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Fabrication and characterisation of two-dimensional transition metal dichalcogenides for applications in nano devices and spintronics

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Abstract

Two dimensional transition metal dichalcogenides (TMDCs) are unique due to a combination of exhibiting a direct bandgap in the monolayer structure, strong spin–orbit coupling and excellent electronic and mechanical properties. These materials are studied for fundamental interest but are increasingly finding applications in high-end electronics, spintronics, optoelectronics, energy harvesting, flexible electronics, DNA sequencing and personalized medicine. Due of its robustness, MoS_2 is the most studied material in this family. These materials are considered promising candidates to overcome the scarcities belonging to zero-bandgap graphene, providing a possible solution for next-generation electronic applications. In this chapter we discuss the optical and magnetic properties of 2D-TMDCs. In addition, a brief discussion on various methods (mechanical exfoliation, physical vapour deposition, chemical vapour deposition, pulsed laser deposition) used for low-dimensional deposition and synthesis of TMDCs is included. The use of TMDCs in nanodevices and spintronics along with strategies to improve charge carrier mobility and challenges associated with them are explained. Finally, we explain the interplay of 2D physics, semiconducting properties and magnetism in TMDCs for their application in spintronics.

Keywords: Transition metal dichalcogenides; nanodevices; spintronics; flexible electronics; 2D materials

1. Introduction

With advanced fabrication methods, it is now possible to thin down many bulk layered materials down to a single monolayer. This has enabled exploration of new low-dimensional physics such as the anomalous quantum hall effect and massless Dirac fermions in the case of graphene [1][2]. Transition metal dichalcogenides (TMDCs) form another class of layered materials, in which the interactions of *d*-electrons generates new physical phenomena [3][4]. TMDCs are semiconductors of the type MX_2, where M is a transition metal atom (Mo or W) and X is a chalcogen atom (S, Se or Te) [5,6]. Similar to graphite structure, single layers of the sandwich structure X–M–X can exist and multiple layers, stacked by weak van der Waals interactions, can form bulk solids [5,6]. The structure of TMDCs was first time determined by Linus Pauling in 1923 [7]. Later in 1963, ultrathin layers of MoS_2 were produced by Robert Frindt by exfoliation using adhesive tapes and the monolayer of MoS_2 suspensions were first produced in 1986[8]. The discovery of graphene in 2004, fuelled the development of techniques needed for working with layered materials leading to new studies related to 2D TMDCs both of fundamental and of technological importance[9]. These materials have a wide range of applications in high-end electronics, spintronics, optoelectronics, energy harvesting, flexible electronics, DNA sequencing and personalized medicine[8,10]. TMDCs are considered promising candidates to overcome the scarcities belonging to zero-bandgap graphene, providing a possible solution for next-generation electronic applications. In particular, among the various TMDC materials that exhibit stable 2D crystalline structures (WSe_2, $MoSe_2$, WS_2 and MoS_2), MoS_2 has received considerable attention due to its unique optical, electronic and other characteristics including its size-dependent bandgap[8,10][3–5].

In this chapter, taking MoS_2 as a benchmark material, a basic outlook of the large family of 2D TMDCs, highlighting their physical properties and introducing the recent preparation methods, are discussed. Finally, the emerging applications of MoS_2 in nanodevices and spintronics are presented.

2. Structure

TMDCs have a general chemical formula of MX_2, in which M represents transition metal and X stands for S, Se and Te. In bulk form these material consists of X-M-X layers stacked together. These materials can exist in different structural phases (2H (thermodynamically stable), 1T (metastable form)[11,12]. MoS_2 is most explored of all the TMDCs for a variety of technological applications such as optoelectronics, nanoelectronics and spintronics in different fields [8,10]. In a single layer of MoS_2 each Mo (+4) is surrounded by 6 S (-2) atoms and the

Mo-S bond is predominantly covalent in nature. MoS_2 can exist in four structural phases: 1T, 1H, 2H and 3R[13]. The stacking of layers with respect to Mo coordination influences the structural phases. For example, the 2H structure is formed due to layers stacked in an ABA type. It has hexagonal symmetry with two layers per unit cell. MoS_2 is mostly found in this phase in nature. In the 1T and 1H phase, Mo atoms are octahedrally coordinated by six S atoms. 2H and 3R phases exhibit trigonal prismatic coordination around Mo atoms. The 3R structure with rhombohedral symmetry in MoS_2 is mostly obtained synthetically[12,13][14]. The unit cell consists of three layers. The 3R structure changes to the 2H type under heating due to its unstable nature. In 2H and 3R structures Mo hexagonal arrays are sandwiched between sulphur layers. 1T crystal structures are due to ABC ordering of layers which are formed due to disorientation of one sulphur atom layer. It has a symmetrical Mo–Mo bond and is metallic in nature.

The 2*p* orbitals of sulphur form the valence band whereas the *d* orbitals of Mo form the conduction band. The hybridisation of the p_z orbital of S and the *d* orbital of Mo leads to the formation of a bandgap between K and Γ. The band gap is dependent upon the number of layers. The valence band maximum (VBM) point Γ decreases below zero with decrease in the number of layers but the K point remains unchanged. Hence, for a monolayer the lowest energy transition is vertical and the energy needed for the indirect transition is larger than the direct band edge transition. The band structure of MoS_2 varies as the function of number of layers which in turn affects the chemical, physical and magnetic properties [11,12]. The band gap changes from direct in monolayer MoS_2 (1.9 eV) to indirect (1.3 eV) in bulk. This change is due to the long-range coulumbic effects and quantum confinement in few layer materials [28,29]. The variation in the gap between valence band and the conduction band is shown in figure 1.

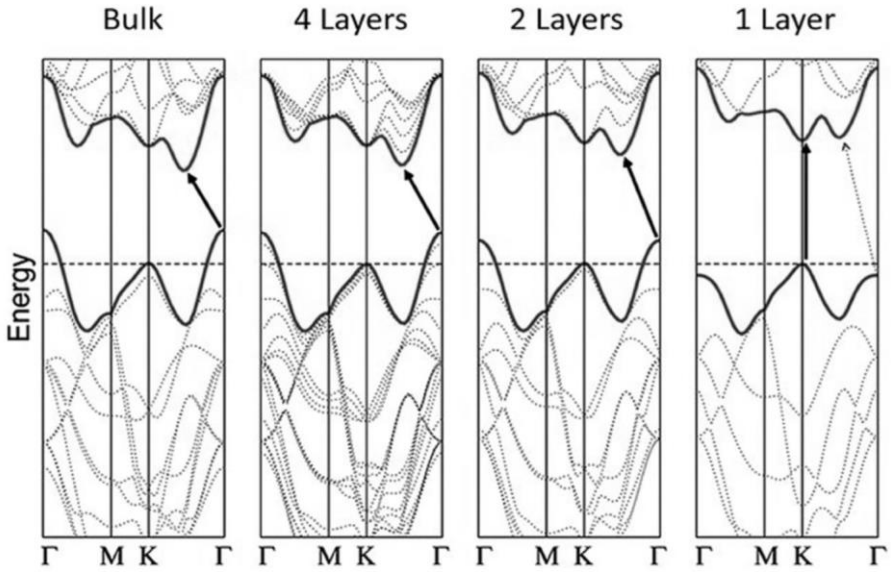

Figure 1 Energy dispersion observed in bulk, 4-layer, 2-layer, and 1-layer MoS_2.[Adapted with permission from Reference [15]]

The semiconducting properties of MoS_2 in the 2H phase is due to the presence of empty d_{xy} and $d_{x^2-y^2}$ and filled d_{Z^2} orbitals. The 1T phase shows metallic properties as the 4*d* orbitals split into e_g and t_{2g} states and the two electron are filled in the t_{2g} state. With reduction in the number of layers, the charge mobility drastically increases due to the direct bandgap and thinness of the material. These materials can be designed for different applications since their properties vary as a function of number of layers. Further, these materials can be engineered by intercalation, reducing dimensions and by forming a variety of heterostructures [12].

2. Properties

2.1 Optical properties

2.1.1 Photoluminescence spectroscopy:

MoS_2 in the bulk form shows negligible photoluminescence and it has an indirect band gap [16]. It becomes strongly photoluminescent when thinned to monolayer thickness. This control over emission characteristics at the atomic scale is due to the quantum confinement effect which provides freedom to engineer the matter at the nanoscale. The interactions between the fundamental particles such as electrons, holes and photons are very strong due to reduced dielectric screening in 2D semiconductors. This leads to strong attractive coulombic interactions between an electron and hole. This results in the formation of a bound quasi particle known as a neutral exciton (X). The charged quasi particles consist of either two electrons and one hole (negative trions conventionally denoted as X− or T−) or one electron and two holes

(positive trions, conventionally denoted as X+ or T+). In addition, either neutral (XX) or charged (XT) biexcitons[17] are also formed due to the large exciton binding energies in 2D TMDCs. The optoelectronic properties of 2D materials depends upon these excitonic species. These are the elementary quasi-particles in 2D materials.

The direct transition between valence and conduction band states around the K and K´ points in 2D materials occur in the near-infrared and visible spectral region [16]. Monolayer TMDCs have theoretically very large exciton binding energies E_B (0.5–1 eV) for an exciton Bohr radius $a_B \approx 1$ nm [16,17]. The experimental absorption spectra of these materials show sharp resonance features due to strong excitonic effects [17]. Some recent experimental studies based on optical spectroscopy[16,18] have verified the large binding energies. Under pulsed laser excitation trions and bi-excitons are formed in doped monolayer TMDCs [18,19]. Due to the large binding energies of the excitonic particles present in 2D TMDCs their observation even at room temperature is quite possible. This makes trions very useful for electrical transport at room temperature. It is also possible to create high-density quantum coherent states of excitons[18].

Andrea Splendiani *et al* investigated the optical properties of few-layer MoS_2 structures through optical reflection, Raman scattering, and photoluminescence spectroscopy[4] (shown in Figure 2). The A1 and B1 excitons show two prominent absorption peaks at 670 nm and 627 nm at the Brillouin zone K point in the spectrum. The spin-orbital splitting of the valence band causes the energy difference in the absorption peaks. Photoluminescence of single layer MoS_2 is shown in Figure 2. It shows strong emissions due to A1 and B1 direct excitonic transitions. These transitions are not present in bulk MoS_2. These transitions inherently belong to single layer MoS_2 monolayer and external perturbations such as defect states might not affect them.

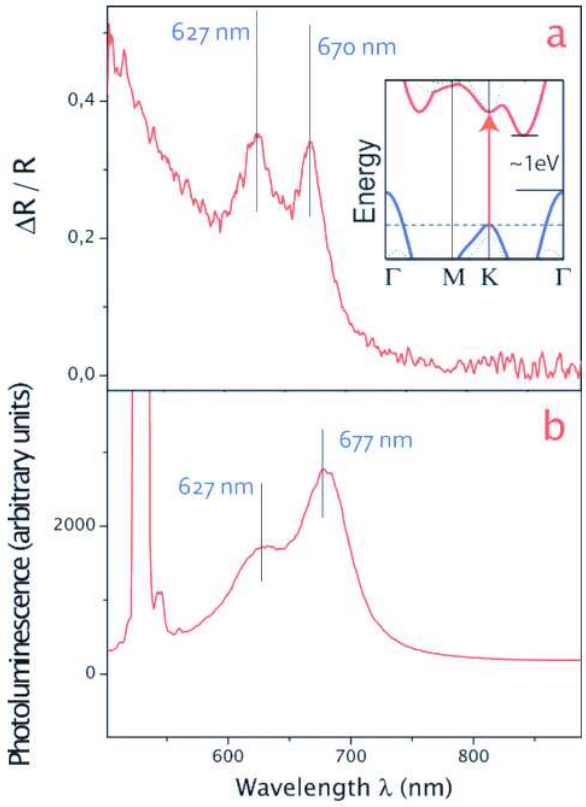

Figure 2: Reflection and photoluminescence spectra of ultrathin MoS_2 layers. (a) Reflection difference due to an ultrathin MoS_2 layer on a quartz substrate. The inset shows the bulk MoS_2 band structure (b) A strong photo-luminescence is observed at the direct excitonic transitions energies in a monolayer MoS_2 [Adapted with permission from Reference [4]]

2.1.2 Raman spectra: Raman spectroscopy is a popular technique to investigate the number of layers, types of edges, controlling the quality, effect of electric and magnetic field, attached chemical groups, strain, doping etc in 2D materials [20]. With rapid development in the Raman spectroscopy techniques and unique engineering of the materials, it is also used to probe the strength of interlayer coupling and interface coupling in the van der Waal heterostructures (vdWHs) [21]. MoS_2 has four Raman active modes, E_{1g}, E^1_{2g}, A_{1g}, and E^2_{2g}. The prominent peaks due to E^1_{2g} and A_{1g} are shown in Figure 3. E^1_{2g} and A_{1g} correspond to in-plane and out-of-plane vibrations of sulphur atoms and are generally used to understand the crystal structure of MoS_2[12,20].

The typical changes in these Raman peaks while going from bulk to monolayer MoS_2 are listed below:

(i) E^1_{2g} shows a blue-shift, whereas A_{1g} displays an opposite red-shift. For single layer MoS_2, E^1_{2g} is located at ~384 cm^{-1} whereas and A_{1g} is at ~ 405 cm^{-1}.

(ii) The difference between E^1_{2g} and A_{1g} decreases as a function of the number of layers. The frequency difference changes from approximately 25 cm^{-1} for bulk to 19 cm^{-1} for monolayer MoS_2.

(iii) The peak intensities of these bands increase linearly up to four layers before decreasing for thicker MoS_2

Figure 3 shows the variation of Raman peaks with increasing thickness. Raman characteristics of 2D materials in solution are quite different from solid-state 2D materials. Until now, Raman studies have focused on 2D material flakes in the solid-state only. Yanqing Zhao *et. al.* [20] has investigated the 2D MoS_2 in solution using angle-resolved polarized, helicity-resolved and resonant Raman spectroscopy. The solution of 2D materials show better and complete Raman spectra in comparison to 2D materials in the solid phase. Solution of 2D materials clearly reveal forbidden E_{1g} mode as shown in Figure 4. The random orientation of the dispersive nanosheets is found to be responsible for the unique Raman characteristic of 2D material in solution. [20].

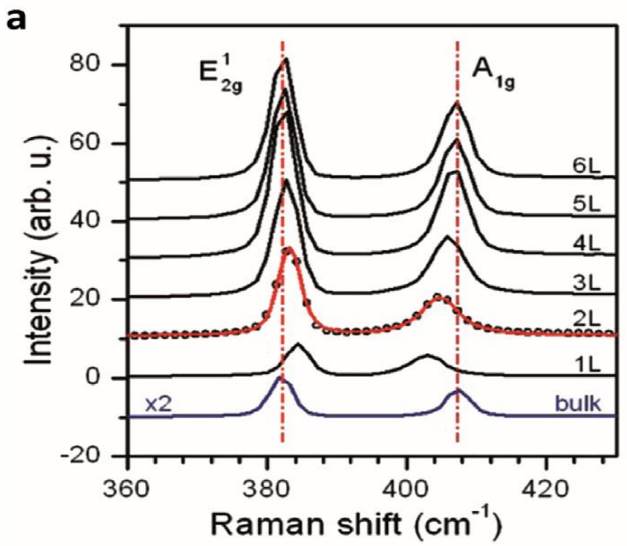

Figure 3: Raman spectra of thin (nL) and bulk MoS2 films. [Adapted with permission from Reference[22]]

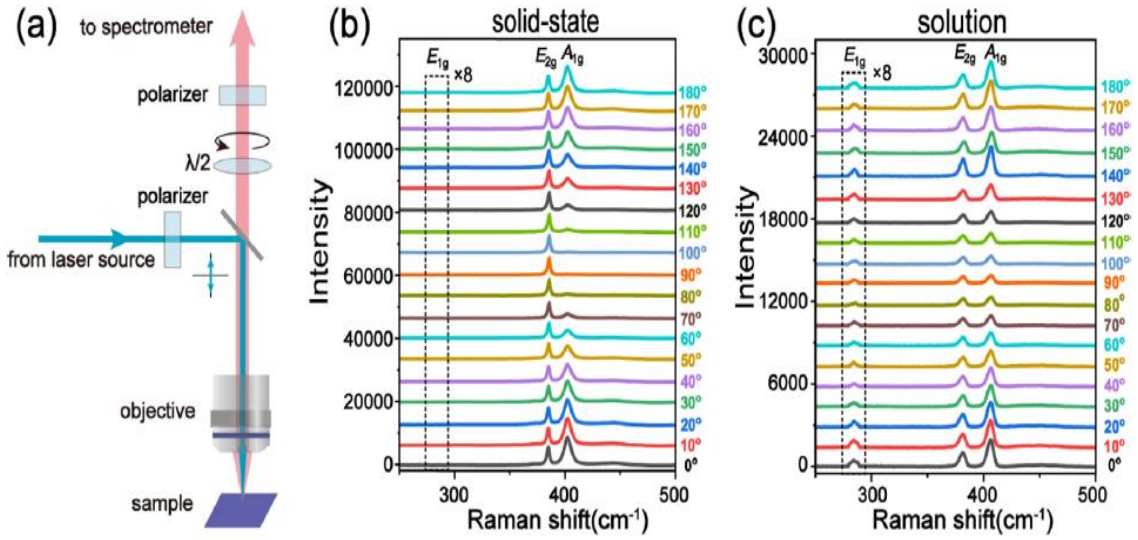

Figure 4: Angle-resolved polarized Raman spectra of solid-state MoS_2 and MoS_2 solution. (a) Experimental setup for the angle-resolved polarized spectroscopy. (b) Raman spectra of solid-state MoS_2 flake with various angles (θ) between e_i and e_s. (c) Raman spectra of MoS_2 solution with various angles (θ) between e_i and e_s [Adapted with permission from Reference [20]]

2.2 Magnetic properties:

Graphene and TMDCs are inherently non-magnetic in nature. Magnetic properties of these materials are modified using gating, doping, functionalization etc. to obtain spin polarised states. In general, magnetism has two origins: spin of elementary particles and moving charges. Both of these are hindered by thermal disturbance in 2D materials. Magnetic properties of non-magnetic 2D materials are altered by suitable doping or by introducing vacancies. Due to these modifications, interactions between unpaired electrons give rise to local magnetic moments thus making it possible to realise long-range magnetism. [23–26].

The optical, electrical and mechanical properties of MoS_2 are well investigated both theoretically and experimentally. The magnetic response is mostly studied through theoretical calculations [27–31] but recently these materials have been studies experimentally[26,32–38]. According to theoretical predictions, depending on the direction of termination of edges there exists different magnetic ground states. For instance, armchair edges show stability in a non-magnetic state while the zig-zag edges possess net magnetic moment and are in a magnetic ground state. Hence, magnetism in MoS_2 nanoribbons, nanocrystalline thin films, and even in bulk can be ascribed to the presence of zig-zag edges (providing the average grain size is small enough). Sefaattin Tongay *et. al.* investigated the magnetic properties of single crystal MoS_2 in the bulk limit experimentally, in the temperature range 300 K to 10 K with an applied

magnetic field ranging from 0 to 5 T [34]. The results indicate that magnetization of MoS_2 is possibly due to existence of zig-zag edges with associated magnetism at grain boundaries and a temperature dependent diamagnetic background. The magnetic response is dominated by diamagnetic character but the diamagnetic background is superimposed onto the ferromagnetic loop shown in Figure 5. With an increase in grain size (or ribbon width) it is expected that the net magnetic moment should decrease thereby diminishing the ferromagnetic response in the bulk limit. However, there are a considerable number of grain boundaries present in these MoS_2 samples due to the small average grain size (75 nm). Due to the presence of large grain boundaries, there is an arbitrary distribution of zig-zag and armchair edges which leads to ferromagnetic behaviour in these samples. The ferromagnetic signal originating from zig-zag edges is estimated to be around 2.6 x 10^{-2} emu/g.

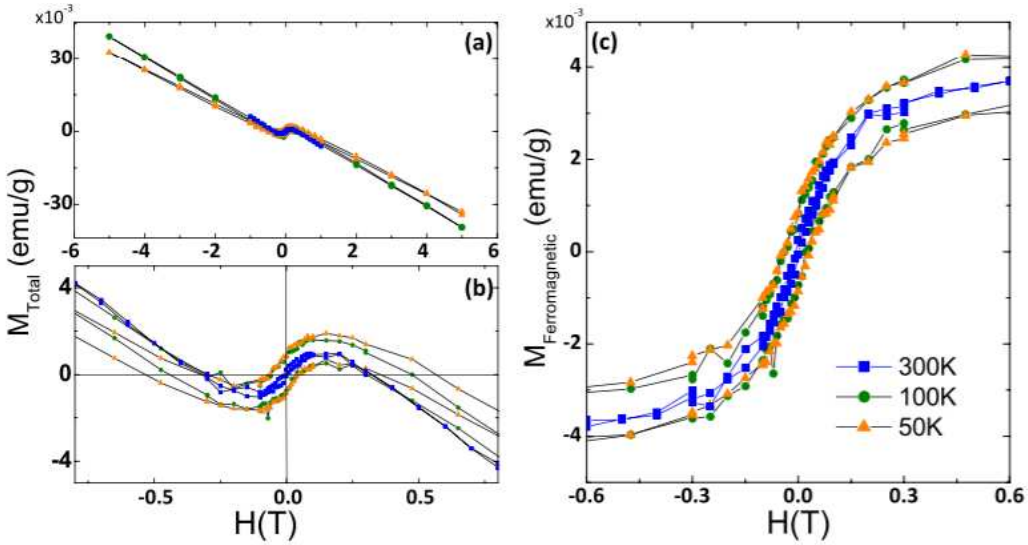

Figure 5(a) Magnetization (M) vs applied field (H) data taken at different temperatures in the field parallel to the c-axis direction. (b) M-H curves displayed at lower magnetic fields. (c) M ferromagnetic vs H curves after subtracting out the diamagnetic background [Adapted with permission from Reference[34]].

In TMDC monolayers, electrical and optical properties are thickness-dependent but show non-magnetic behaviour in their intrinsic form [32,39]. Atomically thin, dilute magnetic semiconductors (DMSs) are formed by doping with transition metal elements (V, Mn, and Fe) in TMDC due to magnetic coupling in these 2D structures. Doping of TMDC monolayers with transition metal ions is considered a promising way to realize DMSs having a Curie temperature above room temperature as predicted by first-principles studies [39]. Fe:MoS_2 monolayers reveal a well-defined M–H hysteresis loop both at low (5 K) and room temperature,

suggesting that ferromagnetism in these materials can be observed even at 300 K [32][40]. Jieqiong Wang *et. al.* demonstrated robust ferromagnetism in Mn-doped MoS_2 nanostructures synthesized by a hydrothermal method [36]. The observed ferromagnetism in Mn-doped MoS_2 shows strong temperature dependence and is quite different from defect-induced magnetism. Observed ferromagnetic phases with Curie temperatures of 80 K and 150 K are shown in Figure 6. It is found that all the Mn^{2+} dopant ions don't contribute equally to the observed magnetism. Mn^{2+} are paramagnetic if they are well isolated whereas the Mn^{2+} ions having nearest neighbours form clusters and are anti-ferromagnetic and do not contribute to the overall magnetism. Some Mn^{2+} ions order ferromagnetically via an indirect coupling mechanism. This is due to the tuning of the spin polarization and magnetic ordering in TMDCs and can have applications in spintronic devices.

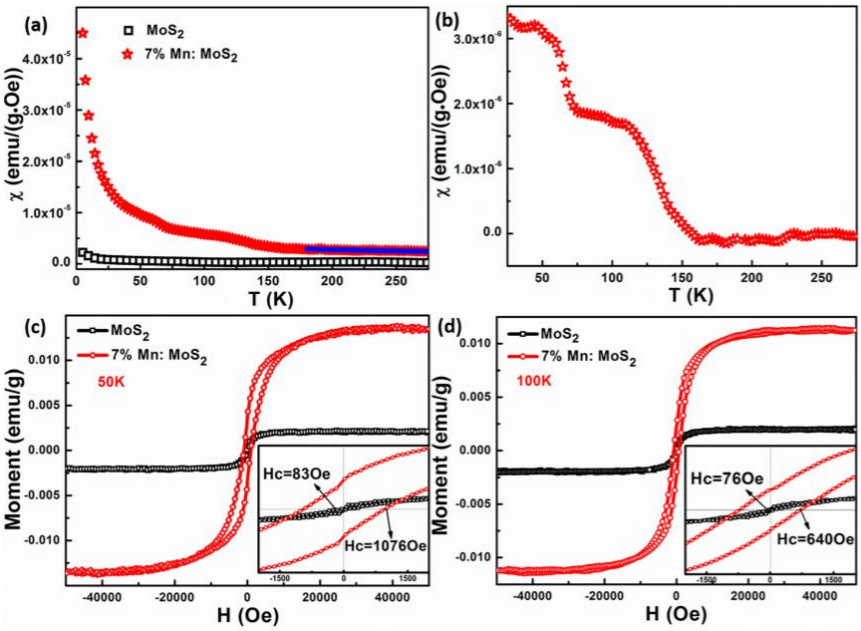

Figure 6: Magnetic properties of the MoS_2 and the 7% Mn^{2+} doped MoS_2. (a) Temperature dependence of magnetic susceptibility (v-T curves) of the undoped and the 7% Mn^{2+} doped MoS_2 measured at a field of 500 O_e, and fitting of the high temperature v-T curve of the Mn-doped MoS_2 by the Curie-Weiss Law (b) the v-T curve of the 7% Mn^{2+} doped MoS_2 after paramagnetic background subtraction; two ferromagnetic transitions are clearly observed. (c) Magnetic hysteresis loops of the undoped and the 7% Mn^{2+} doped MoS_2 measured at (c) 50 K and (d) 100 K, respectively [Adapted with permission from Reference[36]]

Peng Tao *et. al.* have reported strain-induced magnetism in single-layer MoS_2[31]. The delocalized electrons of Mo are believed to be responsible for this unique magnetism in the

defect MoS_2. Due to these induced magnetic moments, MoS_2 can be used in the design of magnetic-switching or logic devices. The magnetic properties are also found to be structurally phase dependent. S. Yan *et. al.* investigated magnetic properties of 2H phase of MoS_2 (2H-MoS_2) and 1T phase of MoS_2 (1T-MoS_2) both experimentally and theoretically in single layer MoS_2 sheets [33]. The pristine MoS_2 (2H-MoS_2) is found to be weakly diamagnetic. After exfoliation, significantly enhanced paramagnetism is observed due to transformation of the crystal structure from 2H to 1T.

3. Synthesis methods

Synthesis techniques play an important role in obtaining material with desired properties. In order to enhance the desired properties (of MoS_2), selection of an effective fabrication technique is necessary. The synthesis techniques are broadly categorised as top-down and bottom-up approaches. The top-down approach involves techniques such as mechanical exfoliation, liquid-phase exfoliation, chemical intercalations, etc., whereas the bottom-up approach includes chemical vapour deposition (CVD) and chemical synthesis[41][11,12] . Some of these methods are discussed below:

3.1 Vapor phase deposition

This technique is used to prepare ultra-thin films by depositing vapor-phased compounds on the desired substrate (with or without chemical reaction) to form layers. The 2D materials formed have high crystallinity and uniformity and high layer controllability. Generally, this technique involves three main approaches: thermal decomposition of precursors, physical vapor deposition (PVD), and chemical vapor deposition (CVD).

- **Physical vapor deposition (PVD):** The PVD approach is to produces 2D materials by re-crystallization of materials through a vapor-solid process. Various 2D materials can be prepared by PVD. However, the random nucleation of the crystals in PVD can make the layer thickness uneven; research is continuing to resolve this issue.
- **Chemical vapor deposition (CVD):** Since the size of MoS_2 films prepared by conventional methods such as exfoliation and vapor deposition are of the order of micrometers, considerable efforts have put into preparing large area, thin-layer MoS_2, though this is still a challenge. Chemical vapor deposition (CVD) has gathered immense attention as 2D TMDCs have being successfully synthesized on a wafer-scale using this method. Another major advantage of this method is that interfacial contamination

introduced during the layer-by-layer transfer process can be reduced and layered heterostructures can be grown using CVD.

- **Thermal decomposition:** Due to difficulties in controlling the thickness, uniformity and polycrystalline nature of the films (such as the deposited Mo film or the $(NH_4)_2MoS_4$ thin film) this method is not widely used.

3.2 Exfoliations:

- **Mechanical Exfoliations:** To obtain one-or few layer nano-sheets, mechanical exfoliation is a versatile and low-cost method in which the crystal structure and properties of material are well maintained. The micromechanical exfoliation method was first used by Novoselov and Geim to obtain single layer graphene from graphite.
- **Ultrasonic exfoliation**

  This method employs the strategy of delaminating van der Waals solids into single layer nanosheets. This method is more advantageous and effective compared to mechanical exfoliation. Various recent reports suggest solvents play an important role in the stabilisation of exfoliated nanosheets. Although this method has many advantages, high-purity single-layer 2D material is difficult to obtain using ultrasonic exfoliation. Recently, Chhowalla *et. al.* reported synthesis of monolayer MoS_2 via lithium-intercalation and exfoliation[42].

4. Applications

The various practical applications of MoS_2 are possible only due to its promising properties which are discussed above. These applications include biosensors, supercapacitors, solid lubricants etc. These properties include a low coefficient of friction, high mechanical strength and high surface area, variable band gap, excellent transport properties accounting for the large number applications[16,43,44][25,27,28,32,36,37,40]. MoS_2 ,in particular, explored now being extensively studied for nanodevices and spintronics applications.

4.1 Nanodevices:

The future semiconductor industry needs high performance nanoelectronics, low-power and multifunctional devices as it is not possible to further add new components into the existing silicon platform. Two-dimensional (2D) layered semiconductors possess ultrathin structures, atomic scale smoothness, dangling bond-free surfaces, high carrier mobility, and a sizable bandgap. Flexible nanotechnology is desired for next generation electronics and energy

devices. 2D materials are suitable candidates for these applications (sensors, thin film transistors (TFTs), displays, solar cells, energy storage etc.). 2D TFTs based on MoS_2 operating at room temperature show a high on/off current ratio and current saturation. Electron mobility as high as 50 $cm^2V^{-1}s^{-1}$ and a current density of 250 mA/mm is observed from such TFTs [ ]. Flexible monolayer MoS_2 TFTs offer robust electronic performance to 1000s of cycles of mechanical bending [ ]. Because of these encouraging properties, their is great interest in their use for low-power RF TFTs for advanced flexible Internet of Things (IoT) and wearable connected nano-systems.

2D materials are considered as a reliable material for logic applications *such as* MOSFETs due to their easy and cost-effective large scale synthesis and compatibility with CMOS technology. High mobility, band gap (~1 eV) and good ohmic contacts are basic requirements of the material to be used in the aforementioned applications. The layered structure of these materials are bonded together by weak van der Waals forces [45]. The large relative effective mass of 2D TMDCs (~0.5 for electrons and ~0.66 for holes) as compared to Si (~0.29) leads to a reduction in the source-drain tunnelling component in TFETs [46]. Intense research is being carried out to develop novel 2D materials with high-performance and/or to improve the performance of current 2D materials. Considerable progress in the field of 2D materials for state-of-the-art electronic nano-devices has been achieved in recent years However, there is still a paucity of 2D materials which can be potentially used for high-performance 2D-based electronic devices. MoS_2 has low electron mobility [47,48] and a relatively large band gap [49–52] resulting in a high I_{on}/I_{off} ratio (~108) [47]. It has been reported by several researchers that the performance of electronic devices is affected by the number of the layers and the properties of these layers in turn are affected by the nature of the substrate or another 2D layered material coupled with them. Therefore, to achieve the aforementioned properties simultaneously, hetero-structures from two different kinds of 2D materials, such as graphene and MoS_2 can be used [11,53]. For the realization and thermal management of the desired high-quality electronic devices, thermal conductivity and heat dissipation along with the above-mentioned properties also play an important role. Graphene and hexagonal-BN are still promising candidates for FET applications in comparison to 2D TMDCs despite the large number of theoretical and experimental studies on the thermal behavior of these materials [54–56]. The difference in the thermal properties of monolayer MoS_2 (2D TMDC) compared with a one-atom thin graphene layer can be attributed to its sandwich structure due to the dominance of the phonon contribution over the electron contribution in thermal conductivity [57]. Recent investigations

revealed that the theoretical thermal conductivity of MoS_2 is 1.35 [58][59] or 23.2 W m^{-1} K^{-1} [57]. Further, the values of thermal conductivity of MoS_2 with a few layers are found to be 1.59[60] and 52 W m^{-1} K^{-1} [61] experimentally at room temperature. For the realisation of state of art electronic device applications, a deep insight in the thermal properties of MoS_2 (TMDCs), is of utmost importance.

The TMDCs are proving themselves very promising candidates for optoelectronic applications as single layers of these materials show excellent PL and electroluminescent properties and their flexibility allows novel innovative device designs. These materials show strong inter-band transitions due to the heavy effective mass of the '*d*' electrons and the van Hove singularity peaks in the electronic density of states. An optical absorption as high as 107 m^{-1} is observed in a 300 nm thick TMD which leads to 95 % absorption. The carrier mobility in 2D TMDCs is further enhanced by the low density of traps. The carrier mobility of MoS_2 nanosheets is reported as 0.5 cm^2 $V^{-1}s^{-1}$ – 200 cm^2 $V^{-1}s^{-1}$[ ]. This wide range is attributed to the sample quality, presence of absorbates, suppression of impurities and grain boundaries etc. The TMDC based photo-detectors have a limitation of low photo-response because the active photo-response area is only limited to the regions at the metal-TMDC interface as most of the incident light is not absorbed. Heterostructures of TMDCs with other 2D materials are particularly desired for practical optoelectronic application since there is a better control of photocurrent separation and carrier transport. The TMDCs are also explored for photonic applications. It is found that MoS_2 shows greater saturation absorption near 800 nm but the lack of gain medium around this wavelength inhibits its usage. The saturation absorption is wavelength dependent, hence a high pump power is needed to saturate absorption at shorter wavelengths. Research related to usage of MoS_2 in mode locking laser applications is increasing these days [ ] but there is limited understanding of the underlying physics of TMDCs for these applications.hence more experimental work is needed.

4.2 Spintronics:

The poor spin-orbit interaction on traditional spintronics materials permits the operation of the devices below room temperature. Further, ultra-pure materials are needed to avoid spin-flip scattering [62]. For next-generation nano-electronic and spintronic devices, new materials such as 2D materials are being investigated. High electron mobility and long-distance spin transport is possible in graphene at room temperature. However, high spin orbit coupling and a direct bandgap are a primary need for a switching action in charge- or spin-based transistors. Graphene lacks a band gap and spin-orbit coupling in its pristine state. The properties of

graphene may be modified by doping, this being necessary for opening up the band gap. Strong spin−orbit coupling induces spin splitting of up to 0.4 eV in 2D transition-metal dichalcogenides (TMDs). This enables the possibility of room temperature operation of spintronics devices [63]. These properties make TMDCs suitable for novel spintronics applications for example magnetic sensors, ultrathin high-density data storage devices, spin-field-effect switches, spin valves, magnetic logic gates, magnetic random-access memory etc. There are several challenges for developing two dimensional (2D) spintronics: (i) increasing the magnetism in the system by spin injection and (ii) efficient manipulation of the spin [64,65]. Among various TMDCs reported, MoS_2 is special because of its interesting physical properties, which are a function of its thickness and structural phase transitions. Some of the properties which make MoS_2 a potential candidate for spintronic and nanodevice applications are: absence of inversion symmetry, high atomic mass, very strong spin-orbit splitting due to confinement of electron motion in the plane, high on/off current ratios and bandgap tunability (1.2−1.8 eV). Pristine 2H-MoS_2 has a non-magnetic ground state due to spin (S) = 0 Mo 4+ in a trigonal prismatic geometry, therefore a significant modification in the physical properties is essential before exploring it for spintronics applications. There are several reports of ferromagnetism in MoS_2 via transition-metal, non-metal, and lanthanide ion doping, adsorption of non-metals, structural phase transitions and strain induced defects. For the practical realization of spin-based devices, the electrical injection, transport, manipulation, and detection of spin-polarized carriers in the MoS_2/ferromagnet (FM) heterostructures are primary requirements[63].

5. Conclusions

Intensive research on MoS_2 is still going on, to expolit its favourable chemical, photonic, and electronic characteristics. These materials can be explored with reference to the synthesis techniques and their compatibility with other materials. Some of the on-going challenges are listed below:

(i) Separation of different 2D structures is still a challenge. Efforts are being made to develop synthesis techniques for the production of such materials. Additionally, the effect of moisture and environmental conditions on the stability of MoS_2 needs to be investigated.

(ii) MoS_2 layers under laser operation (when used as optical modulators) are prone to damage. A large amount of heat is produced while in operation due to their fast response. This can result in burning of the material.

(iii) Defects in the MoS_2 structure such as point defects, dangling bonds on the surface of MoS_2 layers grown by CVD, grain boundaries etc can lead to low performance in device applications. These can be minimised using defect engineering methods.

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