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Review

A Review on MoS₂ Properties, Synthesis, Sensing Applications and Challenges

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Abstract: Molybdenum disulfide (MoS₂) is one of the compounds discussed nowadays due to its outstanding properties that allowed its usage in different applications. Its band gap and its distinctive structure make it a promising material to substitute graphene and other semiconductor devices. It has different applications in electronics especially sensors like optical sensors, biosensors, electrochemical biosensors that play an important role in the detection of various diseases' like cancer and Alzheimer. It has a wide range of energy applications in batteries, solar cells, microwave, and Terahertz applications. It is a promising material on a nanoscale level, with favorable characteristics in spintronics and magnetoresistance. In this review, we will discuss MoS₂ properties, structure and synthesis techniques with a focus on its applications and future challenges.

Keywords: Molybdenum disulfide (MoS₂); Molybdenum disulfide properties; Molybdenum disulfide synthesis; Molybdenum disulfide applications; transition metal dichalcogenides (TMDs)



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1. Introduction

Molybdenum disulfide (MoS₂) is an inorganic compound of the transition metal dichalcogenides (TMDs) series, that has one atom of Molybdenum and two atoms of Sulfur. Dichalcogenides are chemical compounds consisting of a transition metal, like Molybdenum, and a chalcogen (element of group 16 in the periodic table) like sulfur (S) [1]. The physical, chemical, and electronic properties of this compound grabbed the attention of many researchers and were found promising materials to substitute previously used semiconductor and/or graphene devices. As the world is moving towards miniaturization, researchers were searching for a material to substitute semiconductor devices that seemed to reach an end when entering the nanoscale era [2]. While semiconductors devices based on Silicon were facing quantum and tunneling effects on a nanoscale level, MoS₂ showed favorable and promising electronic and quantum characteristics when going from bulk to two-dimensional (2D) structure [3].

MoS₂ seems to solve many problems facing previous devices [4–8], it has a large band gap (~1.8 eV) which changes from an indirect gap to a direct one in thin structures. This would permit downscaling electronic devices, rather than graphene which nearly has a zero-band gap [9,10]. It does not have surface dangling bonds and has high mobility even with high- κ dielectric materials. It is ideal for thin-film transistors, and its fabrication is simple which means large production yield and low cost [11,12]. The covalent bonds between Molybdenum and Sulfur and the Van der Waals bonds between its layers make it optimal for gas sensing. One of the major problems with Silicon devices was that related

to the metal-semiconductor interface [13]. MoS₂ has less contact resistance and high performance. In other words, MoS₂ has potency to be used in 1 nm gate transistors with excellent on/off switching characteristics and high efficiency [14].

Silicon transistors fabrication faced some problems on the bulk scale that were overcome by new structures such as multi-gate transistors, but when going down to the nanoscale, the fabrication process seems to reach an end. The metal interconnection lines between transistors have high density and are very narrow, which cause an increase in resistance and capacitance between interconnect lines and high delays. Tunneling problems are more obvious with thin gate oxides and when trying to substitute silicon dioxide with other high- κ dielectric materials, more serious problems like thermal instability, channel mobility degradation, incompatibility with the interface aroused. All these issues lead to performance degradation, and high cost with a small yield. The high lithography resolution needed for small half-pitch (HP) ~20 nm, is not easily achieved and needs high techniques and tools in lithography [15,16]. On the other side, MoS₂ showed easier and simpler ways of synthesis and device fabrication [17]. It is easily prepared by spreading the molybdenum metal and sulfur and letting them self-propagate under a high temperature [18]. A MoS₂ field effect transistor was fabricated in [19] by immersing it in an electrolyte, the device showed lower contact resistance and a better gate control.

MoS₂ has a wide range of applications in different fields. Like Silicon and graphene, it has applications in biosensing, and optical sensors but the most important ones are those related to bio-applications like DNA, cancer, and Corona Virus detection [20–23]. While Silicon and graphene were still under study in their compatibility with human bodies, a study, in [24], showed that MoS₂ may be very effective in curing cancer and Alzheimer's disease. It also showed that the compound has no biological interaction which makes it safe for injection in human bodies. Another study in [25] proposed a biocompatible device made of MoS₂ to restore some visual malfunctioning. The compound applications are not restricted to electronics, but it can serve as a lubricant [26] and is used in hydrogen evolution reactions. It is a suitable material for batteries' electrodes [27]. Indeed, MoS₂ properties and structure made it promising for several electronic, sensing, microwave, and terahertz applications.

Many research articles and reviews have been published on the properties, synthesis and applications of MoS₂ material, but we lack a comprehensive comparison of the different MoS₂ structures and their properties in terms of applications, especially between the bulk and monolayer MoS₂. Besides, the use of MoS₂ as a sensing material in the bio-medical, optoelectronic and IoT-related fields was not sufficiently highlighted in the literature. Newer applications such as in the terahertz technology, the hydrogen detection, hydrogen generation and oil/water separation remain among the less covered areas of studies for MoS₂. In this review, we will first identify the different MoS₂ structures and their synthesizing techniques in details, and we will compare all the structures in terms of their main optical, lattice and electrical properties and applications. Synthesis techniques will be extensively covered with their main pros and cons. Then we will provide a more detailed review on the wide range applications of MoS₂ in electronics, medicine and other new fields of research such as the terahertz field and the hydrogen-related technologies. Finally, we will discuss and compare the different challenges facing the development of MoS₂ applications in different fields of study, since they were not discussed in detail in previous studies that focused more on synthesizing techniques [27,28] or a specific kind of application [29–31].

2. Structure and Properties

MoS₂ structures differ from 3D, 2D, one-dimensional (1D), or dot structures. Its characteristics and applications also change from one dimension to another, they can be semi-conducting, metallic or superconducting. It exists in several layers and shapes. Its bulk (3D) structure can be tri-agonal (T), hexagonal (H), and Rhombohedral (R), where 2H MoS₂ means 2-layer hexagonal shape MoS₂. The three main structures are 1T, 2H and

3R, where the 1T phase coordinates in an octahedral structure, 2H and 3R in a trigonal prismatic structure [32,33] as shown in Figure 1. The lattice constants for each structure are shown in Table 1 [34]. The 1T structure is known to be metallic while the other two are semiconducting. The monolayer of hexagonal MoS₂ is also semiconducting. Both 2H and 3R are used as dry lubricants. Due to the nonlinear optical properties of 3R phase it is used in nonlinear optical mass sensing in quantum measurements and biomedicine [35]. As an example, for gas sensors, the different phase materials of MoS₂ can be interesting in obtaining high sensitivity and rapid desorption [36].

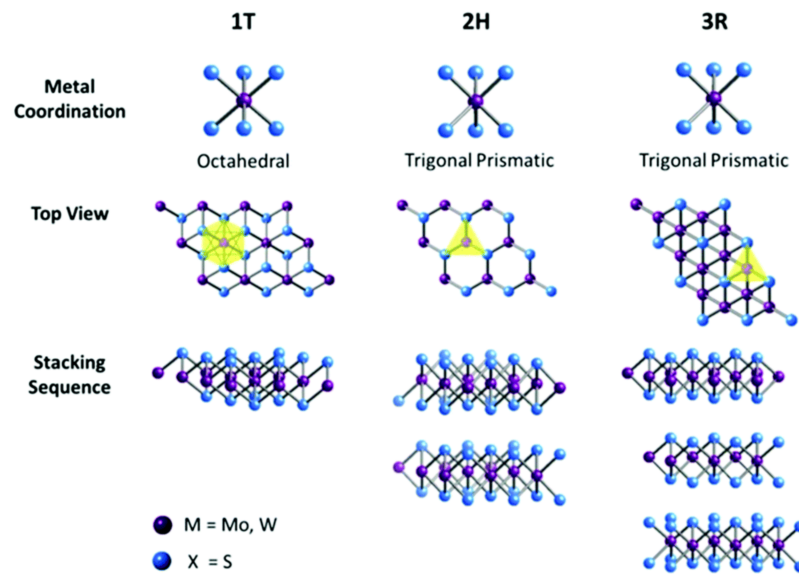


Figure 1. Different coordination and stacking sequences of the three MoS₂ structures 1T, 2H and 3R. Reproduced from [33]. Published by The Royal Society of Chemistry.

Table 1. Comparison between different MoS₂ structures.

	1T	2H	3R
Structure Coordination	Octahedral	Trigonal Prismatic	Trigonal Prismatic
Lattice parameters	a = 5.60 Å, c = 5.99 Å and an edge sharing octahedral [34]	a = 3.15 Å, c = 12.30 Å [34]	a = 3.17 Å, c = 18.38 Å [34]
property	paramagnetic and metallic	Semiconducting	
Electrical conductivity	10 ⁵ times higher than 2H phase	Low (~0.1 S/m)	
Absorption peaks	No peaks at 604 nm and 667 nm	Showed peaks at 604 nm and 667 nm	
Common applications	Intercalation in chemistry	Dry lubricants	Dry lubricants and non-linear optical devices

1H MoS₂ is the most stable configuration and it is formed of one layer of Sulfur and one layer of Mo where S-Mo-S are attached through strong covalent bond like a sandwich, with a thickness of approximately 0.65 nm [28], The sandwiched S-Mo-S layers are attached through weak Vander Val forces [37]. The conductivity of nano MoS₂ depends on the temperature and thickness of the flakes, where conductivity increases with the temperature increase and decreases with increasing the thickness till it reaches the bulk structure [38]. The binding energies and photoluminescence properties are summarized in Table 2 [39].

Table 2. Comparison between Bulk and monolayer MoS₂.

	Bulk	Monolayer
Bandgap	Indirect (~1.2 eV)	Direct (1.8 eV)
Binding energy	0.1 eV	1.1 eV
Photoluminescence intensities	between 10 ⁻⁵ and 10 ⁻⁶	10 ⁴ times higher than that of bulk, up to and up to 4 × 10 ⁻³

MoS₂ exists in different 2D structure like nanosheets, and nanoribbons or 1D structures as nanowires and nanotubes, or 0D structure as quantum dots and nanoplatelets. The thickness of 2D nanoribbons was found to be of 1 to 3 layers of MoS₂, while the thickness of 1D nanowires (NW) can have lengths from 14 to 30 nm and a width of 0.6 nm approximately [40]. The structure of 1D nanoplatelets and their properties were investigated in [41]. The nanoplatelets are 12–30 nm with one-unit cell width. They have very high catalytic activity for hydrodesulphurization. The quantum dots range from 2 to 10 nm in size. They have higher band gap than nanosheets, and stronger bonds between Mo atoms than monolayers. The change in band gap of MoS₂ from one dimension to another, changes the photoluminescence characteristics and thus has different optical properties according to its dimension. Additionally, monolayers or other low dimension forms are also easy to be implemented in optical nanostructures to enhance the photoluminescence intensities and emission rates through light-matter interactions [42–44]. This is a strong motivation for MoS₂ to be included in optical applications [29].

2.1. Optical Properties

The absorption coefficient and refractive index are the parameters that determine the response of a material when a certain wavelength passes through it. The absorption coefficient determines the distance the spectrum pass inside the material before being absorbed. A high absorption coefficient means high attenuation to the wave applied. Semiconductors have high absorption coefficients for short wavelengths (high energy and frequency spectrum) and low absorption coefficients for long wavelengths (they do not have enough energy to excite electrons from the valence band to the conduction band). MoS₂ has a relatively large absorption coefficient for the wavelengths from 400 nm to 500 nm with a sharp decay at 500 nm [45]. The key factor behind the wide use of MoS₂ in optoelectronics is its tunable bandgap that changes with size and structure; Different bandgaps mean tunable photoresponsivity (R), specific detectivity, and response time [46], and thus, a wide range of applications. The MoS₂ multilayers and monolayers have a high refractive index of more than 2, where it can be used in coating. Since the photoluminescence (PL) spectra are affected by the band gap, doping, and structure of the material, MoS₂ has different PL activity. It has a peak exciton (A) in a single layer MoS₂. The PL properties of monolayer MoS₂ are enhanced by adding H₂O₂ solution [47], where it acts as a strong oxidizer without changing the crystalline structure of MoS₂. TMDs are known for their low PL quantum yield (QY) which is the ratio of the number of emitted photons to the number of generated electron-hole pairs and they are between 0.01 to 6%. The work in [48] was able to raise the QY of MoS₂ to 95% using a chemical treatment of an organic superacid. The observed lifetime of MoS₂ carriers were nearly 10.8 ns, which opens the way to be used in high-performance lasers and solar cells.

2.2. Mechanical Properties

A monolayer MoS₂ has high strength, less than that of graphene and good elasticity similar to that of graphene oxide, with Young's modulus of 0.33 ± 0.07 TPa [28]. A single layer of MoS₂ has more flexibility than bulk structures, where its Young's modulus is 0.24 TPa. Unlike other semiconductors, the flexibility of MoS₂ prevents the deformation and band gap shifts that may happen to its crystalline structure when subjected to strain. However, the mechanical strain is used to alter MoS₂ electronic characteristics and trans-

form them from semiconductors to metals. It transforms the direct band gap of MoS₂ monolayers to an indirect one and high strain values can cause structure deformation and transform MoS₂ to metal [49].

2.3. Electronic Properties

In this section, we are going to discuss the density of states and the band structure of MoS₂. Multilayer MoS₂ are known to have an indirect band gap of 1.2 eV, which increase with the decrease in the number of layers until we have a direct band gap of 1.8 eV in monolayer MoS₂ [50]. Although the MoS₂ bandgap value is good, it is still far from 1.12 eV direct bandgap of Silicon [39]. The mechanical strain affects the band gap of MoS₂ and changes it from direct to indirect band gap and transfers the material from a semiconducting material to a metallic one. The 4d and 3p orbitals in Mo and S respectively, determines the properties of MoS₂. The projected density of states (PDOS) of bulk and monolayer MoS₂ are nearly the same, but there are some peaks in PDOS in case of monolayer MoS₂ [51]. A monolayer MoS₂ changes to an n-type semiconductor when doped with chromium, copper, and scandium (Sc) and to a p-type when doped with Nickel or Zinc [52]. Doping with Titanium (Ti) transfers MoS₂ to a p-type or n-type semiconductor according to the levels and sites of doping. At low doping levels of Ti below 2.04%, MoS₂ behaves as a p-type. In case of interstitial doping of Titanium (Ti) at 3.57% doping levels, the covalent bond between MoS₂ and Ti are strong which increases the surface dipole moment that induces a reduction in electron affinity of 0.49 eV, where it behaves as an n-type. At high doping levels of 7.69%, the Fermi level shifts towards the conduction band and merge into the conduction band, where the surface dipole moment declines and the electron affinity rises, pinning Fermi level over the conduction band. In this case, MoS₂ changes to a ferromagnetic half-metal with spin polarization equals to 1, that is promising for spintronics. On the other side the substitutional doping of Ti did not show any change in electronic properties for the three doping concentrations (2.04%, 3.57%, 7.69%).

2.4. Magnetic Properties (Spintronics)

While moving towards the nanoscale era and the evolution of spintronics, the study of electron spin of a promising structure like MoS₂ became a must. TMDs are known to be non-magnetic, and if we managed to add magnetism to them, they can be used as tunable semiconductors [53]. A study in [54] studied the magnetic behavior and characteristics of multilayer MoS₂ specifically. The study showed that MoS₂ has a long spin diffusion length of 235 nm and that an in-plane spin polarization can suppress the electron spin-relaxation. The work in [52] showed that MoS₂ attains semi-metallic ferromagnetic properties when doped with Sc and a unity spin polarization value, which is favorable in spintronics.

3. Synthesis

There are different techniques used to obtain material layers Figure 2, and each one of them results in different quantities, shapes, and sizes. Mainly the approaches used in synthesizing TMDs nanostructures, are the top-down approach and the bottom-up approach [55,56]. The first approach depends on etching crystal planes from a substrate that has the crystals laid over it, while in the second approach, the crystals are stacked over the substrate. Exfoliation is one of the top-bottom techniques for obtaining MoS₂ layers. The weak Van der Waal forces between layers of TMDs paved the way in front of different exfoliation synthesizing techniques [57]. Mechanical exfoliation is done using a sticky tape which is rubbed out and shifted on a substrate having MoS₂ flakes over it. The method gives low yield and is good for lab use. Exfoliation can also be done in the liquid phase by adding a chemical compound and stirring, bubbling, or grinding. This method is simple and cheap but has low quality. The low yield in liquid exfoliation was avoided using carbon aerogel composites in [58]. The synthesizing is fast and completed in 30 minutes. It also avoids pyrophoric materials that are typically used in liquid exfoliation and increases the electrical conductivity and porosity of MoS₂. Sonication is one of the techniques that

showed simple synthesis when used with liquid exfoliation [59,60]. It dispenses of the use of hazardous materials used in liquid exfoliation. It is based on ultrasonic waves emitted from a probe in shape of bubbles that peels MoS₂ layers when they burst. The challenge in using sonication assisted techniques is that it produces relatively small area MoS₂ nanosheets that limits its use in practical applications. Generally Top down techniques are said to have low controllability, and scalability and high cost [55]. The yield is increased to >90% when using ultrasound sonication with supercritical carbon in [61] with an intercalating solvent N-methyl-2-pyrrolidone (NMP). The method is fast, simple and scalable. Sputtering is used to prepare layers of MoS₂ to be used as lubricants, the layers have a low friction coefficient, but these frictional properties can be changed under humidity, especially for thin films of MoS₂.

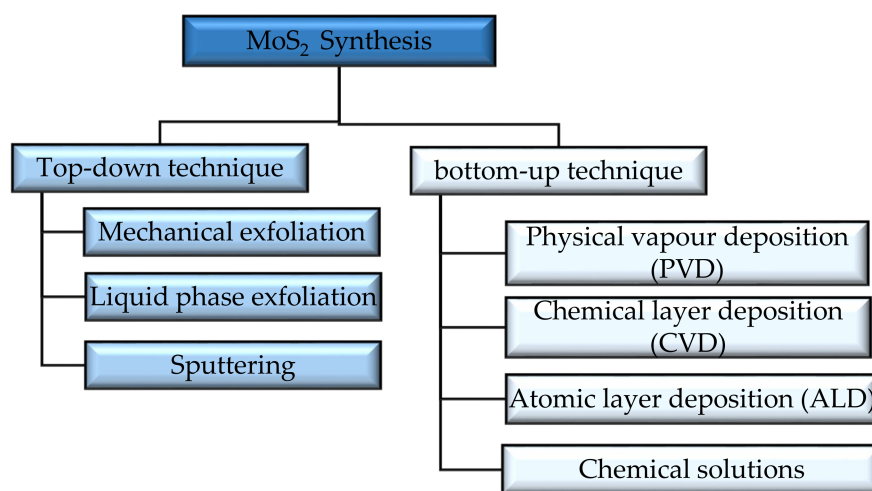


Figure 2. Different MoS₂ synthesis techniques [27].

Physical layer deposition (PVD) is one of the bottom-up techniques that includes ion implantation like molecular beam epitaxy (MBE) [62]. The method can be applied only to thin layers of MoS₂ and the resulting grain sizes are variable [63]. Chemical vapor deposition (CVD) is applied to thin and thick layers, where Mo is laid over a substrate and Sulfur vapor passes over it. This method has good quality, but low yield. The atomic layer deposition (ALD) method is used to fabricate thick and thin films. The method is considered efficient and the layers have fewer impurities that can be used in different applications, including electronics and sensors. MoS₂ layers can be synthesized with the help of chemical solutions, using hydrothermal and solvothermal reactions wherein both cases Mo and S react in an aqueous solution above the boiling point and in a nonaqueous solution at high temperature, respectively. The size and shape of the layers can be controlled where we can get powder and thin films of MoS₂ by this method. It is considered cheap and scalable [64].

In [65], MoS₂ is synthesized using a liquid organic precursor on an insulating substrate using CVD. The used method is more reproducible and is used to obtain larger areas of MoS₂ layers than those obtained with methods using powder Molybdenum oxide and sulfur powder. Another method in [66] used thermal evaporation and ALD, where it used metalloporphyrin as a promoter layer. The method allowed to manipulate the carrier density and conductivity of MoS₂ according to the thickness of the metalloporphyrin layer used. It is used to produce MoS₂ nanosheets on a large scale. In [18], MoS₂ is synthesized using self-propagating, under high temperature, where Mo nanopowders and elementary Sulfur are used. The mixture is put into cylinders and then under pressure. The main resulting structure is 2H MoS₂, but there are other phases like rhombohedral MoS₂ and Mo₂S₃. Thermal sulfidation is another method like CVD that uses Sulfur gas as a precursor. It uses a Mo [67] or Mo-oxide [68] film deposited on a substrate, where evaporated sulfur passes over it under certain temperature. The method is known to reduce the effect of gas

flows that occurs in CVD, and results in self-aligned patterns of MoS₂. The sulfidation of two different oxides of Mo: MoO₃, and MoO₂ discussed in [68], showed more stable MoS₂ monolayer films, produced from MoO₂. The films were integrated with bottom-gate transistors and they showed on/off ratio of 10³–10⁴ and electron mobility of 10^{−4} cm²/V·s. The PL spectrum of the synthesized monolayers has an exciton peak at 1.89 eV.

Another approach to avoid the drawbacks of exfoliation and intercalation or liquid exfoliation like low electrical performance (low mobility of 0.3–0.4 square centimeters per volt per second and low on/off ratios ~10–100) is using electrochemical intercalation [69]. The method involves quaternary ammonium molecules into 2D crystals, with mild sonication and exfoliation techniques. The technique gives high performance MoS₂ nanosheets with 10 square centimeters per volt per second mobility, and on/off ratios of 10⁶. Table 3 summarizes some synthesis techniques that are already known until now.

Table 3. Summary of synthesis techniques.

Technique	Charecteristics of the Obtained MoS ₂ Sheets	Publisher	Year	Reference
Using aerogel	A rapid synthesis technique for TMDs- carbon aerogel composites to be used in supercapacitor. The preparation time is 30 min which is approximately 2% of typical aerogel techniques that take 24 h	Nature	2017	[58]
Liquid assisted Sonication	Studied the PL, Raman analysis resulting from bath and probe sonication synthesis	Elsevier	2020	[59]
Liquid exfoliation & ultrasonic cavitation	Obtain less defective and high concentration nanosheets in a short time	Nature	2014	[60]
Exfoliation of & Ultrasound Sonication in Supercritical CO ₂	Exfoliation efficiency > 90%	Springer	2019	[61]
Exfoliation & sonication	Mobility = 10 cm ² /V, on/off ratios = 10 ⁶	Nature	2018	[69]
ALD & thermal evaporation	Enhanced electrical conductivity	Nature	2016	[66]
CVD & liquid precursor	The method uses water to remove impurities like carbon and sulphur. It ensures full coverage of MoS ₂ for the substrate	Nature	2017	[65]
ALD & thermal evaporation	The carrier density and conductivity of MoS ₂ are adjusted according to the thickness of the metalloporphyrin layer used. Produce large scale MoS ₂ nanosheets	Nature	2016	[66]
Self propagation of Mo powder and elementary Sulfur	Resulted MoS ₂ nanosheets have thermal stability up to 400 °C.	IEEE	2013	[18]
CVD with Sulfur as a precursor (Sulfidation)	on/off current ratio of 10 ⁵ , a mobility of 0.12 cm ² /V·s (mean mobility value of 0.07 cm ² /V·s)	Royal society of chemistry	2014	[67]
Sulfidation	The on/off ratio of 10 ³ –10 ⁴ and electron mobility of 10 ^{−4} cm ² /V·s	Elsevier	2020	[68]
Intercalation & exfoliation	To be used in high-performance thin-film transistors, on/off ratio of 10 ⁶ and electron mobility of 10 cm ² /V·s	Springer Nature	2018	[69]

4. Applications

MoS₂ optical, electrical, and chemical properties allowed this metal dichalcogenide to have a wide range of applications in different fields. Its electronic properties allowed

it to enter the nanoelectronics and sensor application field and in turn the medical field. These special electronic properties, together with its biocompatibility, open up the way to further medical and curing applications. The photoluminescence and chemical properties broadened its application field. MoS₂ applications are countless, and, in this review, we are trying to introduce the newest and the most important ones.

4.1. Electronics Applications

In this part, we will discuss electronic, optoelectronic, and sensing applications. MoS₂ monolayers achieved good device characteristics at 5 nm channel length FET [70]. It has on/off ratio of 10⁶ and a subthreshold swing of ~65 mV/decade, but with low on current of ~700 μA/μm. In [71], a 2D MoS₂ field effect transistor (FET) was developed to be used in operational amplifiers (OPA) in analogue circuits, the device has good performance with an open-loop gain of 36 dB at low frequency and high uniformity. The idea that MoS₂ can be integrated with flexible substrate materials like Kapton opens the way to be used in analogue circuits more than other bulk semiconductors. The device has acceptable bandwidth and gain (the gain roll-off after 5 kHz), compared to other Silicon devices. A heterostructure of MoS₂ and amorphous Silicon was developed to be used as a photodetector in [72]. The proposed photodetector has a fast response and simple fabrication so it is ideal to be used in bioimaging like x-ray imaging devices. In [73], a high-quality photodetector, including MoS₂ is proposed using CVD and PVD techniques. The photodetector is suitable for UV applications. It has high photocurrent gain of 1.6 and a specified detectivity of 4.32 × 10⁸ Jones. It has external quantum efficiency (EQE), which is the amount of extracted free charge carriers converting to photo flux- of ~1.0 × 10¹⁰ at 365 nm. According to the thickness of the MoS₂ layer used, the PL and Ramen spectra peaks are shifted. MoS₂ has a role in photodetectors in the field of robotics, where an efficient nanoscale photodetector of a monolayer MoS₂ was proposed in [74]. The detector consumes a low amount of energy (from 1 to 1000 nanojoules) with a small fingerprint of (~1 μm × 5 μm).

A Sulfur treatment with Alcohol is performed to enhance the contact resistance of MoS₂ FETs of gate lengths (500 to 80 nm) to be 1.3 kΩ [75]. An enhancement in the on/off switching characteristics and subthreshold swing (SS) of MoS₂ FET using Ag is presented in [76], where the device has SS ~4.5 mV/decade with less leakage and steep on/off characteristics. MoS₂ monolayer is used in nonvolatile memory applications [77], with high charge storage capacity.

A low power MoS₂ RF thin film transistor (TFT) was proposed in [78] that can be used in IoT systems like amplifiers and mixers. It can work at relatively high strain ~3%. The on/off ratio MoS₂ FETs exceeds 10⁸ [79]. The band gap structure of TMDs can be engineered using strain, or dielectric screening [80]. Another low power analogue memory in [81] can be integrated with computing devices to enhance their efficiency. Finding a low contact resistance in TMDs based devices is still a challenge, due to the Fermi level pinning that occurs in metal/2D TMD interface, but in [82] a MoS₂/MoO₃ tunnel field effect (TFET) was introduced, making use of oxygen vacancies in the metal oxide that aligns with the valance band of MoS₂ and assure a good contact with MoS₂. Nanoscrolls (NSs) of MoS₂ is obtained in [83] using one drop of ethanol. The NSs are said to have 10 times higher mobility than monolayer MoS₂ and with a 100% yield.

A neuromorphic image sensor based on MoS₂-organic heterostructure similar to human vision system in [84], showed simple design and better image in case of noisy inputs Figure 3. The idea of the image sensor lies in the quasi-linear time-dependent photocurrent generation and prolonged photocurrent decay, by the trapping effect of MoS₂ stack.

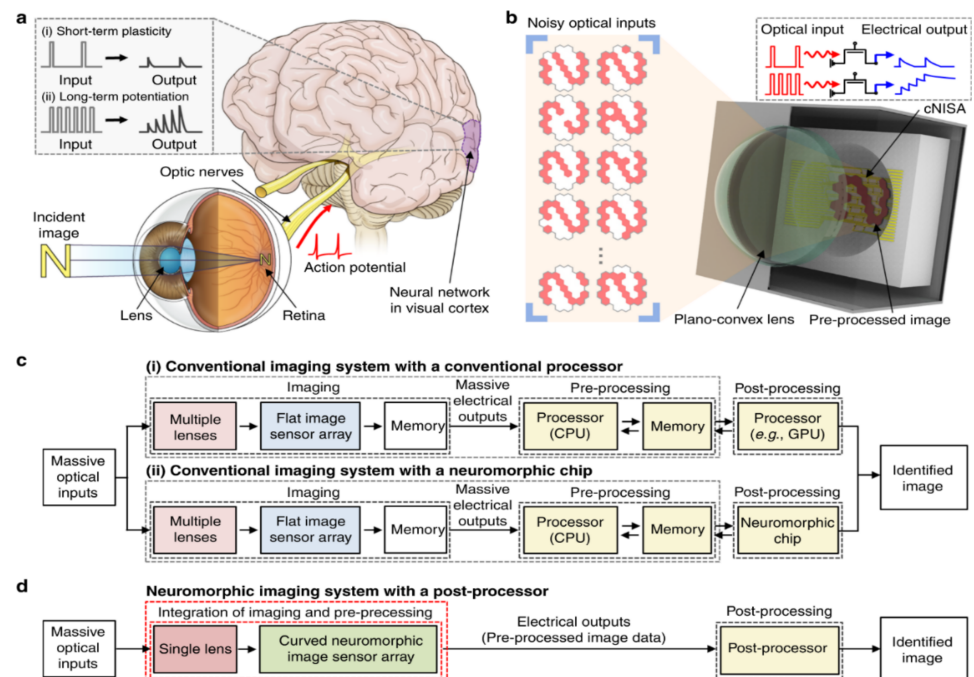


Figure 3. Optical application of MoS₂. Curved neuromorphic imaging device inspired by the human visual recognition system. (a) Human visual recognition system (b) Curved neuromorphic imaging device (c) Block diagram of conventional imaging system (d) Proposed Curved neuromorphic imaging system. Reproduced from [84]. Springer Nature 2020.

4.2. Medical Applications

MoS₂ has a role in diseases' detection and curing, making use of its PL, chemical properties, and biocompatibility. Molybdenum disulfide/graphene oxide (MoS₂/GO) with doxorubicin (a chemotherapeutic agent) was found to cure lung cancer [85], the nanocomposite showed good results in vitro, and in vivo and was experimented on mice lungs Figure 4. MoS₂/GO was compared with other complexes (doxorubicin (DOX), Lysine (Lys)-MoS₂) and it showed best results with GO and DOX. Mo is known to form a linkage with DOX and though serves as a drug delivery. In [20], a biosensor microfluidic device was proposed that detect an avian Coronavirus using 2D MoS₂. In [86], a MoS₂/ graphene oxide (RGO) Field Effect Transistor Sensor to detect Hydrogen Peroxide (H₂O₂) is proposed. H₂O₂ is a biomarker for many diseases like cancer, and Alzheimer's disease, Figure 5. In [23], MoS₂ nanosheets are used to detect Prostate antigens and in [21], MoS₂ flakes were used as biomarkers for breast cancer based on the PL properties of MoS₂. Using a bottom-up synthesizing technique and defect engineering in [87], the photodynamic property of MoS₂ quantum dots (QD) was able of killing cancer cells with high efficiency.

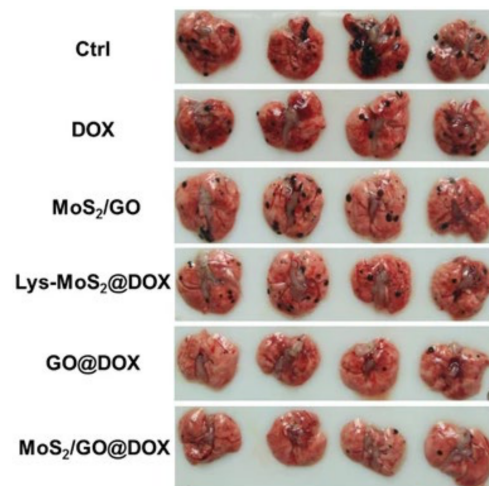


Figure 4. The effect of different complexes in killing cancer cells in mice lungs. Adapted from [85]. Springer Nature 2018.

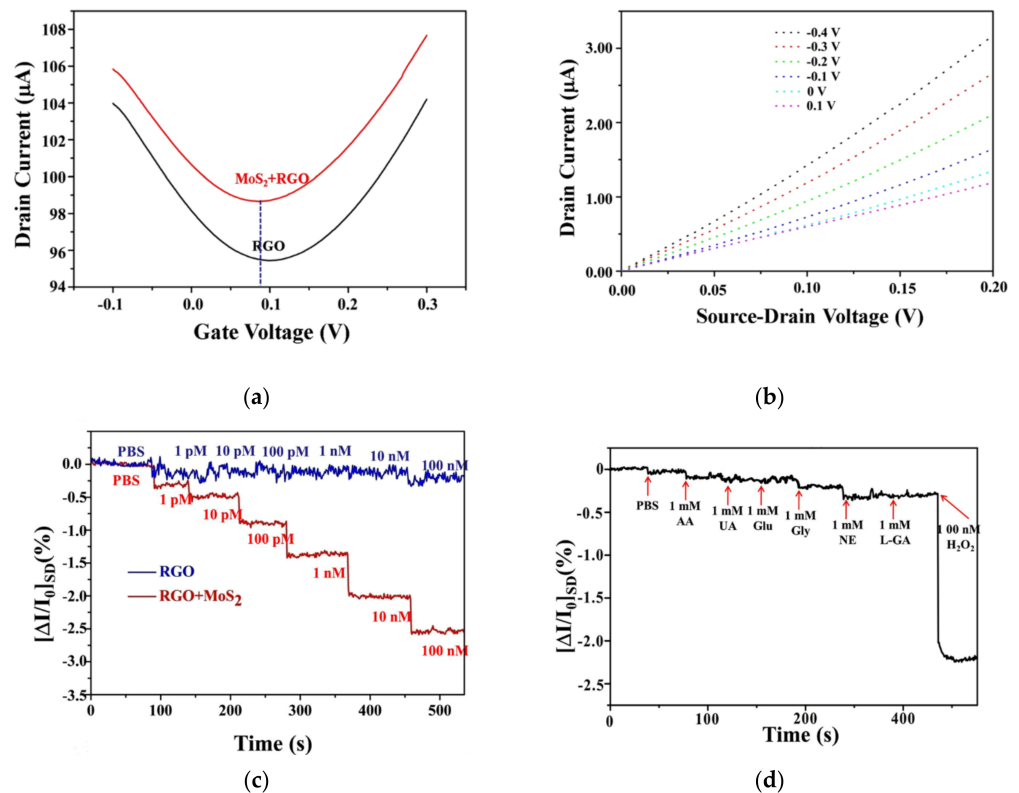


Figure 5. MoS₂/RGO FET for detecting H₂O₂, (a) Transfer characteristics for MoS₂/RGO FET, Drain current versus gate voltage for MoS₂/RGO and RGO FETs (b) Drain current versus source-drain voltage for MoS₂/RGO, (c) The change in drain-source current for different concentrations of H₂O₂ (d) Negligible current change for different interferents (PBS, 1 mM AA, 1 mM UA, 1 mM Glu, 1 mM GLY, 1 mM NE, 1 mM L-GA) and a noticeable change for H₂O₂. Adapted from [86]. Springer Nature 2019.

MoS₂ has a wide range of applications in microfluidic devices and immunosensors, making use of its chemical and photoluminescence properties [88]. MoS₂ nanosheets were used with microfluidics electrode for detecting Salmonella typhimurium (*S.typhimurium*) [89] the proposed device has fast detection and high sensitivity and can be used for other food related pathogens like *E.coli*, Cholera. Depending on the dye-quenching properties of MoS₂, its nanosheets were used with microfluidic devices to detect single-stranded DNA (ssDNA),

where MoS₂ showed high fluorescence quenching within few minutes, besides it behaves differently towards ssDNA and double-stranded DNA (dsDNA) where it did not affect the dye of dsDNA [22]. This opens the way for various DNA and diseases' detection, especially cancer. Many diseases like diabetes, digestive disorders and cancer cause a change in the amino acid chain. Amino acids are the building blocks of proteins. The detecting of amino acids is more complex than DNA, since they have 20 bases rather than four in case of DNA and changing their sequence gives different kinds of proteins. Nanopores were recently used in detecting DNA and amino acids, where the amino acid is forced to pass through a nanopore, then the ionic current and the residence time is measured. Each amino acid or DNA has a different ionic current and residence time; however, they are very similar in case of amino acids which make them hard to differentiate. Machine learning techniques are then used to detect the sequence of the amino acids. Biomolecules are easily stuck to MoS₂ so they can be easily detected. They also have better signal to noise ratio. The MoS₂ nanopore with machine learning is used to detect various kinds of amino acids, with high accuracy up to 99.6% and in a very short time (several ps) [90].

An interesting research in [91] used nanohole-enriched MoS₂ (NR-MoS₂) nanosheets to destroy bacteria and biofilms. The cure is based on the electron transport between NR-MoS₂ and the bacteria, where NR-MoS₂ is a nanosheet of MoS₂ defects and holes. The results were excellent in vivo and vitro and MoS₂ showed high biocompatibility. The idea behind antimicrobial nanomaterials is that they act as anti-bacterial but without the generation of resistance that happens in typical antibiotics.

4.3. Sensing Applications

The sensing applications of MoS₂ are related, where we can't separate the use of optical, medical, and electronic applications in sensing, but this section summarizes most of the sensing applications reported in the literature. Figure 6 divides the sensing applications into four main categories: biosensing, gas sensing, refractive index sensing, and photo-sensing (photodetectors) [92]. Each application includes different types of sensors, for example, biosensing includes electrochemical sensors, FET based sensors, optical and surface plasmon resonance (SPR) sensors. Both gas sensors [93–96] and photodetectors [72–74] are FET-based sensors. Electrochemical sensing is being studied recently for ultrasensitive sensing, and MoS₂ shows sensitive electrochemical detection properties when combined with other materials where a notable change in the electrochemical impedance occurs. This technique was used in [89] to detect food pathogens.

Based on the fluorescence and quenching properties of MoS₂, it can be used in biosensing to detect DNA, cancer biomarkers, and different amino acids [21,23,97]. FET-based sensors are also used for biomolecular sensing like DNA, antigens, proteins, biotin, and pH values [97]. Optical sensors are mainly based on the PL characteristics and fluorescence quenching and recovery properties of MoS₂. It can be used in detecting DNA, H₂O₂, and ion sensors.

The SPR biosensors, optical and refractive index biosensors are all related. SPR sensors are based on an optical technique that urges the emission of electromagnetic waves (plasmons). The propagation of plasmons over the material surface is very sensitive to any refractive index change on the surface, and though can detect thin films on the surface [98]. MoS₂ is used with other materials in a SPR sensor to enhance sensitivity to 101.42 °/RIU [99]. It shows a polarization-dependent optical absorption that can be integrated in waveguides to sense refractive index [100]. Table 4 gives a summary of the sensing applications along with the MoS₂ property that enables such sensing.

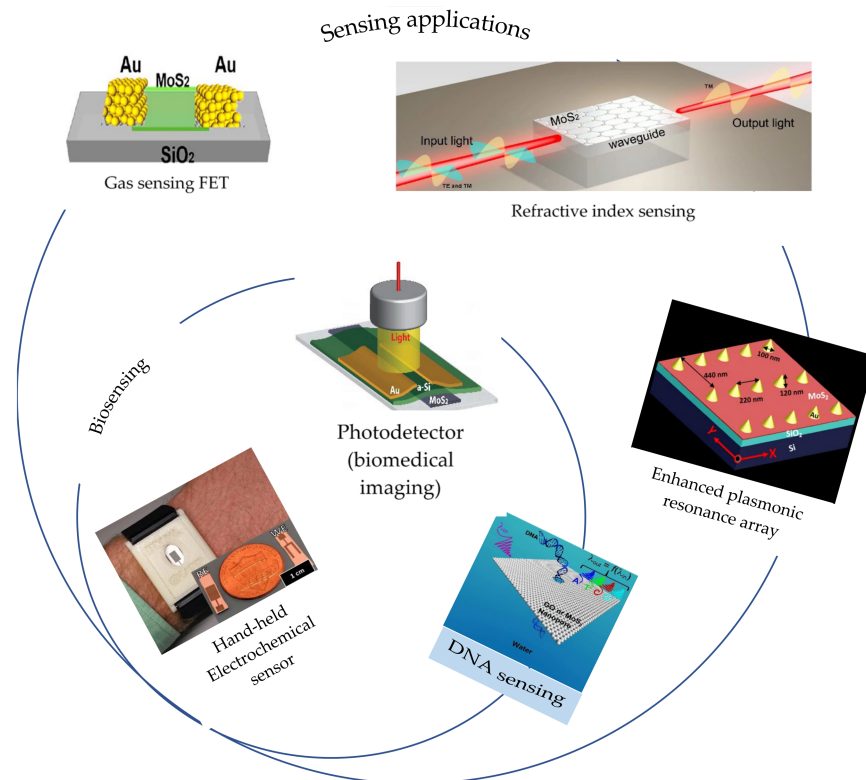


Figure 6. Illustrative diagram of different sensing applications of MoS₂. Enhanced plasmonic resonance array [101], DNA sensing using MoS₂ nanopores [88,102], photodetector for biomedical imaging [72], refractive index sensing [100], gas sensing FET [103], Electrochemical biosensor for measuring cortisol in human sweat [104].

Table 4. Summary of sensing applications.

Category	Application	MoS ₂ Property	Reference
Optoelectronics	Photosensing (photodetector)	Electronic and optical properties	[72]
	Photosensing (photodetector)		[73]
	Photosensing (photodetector)		[74]
Recognition systems and IoT	Image sensors	Optical properties	[84]
Medical (bio-sensing)	Cancer sensing	PL property	[86]
	Cancer sensing	PL property	[23]
	Cancer sensing	PL property	[21]
	DNA sensing	MoS ₂ nanopores	[88]
	DNA sensing	dye quenching property	[97]
	Amino acids sensing	MoS ₂ nanopores	[90]
	Immunosensors	Electrochemical and optical properties	[89]

4.4. Miscellaneous Applications

MoS₂ has terahertz and microwave applications [105,106] where a tunable terahertz wave reflector made of MoS₂, SiO₂, gold was proposed in [107]. The proposed structure enhances the design of beam manipulation devices and can be used in THz radiation control [108] as an alternative to complex antenna structures [109–114]. A terahertz modulator

based on MoS₂ on Silicon was presented in [115], with higher modulation efficiency when compared to graphene-based devices.

It is used in hydrogen detection [116] and generation [117] (hydrogen evolution reactions HER). Hydrogen production is one of the demanded industries due to its low toxicity and its use in many important fields like the fuel industry [118] and essential chemical processes. MoS₂ represents a cheap electrochemical hydrogen generation method [119], and it is said to substitute platinum-based catalysts in hydrogen generation processes. The strategy used was based on synthesizing edge-terminated MoS₂ nanosheets with wide interlayer spacing under microwave heating technique. The work presents a new catalyst design concept. It also has a role in Oxygen evolution reactions (OER) and CO₂ reduction where it reduces it to CO [120].

MoS₂ has a role in recent environmental issues like adsorption of Organic Contaminants [121], and oil-water separation [122]. In water separation, MoS₂ nanosheets were used to develop a sponge for oil-water separation. MoS₂ has a strong hydrophobicity property that it absorbs other organic solvents with high selectivity. Table 5. provides a comprehensive list of the reported MoS₂ applications with the field of interest.

Table 5. Summary of MoS₂ application.

Application	Category	Description	Publisher	Year	Reference
Electronics	Analogue	Developing a 2D MoS ₂ field-effect transistors (FETs) to be used as operational amplifier	Nature	2020	[71]
Electronics	CMOS	Enhanced back gate MoS ₂ FETs using Sulfur treatment, gate length from 500 to 80 nm, contact resistance = 1.3 kΩ	IEEE	2020	[75]
Electronics	nonvolatile memoryNVM	Hystresses and capacitance of MoS ₂ NVM with 9nm and 15 nm blocking oxide layer of SiO ₂ is investigated. The device has largest hystresses window. And can store both electrons and holes	IEEE	2016	[77]
Electronics	Power electronics	Ultra low power transistor of SS ~4.5 nm/decade and steep on/off characteristics	Nature	2020	[76]
Electronics	optoelectronics	Developing a highly-efficient and fast photodetector using amorphous silicon and MoS ₂	Nature	2013	[72]
Electronics	optoelectronics	Efficient photodetector with photocurrent gain of 1.6, specific detectivity of 4.32×10^8 Jones and quantum efficiency $\sim 1.0 \times 10^{10}$ at 365 nm	Nature	2020	[73]
Electronics	optoelectronics	A nanoscale photodetector, energy efficient (consumes from 1 to 1000 nanojoules), and has a small fingerprint of ($\sim 1 \mu\text{m} \times 5 \mu\text{m}$).	Nature	2020	[74]
Electronics	Image sensors	A MoS ₂ -organic heterostructure image sensor similar to human vision system using simple design. The output has less noise and without redundant input data	Nature	2020	[84]
Medical	Cancer cure	Using MoS ₂ /GO nanocomposites to cure lung cancer in mice	Nature	2018	[85]
Medical	Cancer cure	Using defect engineering (Sulfur defects) in MoS ₂ quantum dots to kill cancer cells. The Sulfur defects increased oxidation stress and was able to inhibit cancer growth cells	Nature	2019	[87]
Medical	Cancer detection	A real-time MoS ₂ FET sensor to detect H ₂ O ₂ in biological cells	Nature	2019	[86]

Table 5. Cont.

Application	Category	Description	Publisher	Year	Reference
Medical	Cancer detection	MoS ₂ nanosheet fluorescent biosensor for detecting prostate antigen. A 20 µg/mL of MoS ₂ nanosheets quenched up to 97% of the dye	Springer	2014	[23]
Medical	Cancer detection	Detecting breast cancer based on PL property of MoS ₂ . A redshift of 16 nm takes place for miRNA21c (a cancer biomarker)	Nature	2020	[21]
Medical	DNA detection	Sensing DNA nucleobases using MoS ₂ nanopores. Molar absorption of MoS ₂ nanopore of 0.65 nm thick, and lengths 2 nm, 3 nm, 5 nm.	Nature	2019	[88]
Medical	DNA detection	Detecting DNA based on dye quenching property of MoS ₂ . The device has linear range (0 to 50 nM), and a detection limit = 500 pM	Royal Society of chemistry	2015	[97]
Medical	Amino acid detection	Using MoS ₂ nanopores and machine learning to detect ionic current and residence time of 20 different amino acids with accuracy range 72.45% to 99.6%	Nature	2018	[90]
Medical	Microfluidic immunosensor	Use of MoS ₂ nanosheets on microfluidic electrodes to detect Salmonella typhimurium (S.typhimurium) sensitivity = 1.79 kΩ/(CFU/mL.cm ²) detection limit = 1.56 CFU/mL detection range = 10–10 ⁷ CFU/mL.	Elsevier	2017	[89]
Medical	Antibacterial materials	Using nanohole enriched MoS ₂ to destroy bacteria. MoS ₂ concentration used is 4 µg/mL. It has affinity response with biofilms of 14.71 nM, 1.3-fold > 11.44 nM obtained for pristine MoS ₂	Nature	2021	[91]
Energy	Solar cells	Verified in vitro and viro Using MoS ₂ as a buffer in solar cells to enhance efficiency and stability	IEEE	2016	[123]
Energy	Solar cells	Using MoS ₂ as a hole transport layer in solar cells a peak at 404 cm ⁻¹ , at 200 °C, and two more peaks at at 380 and 404 cm ⁻¹ , at 300 °C,	Wiley	2019	[124]

Table 5. Cont.

Application	Category	Description	Publisher	Year	Reference
Energy	Solar cells	MoS ₂ as a transport layer in perovskite solar cells PCE (η) = 3.9% compared to other cells of (η = 3.1%). High stability for 800-hour shelf life (Δ PCE/PCE = -17%) when compared to other cells of (Δ PCE/PCE = -45%).	IEEE	2015	[125]
Energy	Solar cells	Using MoS ₂ /Si heterojunction in solar cells to enhance conversion efficiency from 1.1% to 4.6%.	Elsevier	2018	[126]
Energy	Solar cells	Enhancing organometallic-halide perovskite solar using MoS ₂ as a buffer Cells (PCE) = 14.9%, and maintaing 93.1% of its PCE after 1 hour	Nature	2020	[127]
Energy	lithium-ion batteries	Using MoS ₂ as as anode material for lithium-ion batteries.It has capacity of 1103.6 mAh/g and maintains a reversible capacity of 786.4 mAh/g after 50 cycles at 0.1 A/g	Elsevier	2019	[128]
THz applications	THz wave reflector	Switchable THz wave reflector made of MoS ₂ , SiO ₂ , and gold layers. reflection phase ranges from 0 to 2 π linear phase shift according to the geometric dimension	IEEE	2018	[107]
THz applications	THz modulator	Terahertz modulator of multilayer-MoS ₂ on Silicon (MOS). Moudulation efficiency of annealed MOS is higher that that of graphene over Silicon and graphene metamaterials	Nature	2016	[115]
Other	Hydrogen detection	MoS ₂ -PVP (Polyvinyl pyridine) nanocomposite with ZnO to detect hydrogen. A 5 mg/mL sensor has 8 times better ensing than pristine ZnO	IEEE	2021	[116]
Other	Hydrogen generation	coordination polymer based on [Mo ₃ S ₁₃] ²⁻ clusters from amorphous MoS ₂ to be used in hydrogen evolution reactions.	Nature	2016	[117]
Other	Hydrogen generation	A edge-terminated and interlayer-expanded MoS ₂ catalyst fabricated using a microwave heating strategy. The proposed structure has the highest hydrogen evolution activity and best stability	Nature	2015	[118]
Other	Oil separation from water	MoS ₂ Sponge to absorb oil from water. Simple fabrication and easy scaling up.	Nature	2016	[122]

5. Challenges

Molybdenum disulfide material is still under study, although it has favorable chemical, photonic, and electronic characteristics, there are still more to be done regarding its way of preparation and compatibility with other materials, as summarized in Figure 7.



Figure 7. Illustrative diagram of challenges facing MoS₂.

Although MoS₂ showed acceptable electronic characteristics, it has less mobility (30–60 cm²/Vs) and higher band gap (1.8 eV) than Silicon (~1000 cm²/Vs and 1.1eV) [129–131]. MoS₂ FETs have some issues with mobility, electro-statistics and strain below 6.6 nm gate lengths [132], which means we cannot achieve the required sub 10 nm International Technology Road Map (ITRS). We are still facing challenges in synthesizing techniques for the production of different 2D structures that are hard to separate. Moreover, the stability of MoS₂ against moisture, humidity, and other environmental conditions needs more study [133].

The researchers in [134] studied the effect of impurities and atomic vacancies of Mo and S in MoS₂ structure. The absence of Mo or S and especially Mo vacancy leads to gap states that result in a noticeable current at low voltage biasing. Atomic vacancies affect the electron and hole transport of MoS₂.

MoS₂ layers like other 2D materials are prone to laser damage when used as optical modulators [135]. The fast response of these materials transfers a remarkable portion of light into heat that can result in complete damage or burn to the material. Additionally, MoS₂ structure has some defects that cause performance degradation and low reliability when used in device applications. As an example, MoS₂ layers fabricated through CVD have many dangling bonds and high reactivity. The grain boundaries and point defects were studied in [136], while those studies are references to control MoS₂ defects and other TMDs using defect engineering methods.

More studies are needed for the lattice mismatch that occurs between monolayers. The mismatch cause band gap moiré and affect spectroscopy of MoS₂ bilayer [137].

Although MoS₂ has mechanical flexibility and strength that facilitates its strain engineering, the material exhibits nonuniform strain distribution. This happens because of the large number of atoms involved under strain which needs further study [138,139]. The non-equilibrium in MoS₂ structure is related to the temperature and the heating rate applied during synthesizing [140], which calls for new synthesizing methods.

Although MoS₂ is said to have good biocompatibility, bio absorbability, cancer killing, and anti-bacterial effect, a very important research published in Nature in 2018 states a highly toxic effect of MoS₂ nanosheets [141]. MoS₂ were investigated to induce cytotoxic effect and cell damage when interacting with tumor cells, while no effect in case of normal cells. The cytotoxic effect depends on the concentration and number of layers of MoS₂ that can be manipulated in the future. The nano- and micro- MoS₂ sheets showed a change in the metabolic profiles on the intestine of mice [142]. Also nano-MoS₂ sheets showed greater intestine inflammation. Both changed the intestinal microbiota. Table 6 provides a summary of the reported challenges facing MoS₂ in the literature, and their types.

Table 6. Summary of challenges facing MoS₂.

Challenge	Description	Publisher	Year	Reference
Properties	Effect of lattice imperfections and atomic vacancies on density of states and electron-hole transport	IEEE	2015	[134]
Properties	Degradation behavior of MoS ₂ crystals	NPG Asia Materials	2018	[136]
Properties	structural transformations in MoS ₂ thin layers under high temperature	Nature	2020	[140]
Electronics	Sub 10 nm FETs challenges and Strain effects	IEEE	2015	[132]
Optoelectronics	Optical modulation challenges and laser damage	Advanced Materials	2017	[135]
Optoelectronics	optical spectroscopy for MoS ₂ layers, the absorption and emission behavior and how to tune them	Nature	2021	[137]
Optoelectronics	Strain engineering to develop optical properties and using it in photonics applications	Nature	2020	[138]
Optoelectronics	Failure mechanisms of monolayer MoS ₂ under large strain	Journal of physics	2015	[139]
Biomedical (biocompatibility)	Cytotoxic effect of MoS ₂ when used to cure cancer cells	Nature	2018	[141]
Biomedical (biocompatibility)	Effect of nano-MoS ₂ on mice intestine where it caused intestinal inflation and changes in the metabolism and the microbiota	Royal Society of chemistry	2019	[142]

6. Conclusions

In this review, we highlighted the different MoS₂ structures and their synthesizing techniques in detail, and we provided a comprehensive comparison between all the structures, in term of their main optical, lattice and electrical properties and applications. Synthesis techniques were also covered with their main advantages and inconveniences. A review of the wide range applications of MoS₂ from electronics, medicine to new fields of research such as the terahertz field and the hydrogen-related technologies was made. We also discussed and compared the different challenges facing the development of MoS₂ applications in different fields of study, since they were not discussed in detail in previous studies that focused more on synthesizing techniques or specific kinds of applications.

MoS₂ is a promising material with a wide range of applications. Its outstanding properties and band gap characteristics allowed its use in biosensing, electronics, optoelectronics, and energy applications. It has good biocompatibility and bio absorbability

that allowed its use in several diseases' curing like cancer, Alzheimer, and Coronavirus. Its photoluminescence properties helped in DNA detection. It is believed that MoS₂ can substitute Silicon semiconductor devices. On the other hand, there are some challenges facing MoS₂ that needs to be studied, like managing its impurities, lattice imperfections, and finding the best way of synthesizing that guarantees the largest yield, the cheapest cost, and the highest quality without changing its chemical and physical properties.

In a summary, this review provides an understanding of the major challenges facing the development of MoS₂-based solutions, especially in the untapped new fields of applications. The integration of MoS₂ with other 2D nanomaterials, such as graphene, in hybrid structures can provide a tradeoff between the shortcomings of both materials and a better combination of their main advantages to overcome the existing challenges.

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