixation using chalcogenide-based nanomaterials. In this chapter the state-of-art engineering of efficient photocatalysts based on chalcogenide nanostructured for N_2 fixation toward NH_3 synthesis under visible light irradiation have been discussed.

Chapter 13. Photocatalytic CO_2 reduction using chalcogenide-based nanomaterials. In this chapter, the general mechanism of photocatalytic reduction of CO_2 and series of metal chalcogenide materials used in the photocatalytic reduction of CO_2 have been summarized.

Chapter 14. Challenges, novel applications, and future prospects of chalcogenides and chalcogenide-based nanomaterials for photocatalysis. This chapter discusses vovel applications of metal chalcogenide-based materials like water splitters, organic pollutant degraders, self-cleaning agents, chalcogenide glasses, and thermoelectric materials are explained in detail under the relevant headings.

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First and foremost, I would like to thank Almighty God for giving me the idea, strength, and opportunity to propose, compile, and successfully complete this book **Chalcogenide-based nanomaterials as photocatalysts**. Also, I would like to thanks and acknowledge the administration of Universiti Brunei Darussalam for continuous encouragement and support.

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Advances in chalcogenides and chalcogenides-based nanomaterials such as sulfides, selenides, and tellurides

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1 Introduction

In the periodic table, the elements are grouped in a simple arrangement so that they are easy to study. Commonly, they are arranged by atomic numbers and grouped by the similarity of their properties. Among them, there is one element group which is named chalcogen that consists of elements in group 16 or also called the oxygen group. Interestingly, this group of chalcogen does not include oxygen and radioactive elements, but only elements such as sulfur, selenium, and tellurium are included in this group of chalcogen. The term chalcogen comes from the Greek language, *khalkós* ($\chi\alpha\lambda\kappa\acute{o}\zeta$) which means copper and the term of *-gene* means produced. So, the term chalcogen comes by combining both terms.

The elements in this chalcogen group such as sulfur, selenium, and tellurium, are obtained from nature. Sulfur is an abundant element in the earth's crust layer with an average amount of 470 ppm, followed by selenium and then tellurium with amounts of 0.05 ppm and 0.001 ppm, respectively [1]. These elements are obtained by mining and then processed into pure elements or combined with other elements such as metals or commonly known as metal chalcogenides.

The use of these chalcogen elements is wide. Sulfur is widely used in many industries such as tire and chemical industries [2,3]. Selenium and tellurium, also as important as sulfur does. Although the amount of selenium and tellurium is not as much as sulfur, their presence is quite important, especially if they are processed with other elements or undergoes further processes to become nanomaterials [4,5]. These chalcogen-based materials

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are important in several applications such as photovoltaics, photocatalytic, batteries, and other products based on optical and electronic functional materials [6–10].

2 Sulfur

Sulfur is an abundant element in nature that exploited by industries to produce many derivative products. The vast majority product is sulfuric acid and sulfur dioxide. Sulfur is a crystalline solid (c-S) in hexagonal structure and amorphous (a-S) forms with few allotropes. The sulfur atom has the same number of valence electrons as $O_{2;}$ thus, sulfur atoms can arrange as S_2 or S_3 and have physical and chemical properties analogous to O_2 or O_3. However, unlike S_2, S_8 molecules are almost completely different because of different molecular electronic configuration. The S_8 molecules have a low 3d orbital near 4s orbital. Both orbitals similarly participate in bonding as hybridization orbitals in carbon. Thus, sulfur has many allotropes structures like carbon, including cycle structure. Fig. 2.1 shows configuration of S_8(g) molecular orbital.

Walsh et al. predicted the structure of vapor sulfur (S_8) using symmetry assignment modeling and shows the structure is different to molecular gases like O_2 and N_2. There is no widely accepted thermodynamic potentials for sulfur and combining a first-principles global structure search for the low-energy clusters from S_2 to S_8 with a thermodynamic model for the mixed-allotrope system, including the Gibbs free energy for all gas-phase sulfur on an atomic basis [11]. All sulfur allotropes on gas state are shown in Fig. 2.2.

Norwood et al. reported that sulfur has a transparent transmission spectrum above 500 nm, possesses a high-refractive index (>1.8) and takes advantage of the low-infrared absorption of S–S bonds for potential use in the mid-infrared at 3–5 microns [12]. As an infrared absorbent, due to its optical and electrical properties, sulfur also potentially used as photovoltaic, photocatalyst and battery chalcogenide-based materials. Furthermore, many of these species can be isolated in pure form. It should become possible to study the relative reactivity of different allotropes, selective reactions, which would open simpler and cheaper paths to synthesize sulfur compounds. Sulfur is available in earth abundantly,

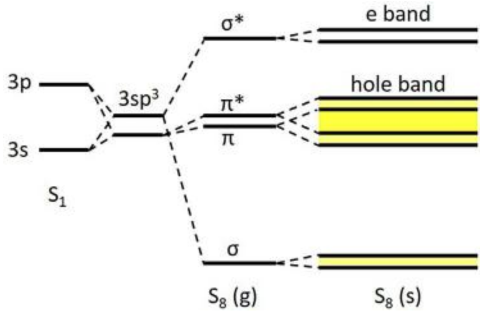

FIGURE 2.1 Configuration of S_8(g) molecular orbitals.

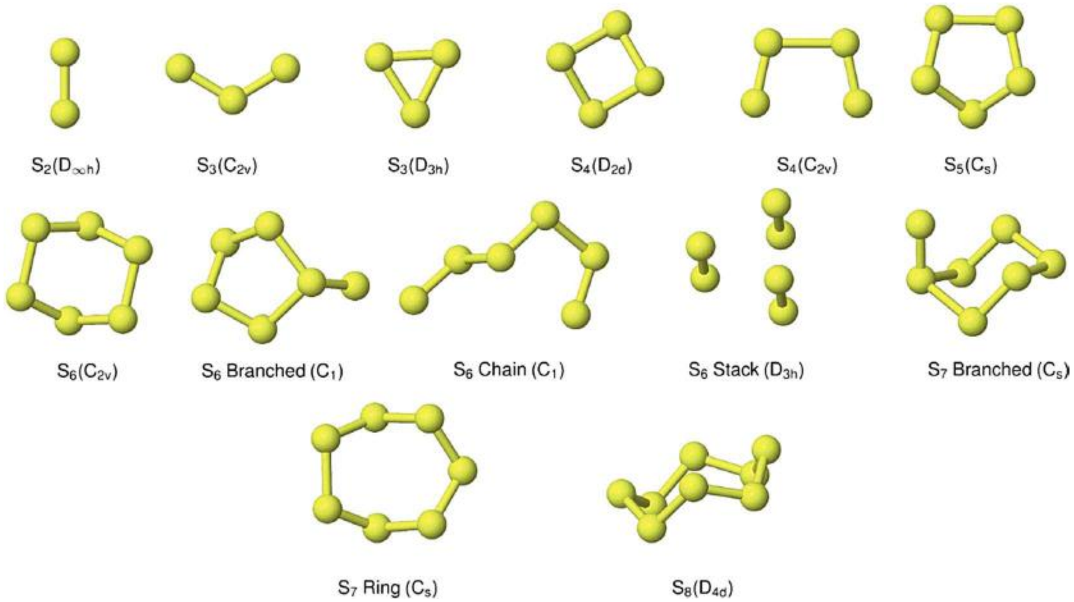

FIGURE 2.2 Predicted low-energy sulfur clusters with symmetry assignment [11].

so there are opportunities to make chalcogenide sulfur-based materials for many kinds of applications in a cheaper way and to make industrial-scale production.

3 Selenium

Moreover, likely sulfur, elemental selenium (Se) exists in the crystalline and amorphous state. Amorphous selenium (a-Se) has six allotropic forms, one of them is Se_8 ring and may sometimes compose polymeric chains, more like a-S. Crystalline Se (c-Se) state consists of α-monoclinic, β-monoclinic, and hexagonal structure. Both α-monoclinic and β-monoclinic Se contain four Se_8 rings in a unit cell stacked either parallel to each other (β monoclinic) or with two different stacking directions (α). Crystalline Se is a semiconductor with a direct bandgap between 1.8 and 2.0 eV, a high-absorption coefficient ($>10^4$ cm^{-1}) in the visible region [13]. Se is known to have a photovoltaic effect and a-Se based optoelectronic devices are advantageous in low dark current with easy upscaling capability. a-Se also composes of Se_8 ring and polymeric chains. The longest Se chain is Se_{19} as reported by Krossing et al. [14]. Fig. 2.3 shows both hexagonal and α-monoclinic selenium structure of selenium.

The electrical properties of crystalline Se (c-Se) depend on the impurity content and thermal treatment of the samples that normally exhibits p-type semiconductor with conductivity of 10^{-5} Ωcm^{-1}, carrier concentration of 10^{14} cm^{-3}, mobility of ~0.14 cm^{2}V^{-1}s^{-1} and resistivity around 10^5–10^6 Ωcm [16–18]. Based on these optical and electrical properties, c-Se can also be utilized as potential material for photovoltaic devices. Table 2.1 shows a compilation of some Se-based solar cells structures and their performances [19].

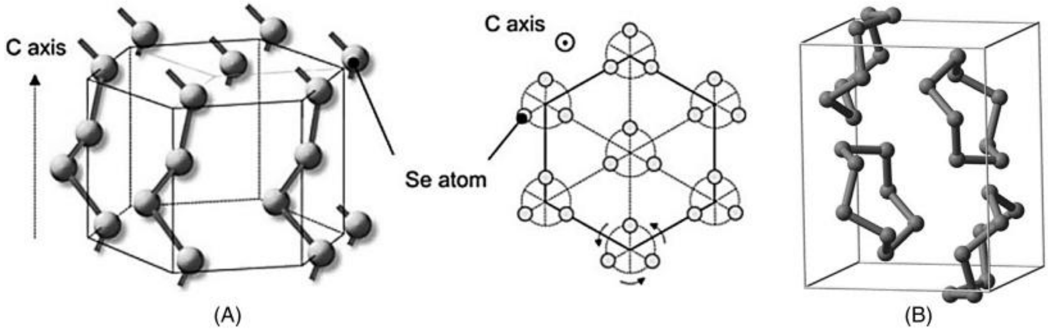

FIGURE 2.3 (A) The hexagonal crystal structure of selenium [15] and (B) α-monoclinic selenium structure.

Table 2.1 Summary of Se-based solar cells.

Se-based solar cells structure	V_{OC} (V)	J_{SC}	FF (%)	PCE (%)	Year	References
ITO/Te/Se/Au	0.54	10.9	56	3.3	1984	[20]
FTO/CdSe/Se/Au	-	-	-	4.6	1984	[21]
ITO/TiO_2/Se/Au	0.88	10.8	25	5.01	1985	[22]
FTO/cp-TiO_2/mp-TiO_2/Se/Au	0.65	8.7	53	3	2013	[23]
FTO/cp-TiO_2/mp-TiO_2/Se/P3HT/PEDOT:PSS/Ag	0.71	9.71	38	2.63	2014	[24]
FTO/cp-TiO_2/mp-TiO_2/Se/Spiro-OMeTAD/PEDOT:PSS/Ag	0.69	8.1	33	1.83	2014	[24]
FTO/bl-TiO_2/mp-TiO_2/Se/PTAA/Au	0.66	9.7	66	3.52	2016	[25]
FTO/ZnMgO/Se/MoOx/Au	0.97	10.6	63	6.51	2017	[26]
FTO/TiO_2/Se/MoOx/Au	0.87	10.9	60	5.73	2017	[26]
FTO/TiO_2/Se/Au	0.73	10.5	50	3.88	2017	[26]

4 Tellurium

Similar to S and Se, tellurium (Te) is also classified as a chalcogenide element. Because of its electron configuration, Te is the heaviest and nonradioactive chalcogenides element yet, Te has similarities like S and Se. Tellurium has six outer electrons in its electron configuration ($5s^2 5p^4$), which contribute to the physical properties such as optical and electrical properties. In Te configuration, electrons are paired in the *s*-orbital, occupying the lower energetic level in the shell with four electrons distributed between three *p*-orbitals [27].

Crystalline tellurium has a trigonal structure that arranged together into the hexagonal structure and trigonal structure. Interestingly, Te shows chiral/helical chains arranged in a hexagonal array, spiraling around axes parallel to the crystalline c-axis, with three atoms in the unit cell in a hexagonal structure. This unique feature is reflected in the liquid-state studies of Te and Se at atmospheric pressure, indicating that the chain structure is retained above the melting temperature [28]. The structures of tellurium are shown in Fig. 2.4.

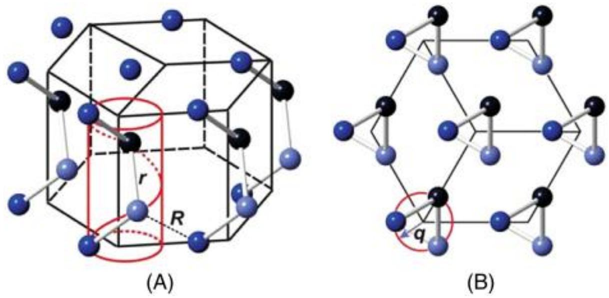

FIGURE 2.4 (A) The hexagonal crystal structure of tellurium with a hexagonal array which spirals around axes parallel to the crystalline c-axis [28] and (B) its top view.

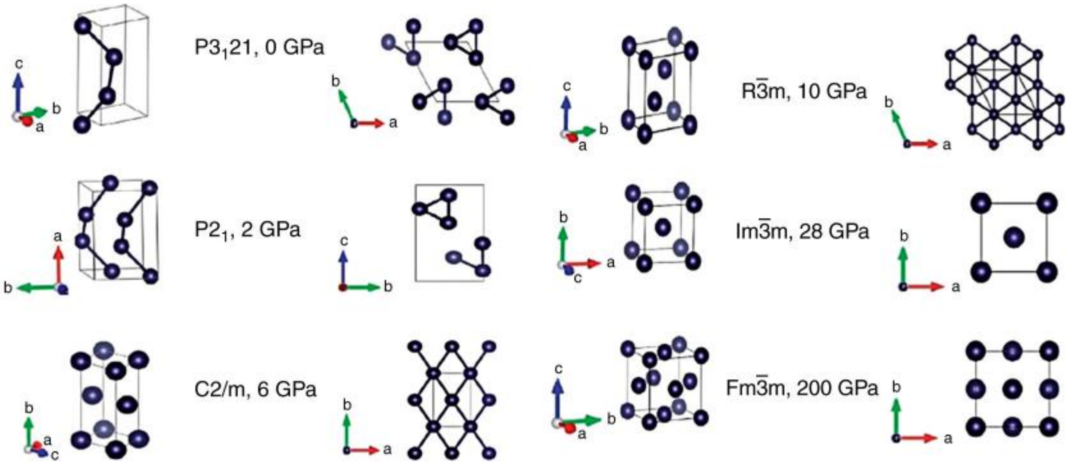

FIGURE 2.5 Structure of Te at different pressure [29].

Besides the crystalline phase (c-Te), tellurium also has amorphous (a-Te) and allotropes. Ren et al. reported that as the pressure increasing, the rhombohedral structure transforms into a stable body-centered cubic structure (bcc) at 28 GPa. At a higher pressure, larger than 100 GPa, the bcc structure transforms into a face-centered cubic (fcc) structure whose lattice turns stable at 200 GPa [29]. All tellurium allotropes on gas state are shown at Fig. 2.5.

Te has a direct bandgap between 0.36 and 0.39 eV and high-absorption coefficient from 0.4 cm^{-1} to $5 \times 10^3\ \mathrm{cm}^{-1}$. Te possesses electrical properties such as Hall mobility and Carrier concentration of $1.20 - 1.30 \times 10^{-3}\ \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$ and $3.8\text{–}4.3 \times 10^{17}\ \mathrm{cm}^{-3}$, respectively [30,31]. With its physical properties advantages, tellurium can be potentially used for many applications such as machining additives, catalysts, chemical uses, photoreceptors, thermoelectric devices, and photovoltaic devices. Fig. 2.6 shows percentage of tellurium applications.

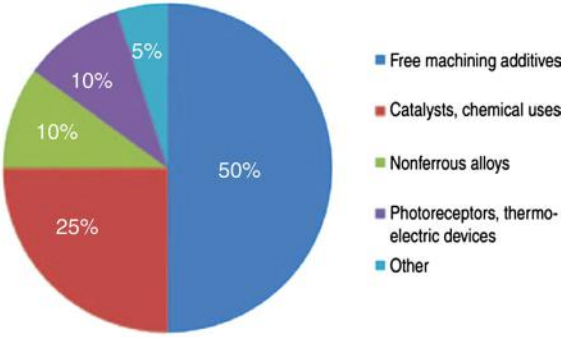

FIGURE 2.6 Applications of tellurium [32].

5 Binary chalcogenides

Many industrial activities produce byproducts such as hydrogen sulfide or other sulfur compounds. In recent years sulfur has had many considerable attentions in the form of metal chalcogenides semiconductors such as ZnS, CdS, PbS, which are widely studied as binary, ternary and quaternary chalcogenide materials [33].

Chalcogenides are the chemical elements in group VIA of the periodic table, consists of oxygen (O), sulfur (S), selenium (Se), and tellurium (Te). Initially, binary chalcogenide or metal-chalcogenide is the primary form of chalcogenide compounds. It consists of metals in group II and chalcogenides in group VI with 1:1 atomic comparation. Thus, metal-chalcogenide also called II-VI compounds, zincblende, or sphalerite, and it has an fcc or cubic closed packing (ccp) lattice. In this structure, the metal cations occupy one of the two types of tetrahedral holes present and have four asymmetric units in its unit cell. Besides zinc (Zn) as a metal site, metal-chalcogenide also could be replaced with other metal such as cadmium (Cd), Titanium (Ti), Mangan (Mn), and tin (Sn).

There are two types of the structure when chalcogenide makes bonding with a transition metal: dichalcogenides and tetrahedral structure. This kind of structure will occur when chalcogen is bound to certain transition metals. Tetrahedral metal-chalcogenide structure will be formed when chalcogenide elements make a bonding with Mn, Fe, Co, Ni, Cu and Zn, whereas Ti, V, Cr, Zr, Nb, Mo, Tc, Hf, Ta, W, and Re will form dichalcogenide structure [33]. The schematic illustration of transition metal dichalcogenides (TMDs) and tetrahedral transition metal chalcogenides (TTMCs) shown in Fig. 2.7.

Binary chalcogenides can be derived into ternary and quaternary compounds. Adding an element from elements from III, IV, or V group into a ternary compound will form I-III-VI_2, I_2-IV-VI_3, and I_3-V-VI_4, whereas adding elements from II and IV groups to a ternary compound, will form a I_2-II-IV-VI_4 compound. A ternary chalcogenide compound is also called a chalcopyrite structure compound because of the structure similarity to the chalcopyrite ($CuFeS_2$), while quaternary chalcogenide is also called kesterite or stannite. Fig. 2.8 shows chalcogenides family in periodic table.

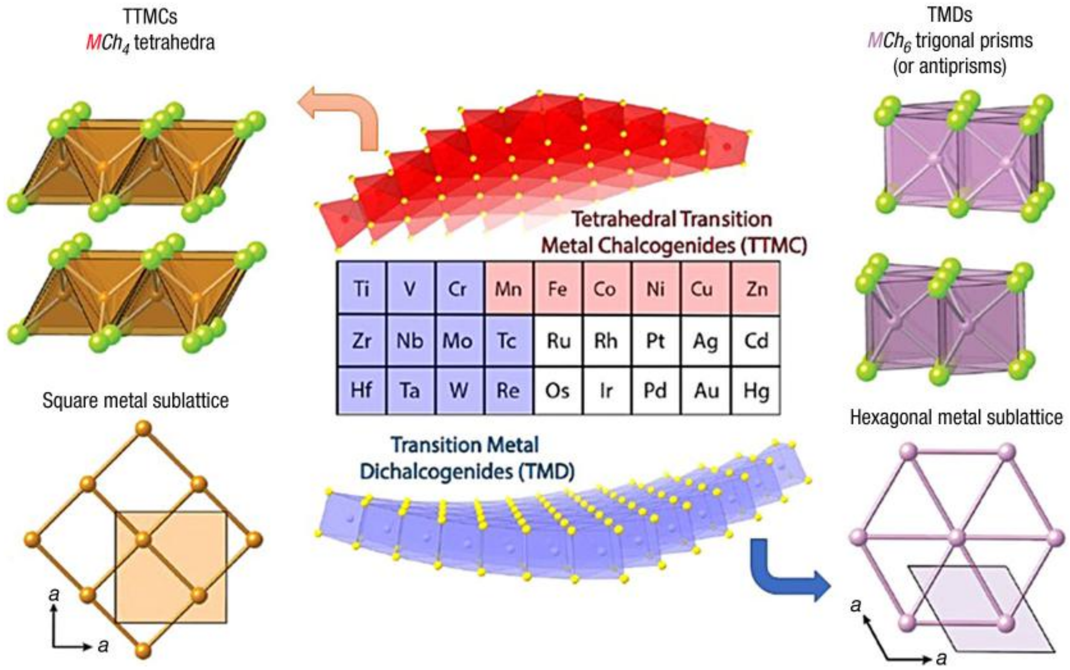

FIGURE 2.7 Comparison of the different sections of the periodic table that transition metal dichalcogenides (TMDs) and tetrahedral transition metal chalcogenides (TTMCs) each claim [33].

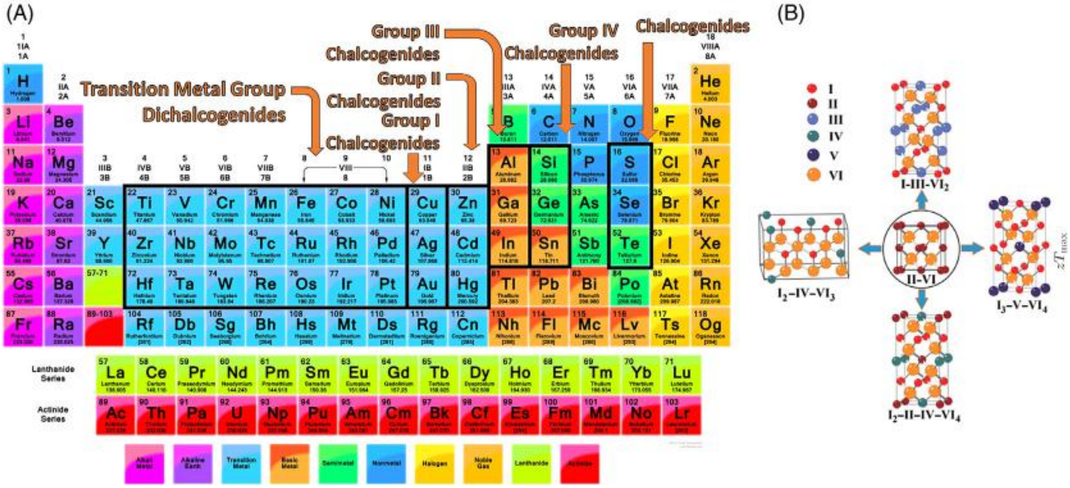

FIGURE 2.8 Periodic table (A) and chal cogenide family structures (B) [34].

Chalcogenide can also form compounds consisting of a combination of two chalcogenide structures, which are a combination of binary chalcogenides such as ZnSe with ternary chalcogenides such as $CuInS_2$ or kesterite such as Cu_2ZnSnS_4. This structure combination called multinary diamond-like chalcogenides (MDLC). An example of this multinary is

$Cu(In,Ga)(S,Se)_2$ [33]. All various chalcogenides are carried out to exhibit specific expected material properties. With this wide variety of chalcogenides, variations and combinations of physical and chemical properties are predicted.

Chalcogenide compounds are well known to have unique properties. In 1873, Smith discovered for the very first-time photoconductivity in selenium. In 1954, Pengelly et al. reported that several chalcopyrite such as $CuInS_2$, $AgInSe_2$, $CuInSe_2$, AgInTe, $CuInTe_2$, and $CuFeS_2$ showed semiconductor properties [35,36]. From then, research on chalcogenide has done extensively and applied for many applications. Photochemical reaction is one of the unique property of chalcogenide semiconductor materials. When photons from sunlight hit the chalcogenide semiconductor material, a pair of electron and hole can be generated simultaneously. Electrons have the negative charges and holes have the positive charges. These electrons and holes can be used for a redox reaction. Therefore, chalcogenide compounds can be used as photovoltaics or as photocatalysts materials.

6 Sulfide-based chalcogenides

Binary or metal sulfide-based chalcogenide, like cadmium sulfide (CdS), is a II-IV chalcogenide compound with a visible-light-responsive photocatalyst and a bandgap of 2.4 eV. Combine with high-carrier transportation capacity, it can be applied for many applications such as photovoltaic and photocatalyst [37,38]. Many methods can be used to synthesize CdS such as hydrothermal, chemical bath deposition, solvothermal, sonochemical, and other methods, which are affected by its properties such as the phase, size, quantum dots, and growth mechanism [37]. Among them, the chemical bath deposition (CBD) method is a low cost and simple method. Zelaya-Ángel et al. reported that a smooth CdS thin film could be synthesized from cadmium salt with thiourea as a sulfur source under basic condition [39]. This process illustration shows in Fig. 2.9 including appearance, XRD pattern and bandgap.

Nair et al. reported in detail explaining about CdS thin film growth mechanism on the substrate. The precursor ions in the critical layer have a higher probability of condensing and make a thin film than the ions in the outside the critical layer. It happens because the condensation takes place over the precipitate already present, particularly when stirring is used. It could lead to nucleation and precipitation of CdS in the bath. [38]. CdS thin film shows various resistivity as 10^2–10^7 Ω/cm with high transmittance values up to 70% and shows direct bandgap as 2.37 eV. All these optical and electrical properties were influenced by starting materials and methods of fabrication. Many chemical methods have been developed to fabricate CdS, as shown in Table 2.2.

Moreover, another metal in group II chalcogenides such as Zinc sulfide (ZnS) also can be made by a chemical process and has an important role in many application fields such as photovoltaic, photocatalytic, light emission diode (LED), and sensor [49–53]. ZnS was categorized into ceramic materials because it exhibited the brittleness and low stiffness. ZnS has two structures, wurtzite, and zinc blende. This material is used to synthesis by sol-gel and hydrothermal methods by utilizing metal-based alkoxide to synthesis ZnS in sol or

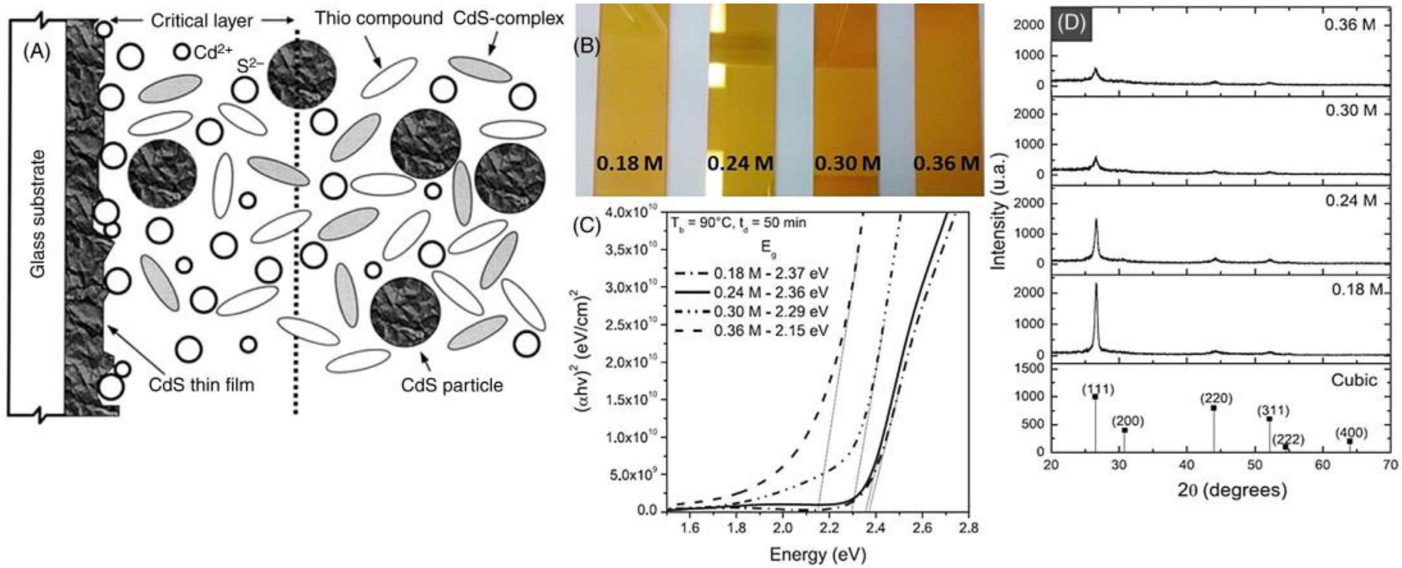

FIGURE 2.9 Schematic for the chemical bath deposition process (A) [38], CdS films images deposited (B), the direct bandgap energy (C), and XRD pattern (D) at different NH_4OH concentration [39].

Table 2.2 CdS synthesis methods including their shapes.

No	Synthesis method	Starting materials	Morphology/ crystal structure	References
1	Hydrothermal	$(NH_4)_6Mo_7O_{24}$, CH_4N_2S	Core/Shell-like	[40]
2	Ion exchange	$Cd(OH)_2$, Na_2S	Hierarchical nanosheet	[41]
3	Template free	$Cd(NO_3)_2.4H_2O$	Hollow spheres	[42]
4	Self-templated	$CdCl_2$, NaOH, Na_2S	Nanoporous	[43]
5	One-pot	$Cd(NO_3)_2.4H_2O$, CH_4N_2S, H_2PtCl_6	Nanorods	[44]
6	In situ growth method	$Cd(SCN)_2$, BNNSs	Spherical-like	[45]
7	Two-step method	$CdCl_2$, $C_4H_{13}N_3$, graphene oxide	Nanosheet-like	[46]
8	Chemical bath deposition	$Cd(NO_3)_2.4H_2O$, ethylene glycol, PVP, $H_2C_2O_4$	Core-shell nanosphere	[47]
9	Chemical bath deposition	$CdCl_2$, CH_4N_2S, ethylenediamine	Nanorod	[48]

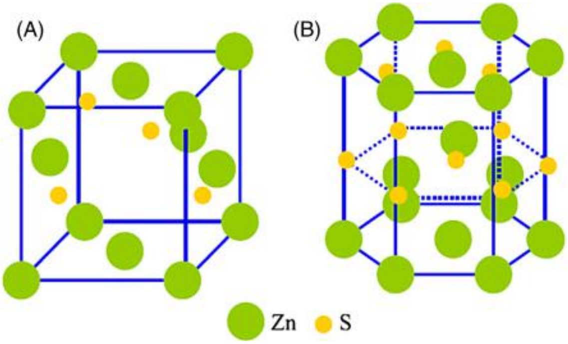

FIGURE 2.10 Crystal structure of ZnS as (A) zinc blende and (B) wurtzite [61].

gel state [54,55]. In this method, reaction time, solvent effect, pH, aging time, and chemical reagents are contributed to the quality of ZnS [56–58]. However, in industrial production, the solid-state reaction is more likely because of the ease of synthesis, low cost, and less production time.

To date, due to the high efficiency of energy conversion, thus ZnS was applied in many areas of research. On the other hand, due to its brittle and low stiffness, ZnS was still limited in some applications such as flexible solar cells, portable sensors or flexible photocatalytic. ZnS in zinc blende and wurtzite have wide and direct bandgaps of 3.72 eV and 3.77 eV, respectively. ZnS has high transmittance of up to 78% and more suitable for ultraviolet (UV) light-based devices such as sensors and photodetectors than conventional materials [59,60]. Fig. 2.10 shows crystal structures of ZnS.

7 Selenide-based chalcogenide

Besides sulfur, cadmium, and zinc also can make a compound with selenium as cadmium selenide (CdSe) and zinc selenide (ZnSe). Even CdSe also has the same ability as CdS on

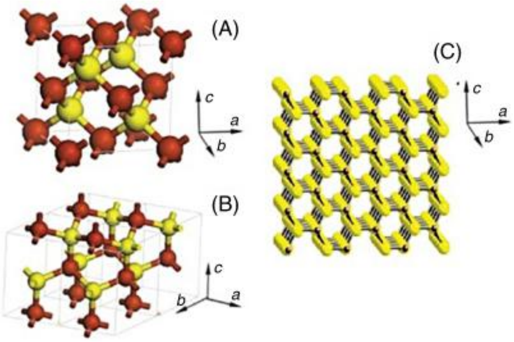

FIGURE 2.11 Crystal structure of CdS zinc blade (A), CdS wurtzite (B), and CdSe (C) [66,67].

photovoltaic and photocatalyst [62,63]. However, because they have different structures, it makes them have different physical and chemical properties that affect their performance as photocatalysts and photovoltaic. CdSe as a semiconductor material can be used as an n-type buffer, window, or absorber layer in thin film solar cells by selecting its thickness appropriately. It is suitable as a buffer layer because of its unique wetting properties on glass or fluorine-doped tin oxide (FTO) surfaces. CdSe has a bandgap of 1.80 eV in the wurtzite structure and 1.71 eV in the zinc blende structure [64,65]. Fig. 2.11 shows crystal structures of CdSe.

Many methods have been developed to synthesize CdSe thin films such as chemical bath deposition (CBD) [67], vacuum evaporation [68], electrodeposition [69], spray pyrolysis [70], and successive ionic layer adsorption and reaction (SILAR) [71]. One of the prominent methods that have been developed is by quantizing CdSe. By quantizing the CdSe particle, it will improve generation electron and hole from the photon in the CdSe particle. Consequently, CdSe gains their charge transport and separation, less recombination, and better quantum confinement effects [72].

CdSe quantum dots (CdSe QDs) give a significant improvement performance both as photovoltaic and photocatalytic efficiency. Frame et al. reported that the application of CdSe particle as hydrogen generation from water splitting was only able to obtain a quantum yield of 0.09% [63]. A couple of years later, by using CdSe photocatalyst and CdS quantum dots (QDs) as cocatalyst, the percentage of quantum yield had significantly increased to 52%–59%. Furthermore, CdSe also reported can be applied to photovoltaic, CdSe QDs show 12% of efficiency [72,73]. Table 2.3 shows several methods to synthesis CdSe QDs including their materials and morphology or crystal structure.

Like CdS and CdSe, ZnSe also has a similar structure and properties like ZnS. The lattice parameters of ZnSe in zinc blende structure are a = b = c = 5.68 Å and those of wurtzite structure are a = b = 3.98 Å, c = 6.53 Å. Owing to a relatively low difference in the total energy between the zinc blende and the wurtzite structure (5.3 meV atom^{-1}), ZnSe exhibits the so-called wurtzite-zinc blende polytypism. However, the zinc blende is the low-temperature ground state structure [62]. ZnSe is an n-type semiconductor, direct bandgap as 2.7 eV, and

Table 2.3 CdSe synthesis methods, including their shapes.

No	Materials	Synthesis method	Morphology / crystal structure	References
1	CdSe QD/a-TiO_2	Reflux	Spherical	[74]
2	CdSe QD/TiO_2:N	Hydrothermal, autoclave, CBD		[75]
3	CdSe-ZnS QD/Au-Pt	Reflux	Spherical	[76]
4	CdSe QD/TiO_2 NC	Solvothermal		[77]
5	CdSe/ZnS	Electrochemical	Core/shell QDs	[78]
6	CdSe QD/ZTP	CBD		[79]
7	ZnS/CdSe/CdS QDs	SILAR and CBD	Nanocrystalline	[80]

CBD, chemical bath deposition; SILAR, successive ionic layer adsorption; ZTP, zinc titanium phosphate

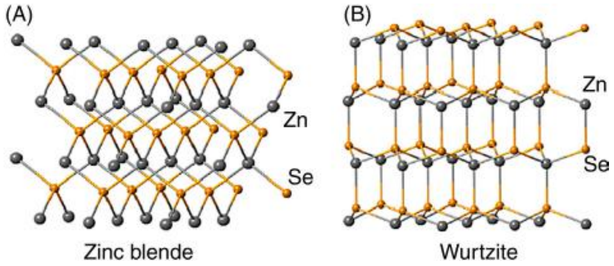

FIGURE 2.12 Crystal structure of ZnSe as (A) zinc blende and (B) wurtzite [62].

Table 2.4 ZnSe synthesis methods including their shapes.

No	Synthesis method	Starting materials	Morphology/crystal structure	References
1	Solvothermal	$ZnSO_4.7H_2O$, Se, N_2H_2	Ribbon-like	[82]
2	One-pot	ZnO, $C_8H_6O_4$, $C_{24}H_{51}PO$	Nanowires, hexagonal nanorods	[83]
3	Microwave-assisted	L-Glutathione (GSH), $Zn(OAc)_2$, Se, KBH_4, NaOH, C_3H_8O, BSA	Nanocrystal	[84]
4	Hydrothermal	$C_4H_6CdO_4$, $ZnC_4H_6O_4$, NH_3, Na_2SeSO_3	Core/shell NCs	[85]
5	Template assisted solution process	p-C_8H_{10}, $Zn(OAc)_2$, H_2Se	Nanotubes	[86]

has attracted considerable attention in many fields such as photovoltaic, photocatalytic [81], light-emitting diodes, and photodetectors. Fig. 2.12 shows ZnSe crystal structures.

ZnSe can be prepared as thin films or as nanoparticles with various methods and various morphology such as core/shell, nanorods, nanowires, nanoribbons, and nanotubes [63,74–76]. All these various shapes are dependent on the method, raw materials, and preparation condition. Table 2.4 shows several methods to synthesis ZnSe including their starting materials and structure.

8 Telluride-based chalcogenide

Like metal sulfur and selenium compounds, cadmium telluride an ideal absorber material for thin film photovoltaic devices and can be applied as a photocatalyst as well. CdTe has a direct bandgap of 1.45 eV, high transmittance yet high-absorption coefficient. Recently, record efficiencies were reported for up to 22% [87]. Whereas photocatalytic, CdTe can be convincing to perform to generate hydrogen from the water-splitting process [88]. As in many II-VI semiconductors, cadmium chalcogenides also exist in both zinc-blend and wurtzite structures. Fig. 2.13 shows CdTe crystal structures.

Among binary metal chalcogenide, CdSe is the most used material to fabricate quantum dots (QDs) solar cell devices such as dye-sensitized solar cells (DSSC) or thin film due to possessing a narrow band gap, a higher conduction band edge relative to TiO_2 as its transport layer. However, CdTe QDs possess a narrower bandgap and higher conductive band edge, which extend the light-absorption range of CdTe to longer wavelengths and faster electron injection rate [90]. Moreover, the performance of CdTe photocatalyst also effected by its quantum dot particle size. Particle size could affect its conduction band (CB) that sufficiently have a positive charge and valance band (VB) that adequately have a positive charge on the electrochemical state. Smaller particle makes smaller CB and VB, hence make the bandgap or gap between CB and VB are wide.

Moreover, when this material adsorbs a photon from light, it will generate an electron-hole pair. Furthermore, if there is enough energy, the electron will jump from VB to CB and jump back to VB by releasing an amount of energy. Wider bandgap will release higher energy with its specific wavelength, and as we know, that wavelength showing a specific color. That is why different particle size has its color. This phenomenon called the quantum confinement effect and shown in Fig. 2.14.

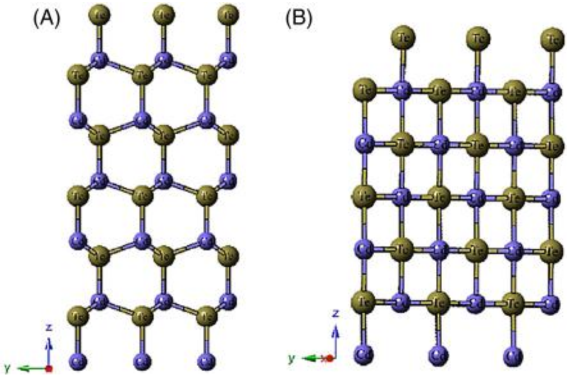

FIGURE 2.13 Structure of CdTe as (A) wurtzite and (B) zinc blende [89].

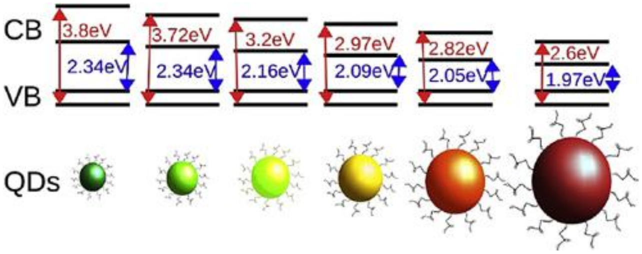

FIGURE 2.14 The quantum confinement effect of CdTe quantum dots [91].

9 Ternary chalcogenides

Binary chalcogenide can be derived into ternary chalcogenide by adding one more element from group III, IV, or V into binary chalcogenide. When a metal element from group III or IV added into binary chalcogenide like CuS, a ternary chalcogenide will form. Sulfur and selenium are elements that lie in group VI in the periodic table. They have similar properties and often found in hydrocarbon compounds together in nature in several ratios [92]. Furthermore, both sulfur and selenium often used simultaneously or individually in ternary and quaternary chalcogenide materials.

The addition of one element can be done for zinc blende, and wurtzite structure by elements from group III, IV, and V. Ternary chalcogenide material, such as $CuInS_2/Se_2$ (CIS) and $CuSnS_3/Se_3$ (CTS) added by element indium (In) from group III and tin (Sn) element from group IV, respectively and produce a chalcopyrite structure. Fig. 2.15 shows different of chalcopyrite, zinc blende, and wurtzite structures.

$CuInS_2/Se_2$ (CIS) is an II-III-VI_2 chalcopyrite material that has been a long time developed. Owing to a high-optical absorption coefficient, good stability against long-term radiation, and desirable bandgap, which matches well with the solar spectrum [94,95], The early claimed efficiency of CIS solar cells was using an n-type crystal with efficiency close to 10% in 1986 [95]. Recently, it has been demonstrated a significant improvement of conversion efficiency as high as 12% under laboratory conditions [96].

CIS solar cells exist in three crystal structures, chalcopyrite, zinc blende, and wurtzite. However, the most common structure is the chalcopyrite structure as shown in Table 2.5

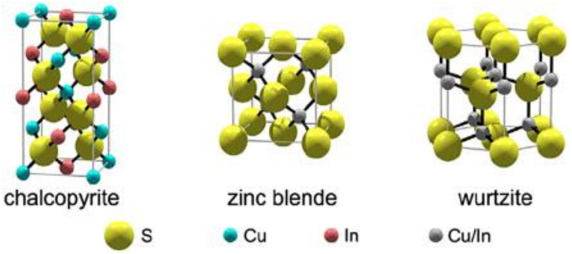

FIGURE 2.15 Crystal structures of chalcopyrite, zinc blende, and wurtzite [93].

Table 2.5 The precursors, crystal phases, and morphologies of CIS fabrication.

Cu precursors	In precursors	Crystal phase	Morphology
2.5 mmol Cu(acac)$_2$	2.5 mmol In(NO$_3$)$_3$	Wurtzite	Irregular nanodisks
2.5 mmol Cu(acac)$_2$	2.5 mmol InCl$_3$	Wurtzite-zinc blende polytypism	Nanoplates
2.5 mmol Cu(acac)$_2$	2.5 mmol In(acac)$_3$	Chalcopyrite	Small nanoparticles
3.1 mmol Cu(acac)$_2$	1.9 mmol In(acac)$_3$	Wurtzite	Nanobullets
2.5 mmol CuCl	2.5 mmol In(acac)$_3$	Zinc blende	Small nanoparticles
2.5 mmol CuCl	2.5 mmol InCl$_3$	Wurtzite-zinc blende poytypism	Nanoplates
2.5 mmol CuCl	2.5 mmol In(NO$_3$)$_3$	Wurtzite-zinc blende polytypism	Nanoplates
2.5 mmol Cu(NO$_3$)$_2$	2.5 mmol In(NO$_3$)$_3$	Wurtzite	Mixture of nanodisks and small nanoparticles

[93]. Teng et al. reported that the structure of CIS could be controlled by adjusting the composition and concentration of precursors [97,98]. Moreover, CIS material can be prepared by many methods, such as vacuum deposition, electrochemical deposition, chemical vapor deposition, sol process, hydrothermal/ solvothermal, and pyrolysis [99–104]. And it can be constructed by adding three kinds of single elements simultaneously or sequences, one element into binary chalcogenide, and binary-to-binary chalcogenide [105–107].

10 Quaternary chalcogenide

Furthermore, the derivative compound from chalcopyrite or ternary chalcogenide is a quaternary chalcogenide which is consist of I_2–II–IV–VI_4 quaternary semiconductor compound that obtained by replacing half of the indium by zinc and another half by tin in $CuInS_2$ chalcopyrite ternary compound. This replacement produces $CuZnSnS_4$/Se_4 kesterite or stannite structure. The two structures are quite similar except different arrangements of Cu and Zn atoms. Between kesterite and stannite, CZTS material usually appears in the kesterite phase because it is thermodynamically more stable as compared to the stannite type [108]. Moreover, one of the benefits of CZTS material is all the constituent elements are nontoxic, low cost, and readily available in the earth's crust.

As a p-type semiconductor, CZTS has a suitable optical bandgap as 1.4–1.65 eV and has a high-absorption coefficient of over 10^4 cm^{-1} in visible wavelength region and showing 12.3% of efficiency with a resistivity as low as 1.482 Ωcm and carrier concentration of 1×10^{19} cm^{-3} [109–112]. Both CIS and CZTS compounds can also be derived from zinc blende and wurtzite phases. Ternary chalcogenide like CIS commonly possess chalcopyrite structure whereas quaternary chalcogenide commonly possesses kesterite structures. Fig. 2.16 shows schematic diagram of the structural derivation of $CuInS_2$ $CuInS_2$ (CIS) and quaternary Cu_2ZnSnS_4 (CZTS) from binary chalcogenide (ZnS).

However, both ternary and quaternary structures also effected by method, materials, and treatment that applied. Like ternary chalcogenides, quaternary chalcogenides like CZTS also can be prepared in several ways. It can be prepared from mixing a few single elements, from mixing the binary compound with a single element or another binary

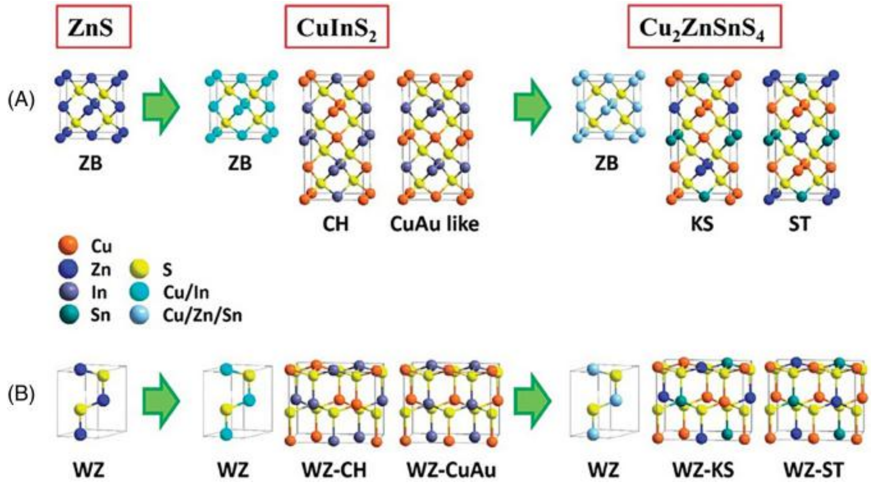

FIGURE 2.16 Schematic diagram of the structural derivation of ternary CuInS$_2$ (CIS) and quaternary Cu$_2$ZnSnS$_4$ (CZTS) from binary ZnS, which possesses (A) the zinc blende and (B) wurtzite phases [113].

compound, and the addition of a single element to the ternary element. However, to fabricate a good CZTS that showing good performance, the composition of its composition must be precise. Stoichiometric and non-stoichiometric composition of CZTS effects to its phases, and it leads to the CZTS performance. Fig. 2.17 shows chemical composition map of CZTS.

There are several prominent quaternary chalcogenides using sulfur and selenium simultaneously in the photovoltaic application. This combination makes a better morphology and structure thus a better optical and electrical properties, which leads to the significant improvement of solar cells performance.

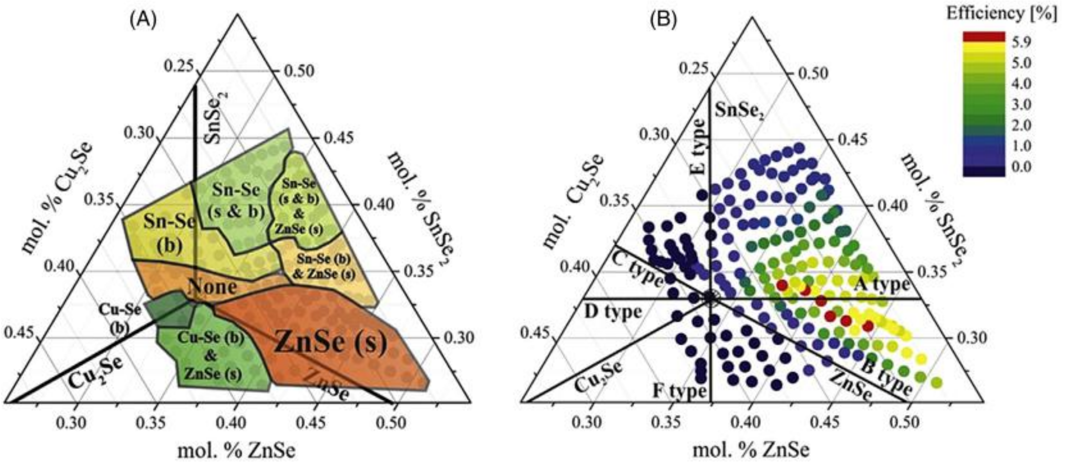

FIGURE 2.17 (A) chemical composition and secondary phases map of CZTS and (B) its performances [114].

11 Chalcogenide-based nanomaterials

Chalcogenide nanostructure is an interesting material with many applications such as superconductors, fuel cells, photovoltaics, photocatalyst, and energy storage [74,111,115]. Another advantage of chalcogenide material is that they can be synthesized through various methods such as hydrothermal/solvothermal, microwave-assisted, sonochemical methods, electrochemical, and can even be synthesized using the vacuum method. Moreover, chalcogenide materials also can be incorporated with advanced carbon materials such as carbon nanotube and graphene [92,93].

Sulfide-based chalcogenides like NiS has attracted much interest because it contains numerous of phases, and it potentially applied as a rechargeable lithium battery [115,116]. Yu et al. investigated the effect of reaction temperature, reaction time, and additive to NiS by using a solvothermal process [116]. Fig. 2.18 shows SEM images of NiS with a different volume ratio of ethylenediamine to glycol and different annealing conditions.

Even though solvothermal/hydrothermal is a wide and common method to synthesis chalcogenide compounds or other organic or inorganic materials, this method still takes long reaction time, requiring high energy and low-reaction rate. On the other side, microwave chemistry developed rapidly for the preparation of various organic and inorganic nanomaterials due to its high-reaction rate, low-processing costs, high yields, and less byproduct. By microwave-assisted reaction, the energy to heat the sample comes from the energy by electromagnetic radiation in the frequency range of 0.3–2.45 GHz, which effectively heat the sample from the inside or its molecules.

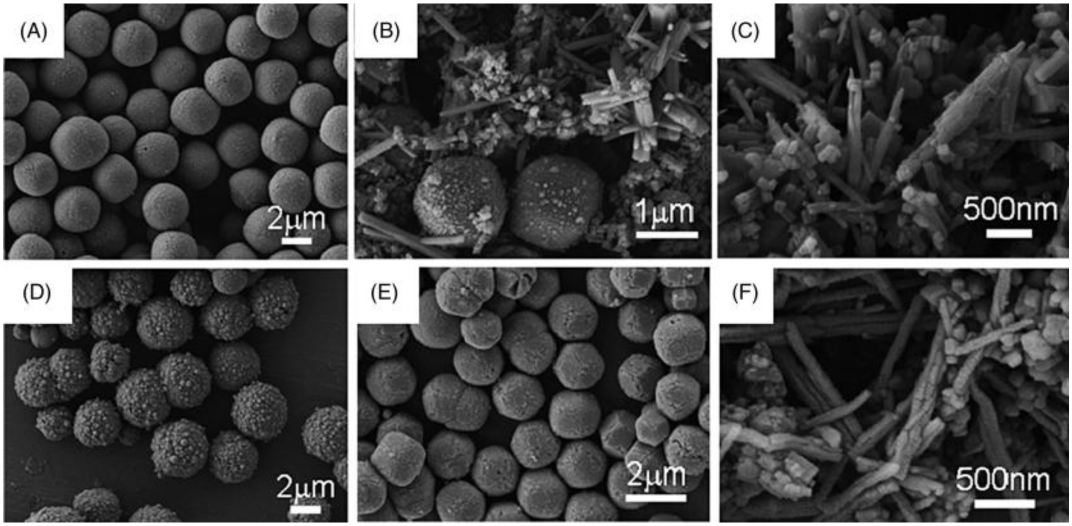

FIGURE 2.18 SEM images of the samples prepared by the reaction of 0.5 mmol $NiCl_2.6H_2O$ and 2 mmol S at 200°C for 6 h in a mixed solvent with a different volume ratio of ethylenediamine to glycol: (A) 1 : 1, (D) 1 : 3, for 6 h at different temperatures: (B) 180°C, (E) 220°C, and at 200°C for different reaction times: (C) 0 h, (F) 1 h [116].

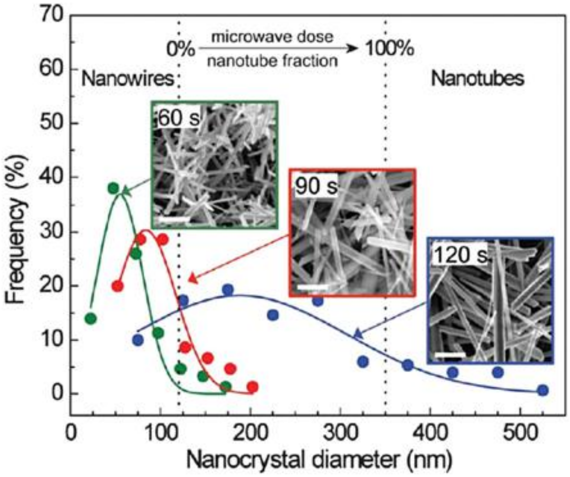

FIGURE 2.19 Size distribution graphs with SEM insets (scale bars = 1 mm) of the Sb_2Se_3 nanocrystals [117].

By utilizing the advantages of microwave properties on solvothermal, Ramanath et al. successfully synthesized and control the diameter and length of Sb_2Se_3 nanowires and nanotube by control the microwave dose (microwave dose - microwave power x time exposure) [117]. Fig. 2.19 shows size distribution graphs with SEM insets of the Sb_2Se_3 nanocrystals.

Like sulfur and selenium, the telluride compound also can be synthesized by hydrothermal method. Yu et al. investigated Bi_2Te_3 nanowire via hydrothermal method using trimethylene glycol (TEG) as a solvent and successfully control the morphology by control the reaction temperature and time [117]. Fig. 2.20 shows TEM images of the Bi_2Te_3 nanowire.

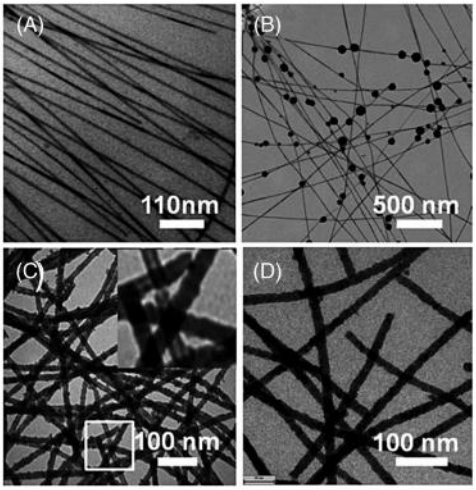

FIGURE 2.20 TEM images of the Bi_2Te_3 nanowire at different temperature process: (A) 100°C, (B) 160°C, (C) reached 200°C for 20 min, and (D) maintained at 200°C for another 20 min [88].

12 Conclusions

Chalcogenides such as sulfide, selenide, and telluride based-chalcogenides are abundant materials. Their derivatives such as binary, ternary, and quaternary chalcogenide materials are applicable in many areas such as photovoltaic, photocatalyst, sensor, fuel cell, and battery. Chalcogenide compounds also can be prepared with many methods such as hydrothermal, solvothermal, one-pot, microwave-assisted, sonochemical, and electrochemical methods. The morphology of chalcogenide materials are also affected by the composition of raw materials, methods of synthesis and treatment. Sulfide, selenide, and telluride-based chalcogenides have their own unique characteristics, structure, and physical as well as chemical properties making them one of the most studied nanostructures. There are numerous chalcogenides that have been studied extensively over the years where future of chalcogenides-related fields can be expected.

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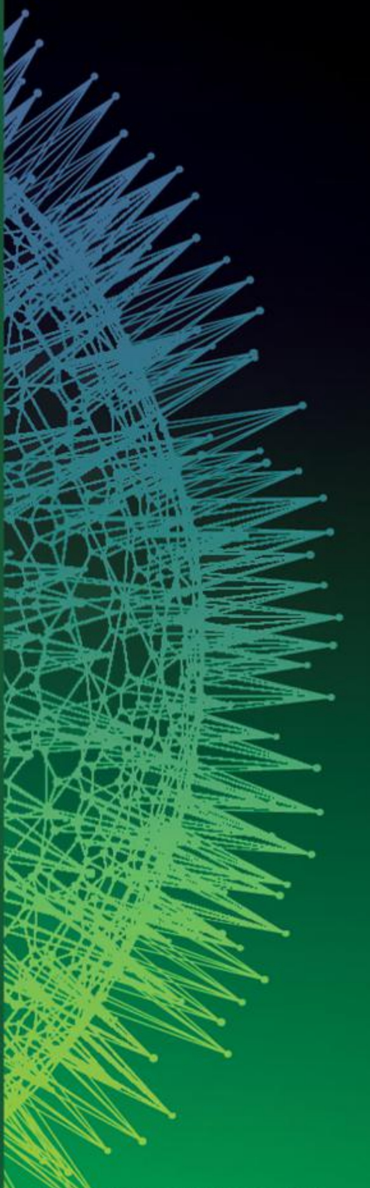
CHALCOGENIDE-BASED NANOMATERIALS AS PHOTOCATALYSTS

Edited by Mohammad Mansoob Khan



Photocatalysis using chalcogenide-based nanomaterials is a green technology that has been widely applied for environment remediation and energy production. Chalcogenide-based nanomaterials are visible-light responsive photocatalysts that have significant advantages including low cost, high efficiency, harmlessness, and stability.

This book deals with the different types of chalcogenide-based photocatalytic nanomaterials. This book will cover the fundamental concepts of photocatalytic reactions, mainly under visible light, involving chalcogenides for a range of energy and environment-related applications.

The book focuses on the nanostructure control, synthesis methods, activity enhancement strategies, environmental applications, and perspectives of chalcogenide-based nanomaterials. It offers guidelines for designing new chalcogenide-based nanoscale photocatalysts, at low cost and high efficiency, for the utilization of solar power in the areas of energy production and environment remediation.

Key Features

- Provides information on developing novel chalcogenide-based nanomaterials
- Outlines the fundamentals of chalcogenides-based photocatalysis
- Includes techniques for heterogeneous catalysis based on chalcogenide-based nanomaterials

About the Editor

Dr. Mohammad Mansoob Khan is an Associate Professor at Chemical Sciences, Faculty of Science, Universiti Brunei Darussalam, Brunei Darussalam. Dr. Khan earned his PhD from Aligarh Muslim University, Aligarh, India. Afterwards he worked as researcher, academician, lecturer, and professor in various countries (India, Ethiopia, Oman, and South Korea), taught several courses at undergraduate and postgraduate levels and has demonstrated excellence in teaching and research. His main research interests are in the field of nanosciences, nanotechnology, materials sciences, and band gap engineering. This includes green syntheses of metal nanoparticles, metal oxides, chalcogenides, inorganic nanohybrid, and nanocomposite materials mainly used for catalysis, photocatalysis, photoelectrodes, optoelectronic devices, H2 production, sensing, and selected biological applications.

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