



REVIEW ON THE RECENT ADVANCES IN LAYERED TUNGSTEN DISULFIDE (WS₂): FROM SYNTHESIS TO TECHNOLOGICAL APPLICATIONS

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ABSTRACT

2D semiconductor tungsten disulfide (WS₂), a member of transition metal dichalcogenides (TMDCs), attracts significant interest in both fundamental physics and many promising applications, such as light emitters, photodetectors/sensors, and flexible nanoelectronics, due to its fascinating optical, electronic, and mechanical properties. Its layer-dependent bandgap—transitioning from a direct bandgap of ~2.1 eV in the monolayer to an indirect bandgap of ~1.3 eV in the bulk—combined with its high aspect ratio, high carrier mobility, and robust chemical and thermal stability, makes WS₂ a compelling candidate for next-generation optoelectronic technologies. Structurally, WS₂ comprises a trilayer fundamental unit in which a plane of W atoms is sandwiched between two planes of S atoms, with adjacent layers held together by weak van der Waals (vdW) forces. This bonding facilitates easy mechanical cleavage and produces ultraclean surfaces free of dangling bonds, enabling the fabrication of high-quality vdW heterostructures. Such heterojunctions have been widely utilised in advanced photodetectors, sensors, and light-emitting devices.

This review offers a comprehensive assessment of recent progress in 2D WS₂, encompassing synthesis methods, structural features, and optical properties. We further highlight three application areas where WS₂ has exhibited exceptional potential—Biosensing, solar cells and photocatalytic hydrogen production, and gas sensing. Finally, we summarize key advances and outline future research opportunities, emphasizing the pivotal role of 2D WS₂ in driving technological innovation across diverse scientific and engineering domains.

KEYWORDS: WS₂, TMDCs, Optoelectronics, Devices, Nanomaterials, Solar Cell, Biosensor and Photocatalytic

INTRODUCTION

For many decades, transition metal dichalcogenides (TMDCs) have been among the most promising materials for a wide range of applications owing to their unique structural and optical properties. Just like graphene, TMDCs are layered materials that can be made up of single or few-layered nanosheets and show unique developing physical features that are completely dissimilar from those of their bulk counterparts. Tungsten disulfide (WS₂) is a highly significant member of the two-dimensional (2D) TMDCs

family after MoS₂ and is regarded as an optimal candidate for optoelectronic devices due to its layer-related bandgap [2], remarkable thermal stability [3], high carrier mobility [4], high aspect ratio [5] and chemical stability [6]. The bandgap of WS₂ exhibits a notable variation, ranging from a direct bandgap in the monolayer (2.1 eV) [1] to an indirect bandgap in the bulk form (1.3 eV) [1]. Due to these properties, WS₂ is used in numerous applications such as, transistors, diodes, LEDs, photodetectors, pulsed lasers, etc. [7,8]. Very recently, WS₂ has become the

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focus of thin-film solar cell materials due to its optoelectrical properties.

WS₂ is composed of a fundamental unit layer comprising a layer of W atoms sandwiched between two layers of S atoms. Each fundamental layers are bonded by a weak van der Waals force (vdW) of interaction between chalcogenide atoms, i.e. Sulphur (S). This type of configuration allows WS₂ to be separated along the basal planes, creating a lack of surface dangling bonds. This allows for the formation of advanced vdW heterojunctions with other semiconductor materials, which are efficiently utilized to fabricate high-performance sensors, photodetectors, light-emitting diodes, and other devices [9]. For instance, Xiaoping Hong et al. have reported [10] the first experimental observation of ultrafast charge transfer in photoexcited MoS₂/WS₂ heterostructures using both photoluminescence mapping and femtosecond pump-probe spectroscopy. However, Chenhao Jin, et al. reported [11] the observation of moiré superlattice exciton states in WSe₂/WS₂ heterostructures, which provide an attractive platform from which to explore and control excited states of matter, such as topological excitons and a correlated exciton Hubbard model, in transition-metal dichalcogenides. In another report, Ashraf, W. et al. have reported [12] an enhanced visible-light-driven photocatalytic response of novel 2D/2D BiOCl/WS₂ hybrid nanosheet heterojunctions ranging from 0–5% of WS₂ content. However, WS₂ is used as a substrate for immobilizing species. WS₂ nanomaterials show an excellent property of conductivity for their use in electronics and biosensors as well. To date, there is a paucity of comprehensive reviews that focus specifically on the application of 2D WS₂-based optoelectronic devices.

This review provides a timely and comprehensive overview of the state-of-the-art in 2D-WS₂, focusing on its synthesis, properties, and applications. It highlights key advances, ongoing challenges, and potential directions for future research. While it is not feasible to cover all developments in this rapidly expanding field, the review emphasizes the most recent progress and trends. The paper is organized as follows: Section 2 discusses various synthesis techniques of 2D-WS₂ materials. Section 3 addresses the crystal structure and optical properties

of layered WS₂, and Section 4 explores three fascinating applications where WS₂ has demonstrated remarkable promise, including Biosensing, Solar cells and Water-Splitting Photocatalysts. Finally, Section 5 summarizes reported findings and highlights for future directions, underscoring the potential of 2D WS₂ as a key technological enabler across multiple domains.

2. SYNTHESIS OF LAYERED-WS₂

The synthesis of 2D-WS₂ materials can broadly be categorized into two main strategies: top-down and bottom-up approaches. The top-down methods primarily rely on mechanical exfoliation [13], the Scotch tape method [14], ultrasound-assisted exfoliation [15], and so forth.

2.1 Top-down approach

Exfoliation methods- To date, mechanical exfoliation is one of the most effective methods of producing the extremely crystalline as well as atomically thin nanosheets of layered materials [16]. During a conventional mechanical exfoliation process, from the bulk crystals, thin TMDC crystals are peeled off on the tape and are then placed onto a target substrate and further cleaved by rubbing them with tools such as plastic tweezers. However, the method suffers from inherent drawbacks, such as low yield, poor scalability, and limited control over sheet size, shape, and layer number.

Scotch tape method- In the scotch tape method, mechanical forces are applied to the bulk sample of WS₂ and eventually remove the thin sheets. Then a substrate is applied to the sheets, which leaves behind fine flakes of different sizes as well as thicknesses [17]. As the Van der Waals forces of interaction between the fundamental layers are weak, the scotch tape can be used to exfoliate the crystals of WS₂ mechanically [18].

Ultrasound-assisted exfoliation- The ultrasonic peeling is a process that utilizes the shear force generated by ultrasonic waves to separate the material into flakes [19]. The irregular nanosheet morphology is typically generated due to the instantaneous high pressure, which can cause damage to the material. Furthermore, this method leads to a phase transition from 2H to 1T.

Chemical exfoliation techniques- This technique is solvent-based and ion intercalation-based [20]. The choice of solvent and solute concentration plays a critical role in determining nanosheet thickness. In this method, lithium (Li) insertion results in the weakening of interlayer vdW interactions between adjacent layers, which are then dispersed in deionized water and exfoliated by ultrasound. In contrast to MoS₂, the lithiation process of WS₂ is more challenging. For instance, Yang and Frindtin et al. [21] observed that the degree of lithiation only significantly increased when the temperature was above 50°C.

2.2 Bottom-up approach

In this method to the fabrication of WS₂, nanostructures are made up by building upon single atoms or molecules. In general, the bottom-up production method takes place in two stages i.e. gas-phase synthesis and liquid-phase formation [22]. Currently, thin films can be achieved cheaply, reliably, and very efficiently using both physical and chemical deposition methods.

a. Physical vapor deposition (PVD)

One of the most promising techniques for synthesizing 2D WS₂ is physical vapor deposition (PVD). Recently, Takuya Hamada et al. [23] have synthesized an atomic layer WS₂ film formed by UHV RF magnetron sputtering using a SiO₂/Si substrate, which was confirmed using TEM images and XRD spectra. This WS₂ film has potential applicability in thermoelectric generators, such as energy harvesters in LSIs and wearable devices. PVD encompasses a broad range of thin-film deposition techniques, such as molecular beam epitaxy (MBE) [24], pulsed laser deposition (PLD) [25], sputtering [26] and vacuum evaporation [27].

b. Chemical vapor deposition (CVD)

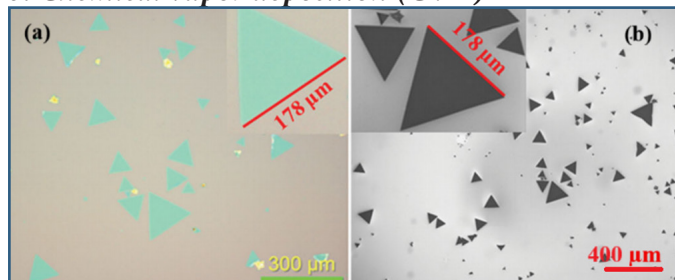


Fig. 1: (a) Optical image of CVD-grown WS₂ on SiO₂/Si substrate. Inset shows a triangular

monolayer WS₂ and (b) SEM image of monolayer WS₂ [28].

Chemical vapor deposition (CVD) has emerged as one of the most promising techniques for the synthesis of layered, large-area, and well-controlled WS₂ material [28]. In a typical CVD process, solid precursors are heated to high temperatures, enabling the formation of thin films on substrates, most commonly Si/SiO₂ wafers [29]. Dong et al. reported a simple CVD method to synthesize the WS₂ monolayer, where different WS₂ domain shapes were obtained by controlling the concentration gradient of WO₃ precursors. Chen et al. [30] pre-deposited smooth WO₃ film on the SiO₂/Si substrates by combining CVD with thermal evaporation technology. This method of surface source supply is beneficial to the uniform nucleation of precursor vapor on the whole substrate. Although great progress has been made in the preparation of WS₂ single crystals, there are still great challenges are there for high quality and diverse morphologies. Jiashuo Yan. et al. [31] have synthesized 2H-WS₂ nanosheets with smooth surface, uniform thickness and of size up to 100 μm by an improved CVD method using with WO₃ (≥99.99%, Aladdin) and S (≥99.99%, Aladdin) powders as the precursors of W and S, respectively, as well as SiO₂/Si as substrates. In addition, several CVD variations have been developed, including **metal-organic chemical vapor deposition (MOCVD)** [32], **Sol-Gel method** [33], and **pulsed laser deposition (PLD)** [34].

3. STRUCTURAL AND OPTICAL PROPERTIES

Tungsten disulfide (WS₂) belongs to the family of layered two-dimensional transition metal dichalcogenides (TMDCs), with the general chemical formula MX₂, where M represents a transition metal (e.g., Mo, W, Ti) and X denotes a chalcogen element (e.g., S, Se) [35]. Bulk WS₂ consists of stacked fundamental S–W–S layers, held together by weak van der Waals force (vdW) interactions shown in Fig. 2 (a), (b) and (c). Within each fundamental layer, a W atom is coordinated by six surrounding S atoms, forming a tri-layer arrangement in which the W plane is sandwiched between two S planes. This tri-layer fundamental unit constitutes a single monolayer of WS₂, and subsequently two fundamental layers constitute a bilayer structure (2M-WS₂) as shown in Fig. 2(b).

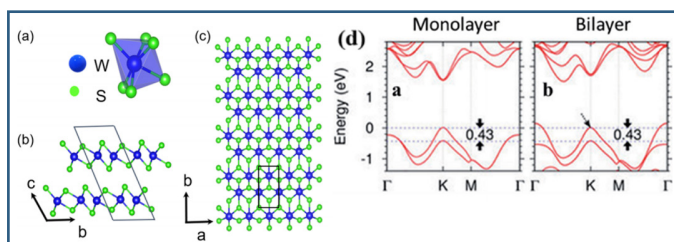


Fig. 2. (a) Schematic of [WS₆] structure (b) Side view of the (c) top view of the 2H-WS₂ crystal structure [36] and (d) Band dispersion of Monolayer and Bilayer band structure [37].

Fig. 2 (d) clearly depicts the band structure of Monolayer and Bilayer of WS₂, which suggests that Monolayer is a direct bandgap material, whereas Bilayer is an indirect one. However, bulk WS₂ has an indirect bandgap of 1.3 eV [1]. This explains that as we keep on increasing the number of layers from a monolayer, the bandgap is transformed from a direct to an indirect bandgap.

4. APPLICATIONS

Being a member of TMDCs family, WS₂ is emerging as one of the choices for various effective applications such as Photovoltaic, biosensing, photocatalytic, etc., because of its fascinating properties in terms of direct band gap, stronger photoluminescence, greater mobility, magnetic field interaction and better thermal stability. It has numerous diverse applications like field-effect transistors (FET) [8], in sensing [9], etc. We will be discussing some of the important applications in the following:

4.1 Biosensing

The properties that WS₂ possesses, such as a large surface-to-volume ratio, tunable bandgaps well and strong interaction with biomolecules which make it as a prominent choice for developing extensively sensitive and selective biosensors [38]. Till now, WS₂ have exhibited remarkable properties by detecting numerous biological entities from small biomolecules such as glucose and cholesterol to very complex molecules like DNA, proteins, as well as pathogens [39]. Some emerging applications of WS₂ in biosensing are [40]:

- 1) Cancer biomarker detection
- 2) DNA and RNA detection
- 3) Protein and enzyme sensing
- 4) Glucose and cholesterol monitoring
- 5) Pathogen detection

The growing applications of WS₂ in biosensing suggest that it has the potential to transform diagnostics, environmental monitoring, and healthcare technologies. A significant direction for the future environment involves the fusion of WS₂ with other 2D materials or nanostructures to create hybrid composites, which can be utilized as different components leading to enhanced sensitivity, selectivity, and robustness in biosensors. AI can significantly enhance the diagnostic capabilities of WS₂ based biosensors. By applying machine learning algorithms to analyze the complex data generated by these sensors, AI can help identify patterns and correlations.

4.2 Solar Cell

TMDCs, especially WS₂, have drawn the notice of the Photovoltaic (PV) community for thin-film solar cells due to their excellent properties such as tunable bandgap, high absorption coefficient (>105 cm⁻¹), high carrier mobility, good conductivity and earth-abundant [41]. However, recently, several research works have been reported on thin-film heterojunction solar cells. For instance, the application of WS₂ as a PV material was first introduced by Wu et al. in a dye sensitized solar cell [42]. WS₂ nanosheets have been reported as an efficient hole transport layer (HTL) for organic solar cells [43].

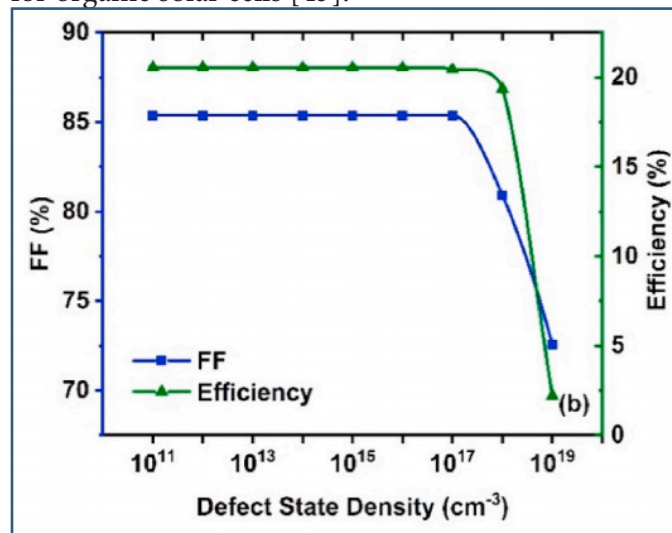


Fig. 3: Performance variation due to variable defect states in the WS₂ buffer: FF and Efficiency [45].

Md. K. S. B. Rafiq et al. [44] have successfully incorporated the low-cost, non-toxic material WS_2 in solar cell devices. For the first time, they fabricated WS_2 thin film as a window layer in CdTe solar cells, resulting in a new device (ITO/ WS_2 /CdTe/Cu:C/Ag) that exhibited $V_{oc}=0.39$ V, $J_{sc}=10.45\text{mA/cm}^2$, fill factor=29.42%, and efficiency=1.2%. Recently, E. I. Emon et al. [45] have demonstrated that by replacing the ITO/ZnO/CdS/CdTe/Au bilayer with a single SnO_2 window and toxic CdS buffer by an environment friendly WS_2 layer, resulting in a proposed structure: $\text{SnO}_2/\text{WS}_2/\text{CdTe}/\text{Au}$. The optimized layer thickness of the WS_2 buffer and SnO_2 layer provides a conversion efficiency of 20.55% ($V_{OC} = 0.85$ V, $J_{SC} = 28.40$ mA/cm^2 , FF = 85%) shown in Fig. 3, which is higher compared to the baseline structure. Overall, the proposed WS_2 -based solar cell structure has exhibited satisfactory performance and shows its potential as an alternative buffer layer to replace the toxic CdS layer.

4.3 Water-Splitting Photocatalysts

One of the probable ways to substitute fossil fuel consumption with an alternative based on renewable sources is to develop efficient catalysts for solar hydrogen generation from water. Such catalysts have been known already for about 40 years, beginning with the work of Honda and Fujishima [47]. Apart from mostly used TiO_2 , alternative non-oxide layered materials, especially TMDCs, gained much attention in the last years because of their narrower band gaps than transition-metal oxides, for instance, WS_2 . However, only one-dimensional (1D) nanostructures such as nanotubes (NTs) [47,48] and nanoribbons [49] or zero-dimensional structures such as fullerene-like nanocages [50] and nano-clusters of WS_2 can possibly be suitable for photocatalysis.

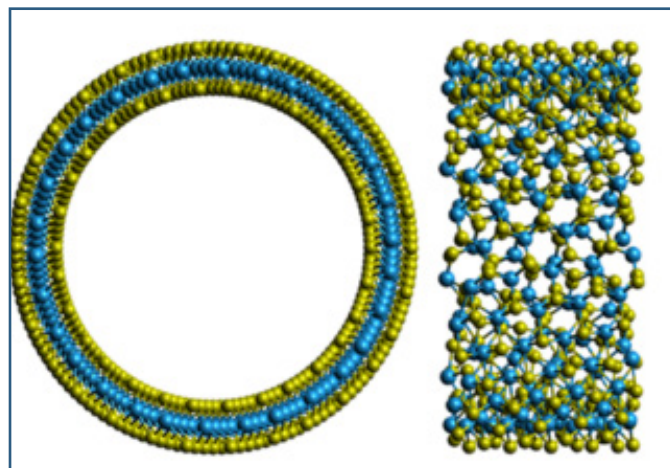


Fig. 4. WS_2 Single Walled Nanotubes (SWNT) with chiral modelled and right-hand side depicts the side view of the NT unit cell [47].

Sergei Piskunov et al. [47] have simulated the electronic structure of pristine single-walled WS_2 (Fig. 4) and shown by ab-initio method that by choosing the NT diameter appropriately, the band gap can be tuned with high-energy resolution, which makes WS_2 single-walled (SW) NTs suitable for photo-catalytic applications in the visible spectrum. Further, have systematically investigated the photocatalytic properties of $\text{C}_2\text{N}/\text{WS}_2$ heterostructure for applications in water splitting based on density functional theory (DFT). The $\text{C}_2\text{N}/\text{WS}_2$ heterostructure shows a large interface binding energy, which indicates a high probability of it being experimentally synthesized. However, using first Principles calculations, Ritesh Kumar et al. [51] have shown that by combining WS_2 and a graphitic carbon nitride (C_2N), $\text{C}_2\text{N}/\text{WS}_2$ is formed, which is a type-II heterostructure and leads to the separation of charge carriers to two monolayers and hence would prevent their recombination. Based on the band alignments of the heterostructure, it is found that the C_2N layer facilitates the hydrogen evolution reaction (HER), which has very high catalytic sites compared to other photocatalysts. The other constituent monolayer WS_2 facilitates oxygen evolution reaction (OER), making it a suitable photocatalyst for water splitting.

5. CONCLUSION

In summary, various synthesis strategies for nanostructured WS_2 have been explored, with chemical vapor deposition (CVD) remaining one of the most practical and scalable methods for

producing high-quality 2D morphologies. Although pinpoint control of growth parameters enables tuning of the optical and electronic properties, achieving reproducible, defect-free structures continues to be a major challenge.

Recent advances have strengthened our understanding of WS₂ crystal structures, optical behavior, and their integration into diverse optoelectronic and electronic devices such as LEDs, sensors, FETs, photodetectors, field emitters, and memory components. This review focused specifically on three key application areas—biosensing, solar cells, and water-splitting photocatalysts—where WS₂ has shown significant promise.

Overall, continued progress will rely on developing new WS₂ morphologies, optimizing engineering routes, engineering heterojunctions, and applying physical modifications and doping strategies to improve device performance. Additionally, integrating advanced semiconductor theories and computational models will be essential for elucidating carrier transport mechanisms and guiding the evolution of next-generation WS₂-based optoelectronic systems.

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