

1.1 Introduction of The Two-Dimensional Materials

Since the isolation of graphene in 2004 by Novoselov and Geim via simple scotch tape, two-dimensional (2D) materials have become a promising candidate for advanced electronic device applications owing to its excellent electrical, mechanical and chemical properties. Very thin nanosheet represents the class of 2D nanomaterials because its two dimensions in terms of length and width are in micrometre range and thickness of the third dimension is less than 1 nm. The last decade has witnessed the exploration of several excellent properties of atomically thin 2D materials for developing devices at rigid as well as flexible substrates [Akinwande et al., 2014; Novoselov et al., 2016; Lin et al., 2016; Kim et al., 2015; and Han et al., 2018]. Their low-power consumption, high mobility of charge carriers, lightweight, high stretchability, reliable mechanical robustness, excellent optical transparency, and good environmental stability make them excellent candidates for advanced devices applications. Recently, several 2D materials, including graphene, TMDCs, and MXenes, have shown their potential for fabricating gas sensors, photodetectors, field effects transistors, supercapacitors, etc. The large surface-to-volume ratio and high adsorption establish 2D materials as the torch-bearer in smart sensing applications, including electronic skin (e-skin), home security, air- and health-monitoring, etc. Graphene registered his strong presence in the field of gas sensing by detecting a single molecule adsorbed on its surface. These exceptionally promising sensing results had never been achieved by using conventional solid-state gas sensors technology. This milestone was achieved due to an exceptionally low-noise in graphene [Schedin et al., 2007]. Moreover, Singh et al. [Singh et al., 2017] have reported chemical and gas sensing behaviour of the graphene on the flexible and wearable platform in review articles. The same group has also demonstrated electrochemical and fluorescent biosensors of the graphene and its nanocomposites. In the past few years, many 2D materials have shown promising results in chemical and biosensors applications [Lei et al., 2019; Sinha et al., 2018; J. Zhu et al., 2017; Ou et al., 2015; and Kannan et al., 2015]. The key figures of merit, such as ultimate sensitivity and detection at room temperature in chemical sensors could easily be achieved by using atomically thin layered 2D materials. In particular, the detection of target gas molecules at room temperature removes the micro-heater from the conventional gas sensor and making them as energy-efficient materials after reducing the consumption power from several hundreds of mW to μ W level. However, the absence of a bandgap in graphene restricts its usage in digital circuits on integrated circuits platforms for IoT applications. Semiconducting properties are still an open challenge for pristine graphene, and the semiconducting behaviour of a sensing material is a crucial factor for tuning the sensing characteristic of the sensor. So, another class of 2D materials, such as transition metal dichalcogenides (TMDCs) (shown in Figure 1.1) can easily be applied in switching applications due to their intrinsic bandgap [Chhowalla et al., 2013; and Samadi et al., 2018]. The bandgap of these materials can easily be tuned between 1.0-2.5 eV by changing the number of layers due to quantum confinement effect [Lu et al., 2016] as well as by numerous other techniques. Several TMDCs, such as MoS₂, MoSe₂, WS₂, WSe₂, and VS₂ etc., have shown their suitability for smart sensors and radiofrequency tags which are widely used for space, defense, security and IoT applications [Q. Zhang et al., 2018; and Liu et al., 2017]. On the other hand, from fabrication prospective, there have been developed many different techniques for growing high-quality 2D materials and their composites from two-approach, i.e., Top-down (e.g., mechanical/chemical exfoliation and sonication assisted exfoliation), Bottom-up (e.g.,

physical/chemical vapor deposition, wet-chemical process, and hydrothermal method). There are still some challenges for a reliable large scale growth of the 2D materials and production of sensing devices at the industry level.

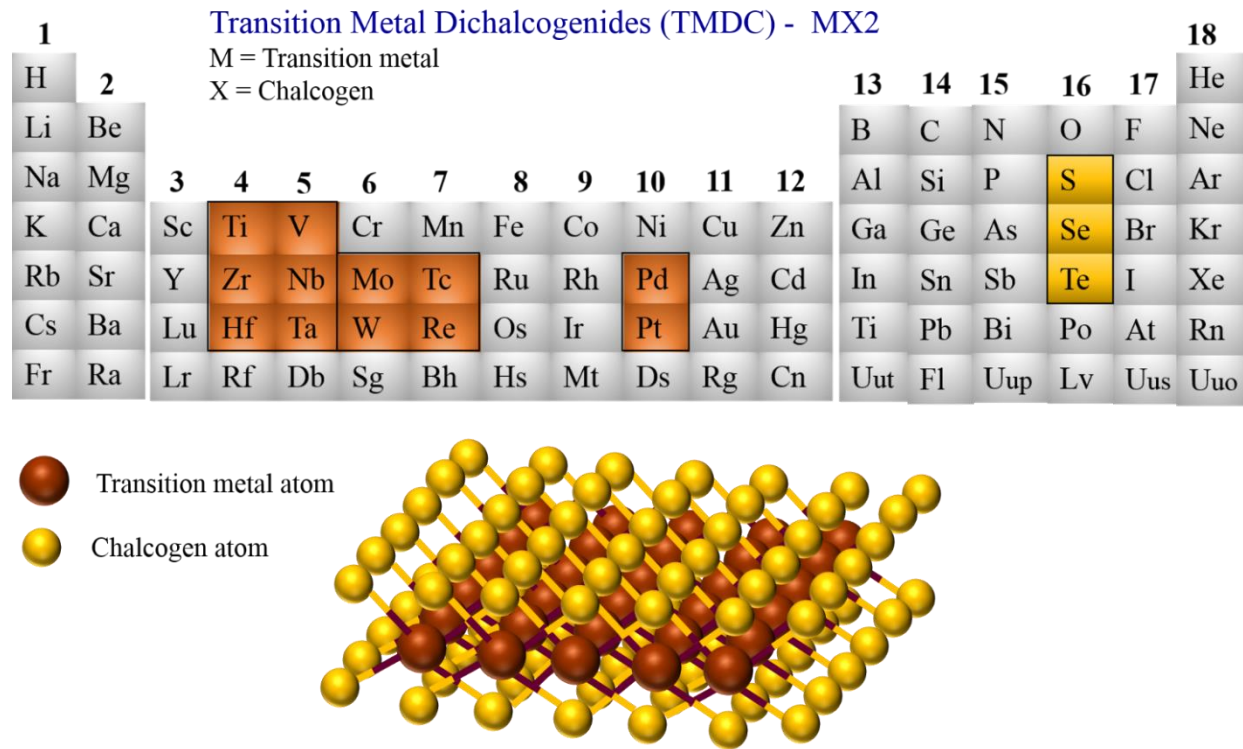


Figure 1.1: Transition metal dichalcogenides materials are layered materials and an example of 2D materials. Schematic representation of the crystalline structure of the layered transition metal dichalcogenides material.

2D MoS₂

Layered MoS₂ material is a prominent member of the TMDCs family owing to its remarkable electrical, mechanical, and chemical properties. A single layer of MoS₂ includes three planes, in which one plane of Mo atoms is sandwiched in between two planes of sulfur atoms and in multilayer MoS₂, different layers are connected through weak van der Waals forces, while in intralayer, Mo atoms are connected with sulfur atoms via strong covalent bonding (Figure 1.2 (a)) [Pan et al., 2012; Radisavljevic et al., 2011; and Ganatra et al., 2014]. The crystal structure of the MoS₂ is commonly classified into four types as 1H, 1T, 2H, and 3R based on coordination of Mo atom with six sulfur atoms and orientation of the MoS₂ layers in stacking, as shown in Figure 1.2 (c) [Benavente et al., 2002]. In the name of four polytypes of the MoS₂, digits 1, 2, and 3 represent a number of the MoS₂ layer in per unit cell and characters H, T, and R represent symmetry of the polytypes as hexagonal, tetragonal and rhombohedral, respectively. For example, 1T-MoS₂ polytype has one layer per unit cell, tetragonal polytype layered crystal and octahedral coordination of central Mo atom with six sulfur atoms (Figure 1.2 (b)). Moreover, the 1T phase is a metastable and metallic phase of the MoS₂, which has been potentially used in hydrogen evolution and other applications [Voiry et al., 2013; Lukowski et al., 2013; Acerce et al., 2015; and Attanayake et al., 2018]. However, 1H and 2H have one and two-layer per unit cell, respectively, hexagonal symmetry and trigonal prismatic arrangement of the six sulfur atoms with central Mo atom (Figure 1.2 (b))[Wilson et al., 1969]. Moreover, the 2H phase is a stable and have thickness-dependent electrical/chemical properties, so, 2H-MoS₂ has been widely recognized as a potential material for a variety of gas sensing applications [Late et al., 2013; and Cho et al., 2015]. The available large surface area promotes high chemical adsorption leading to a significant change in the obtained electrical signals, thus detecting the chemical molecules present even in very low concentration [B. Liu et al., 2014]. In particular, its

semiconducting properties help to integrate the sensor device into an integrated circuit (IC) through fabricating FET structure-based gas sensor. Moreover, its remarkable transparent and mechanical properties such as high strain up to 11 %, reinforce its potential to surpass current commercial sensors on a rigid substrate by a wearable sensor through excellent compatibility with a flexible substrate [Bertolazzi et al., 2011; and Castellanos-Gomez et al., 2012]. Hence, the MoS₂ based flexible gas sensor has also gained vast attention in sensing due to its applicability in advanced electronics such as the internet of things and flexible electronics. Besides the excellent gas adsorption, high adsorption coefficient and direct bandgap semiconductor aspects of the MoS₂ also make it a leading candidate for light sensing technology.

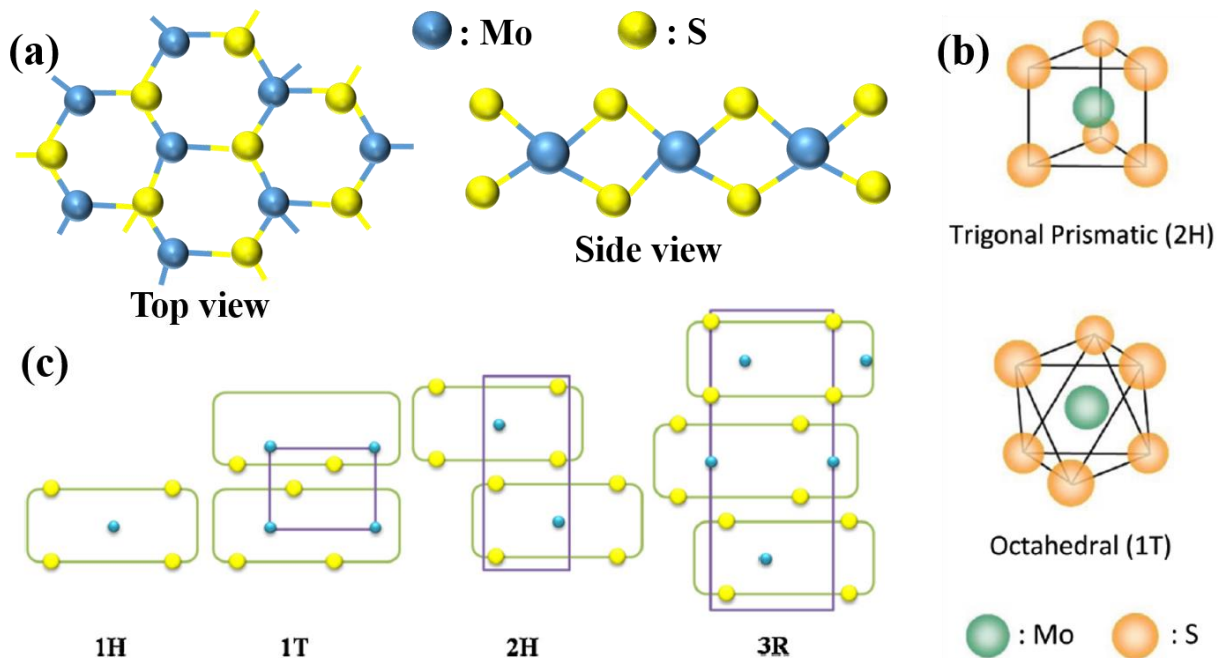


Figure 1.2: (a) Top and side view of MoS₂. (b) The lattice structure of 2H- and 1T-MoS₂. Reproduced with permission from ref. (Eda et al., 2011). Copyright © 2011, American Chemical Society. (c) Schematic representation of the different polytypes of MoS₂. Reproduced with permission from ref. (He et al., 2016). Copyright © 2016 Elsevier Ltd.

1.2 Gas Sensor

Gas sensor is an electronic device as a transducer which converts chemical information into an electrical signal. Gas sensor can be classified from two ways (1) based on sensor operating principle (2) material of sensing layer. In addition, it is very important in gas sensing field that gas sensing performance of the gas sensor can be modulated by changing the structures and morphologies of sensing layers.

1.2.1 NO₂ Gas Sensor

The detection of toxic and combustible gases has become essential to address global issues such as deteriorating environment pollution and hazardous industrial working conditions which affect human life directly [Yamazoe et al., 2005]. Especially, NO₂ is one of the most prominent toxic air pollutants and produced by combustion of fossil fuel, power plant, nuclear tests and automotive engines. Since, the inhalation of even low-concentration of NO₂ is immediately harmful to the human being, causing serious diseases like asthma, bronchitis and emphysema [Strand et al., 1997]. NO₂ is hazardous for human health even at a level greater than 1 ppm. It is also harmful to human and environment in terms of smog and acid rain. Smog is ozone which is synthesized in the environment when NO₂ dissociates in NO and O and then,

this O reacts with oxygen and forms ozone. Acid rain is HNO_3 which also form NO_2 after reacting of NO_2 with available water vapor in the atmosphere. Therefore, detection of parts per million (ppm) NO_2 is inescapable in the atmosphere. However, the detection of a lower concentration of NO_2 in the presence of other gases imposes a significant challenge. To meet this requirement, a highly selective and sensitive miniaturized gas sensor with fast response/recovery is desired, with the capability to operate in ambient conditions. In this regard, metal oxide nanostructures and one-dimensional (1D) semiconductors (carbon nanotube and Si nanowires) have been investigated to enrich the sensing performance of gas sensors from last decade [Strand et al., 2013; and Snow et al., 2006]. However, the operation of metal oxide sensor at high temperature ($>200\text{ }^\circ\text{C}$) and low surface area of 1D semiconductor emphasised to seek the new materials for sensing to avoid these problems. In recent years, several two-dimensional (2D) materials, for instance, graphene, phosphorene, WSe_2 , MoSe_2 , MoS_2 , etc, have attracted worldwide attention in sensing applications on miniaturized electronics device platform due to gas detection at room temperature without using any extra microheater and UV-light source. Graphene the most extensively studied 2D material has shown a response to even a single gas molecule due to its high surface-to-volume ratio, low electrical noise and high conductivity. Nonetheless, pristine graphene sensors exhibit poor selectivity. To date, selectivity is one of the major concerns to avoid wrong interpretation of the sensor due to the presence of many toxic gases simultaneously in the environment. Although, sensor technology has a trade-off among selectivity, sensitivity, and reversibility. Yet, selectivity remains a prerequisite for effective utilization of sensors in gas sensing.

1.2.2 Classification of Gas Sensor Based on Operating Principle

Figure 1.3 is illustrating the classification of gas sensors based on the sensor operating principle [J. Tang et al., 2017]. There are many gas sensor technologies for developing a gas sensor for desired gas sensing applications. External gas environment affects the optical, electrical, chemical and physical properties of the sensor materials and then a measurement of these effects directly or indirectly (some time sensor architecture help for detection) associated to the operating principle of the sensor. In this thesis, sensors were operating on change in electrical resistance under gas environment. In addition, each sensor technology has its advantages and disadvantages. This sensor technology is very easy to fabricate a sensor at a miniaturized level and it is also so cheap as compared to other sensor technology such as optical and electrochemical sensor technology.

1.2.3 Classification of Gas Sensor Based on Sensing Material

Sensing layer of the sensor can be made via different materials. Conductometry gas sensor made from metal oxide semiconductors such as SnO_2 , ZnO , TiO_2 etc and these materials is also using on commercial sensing plate form. However, these materials show a gas response at higher temperature $>250\text{ }^\circ\text{C}$, so, they need extra microheater for showing gas response at elevated temperature. Thus, no gas detection at room temperature is the main problem for metal oxide semiconductor materials. Conducting polymers exhibit gas response at room temperature, however, polymer sensors show less lifetime due to degradation of the polymer in air atmosphere as well as in humidity. Thus, new materials are required for showing stable gas response at room temperature. Detection of single gas molecules at room temperature by using graphene sensor in 2007 has been aroused immense interest in the exploitation of two-dimensional (2D) materials in gas sensing applications. 2D materials have shown great potential in gas sensing field as a result of its high surface-to-volume ratio, availability of most vibrant adsorption sites, and superb physicochemical properties. Detection of gases at room temperature is attributed to the charge transfer mechanism through electronics interaction between gas molecules and adsorption sites on the surface of 2D materials. This room-temperature operation removes the microheater from conventional solid-state gas sensor technology which also helps to develop a miniaturized battery operated gas sensor for advanced internet of things applications.

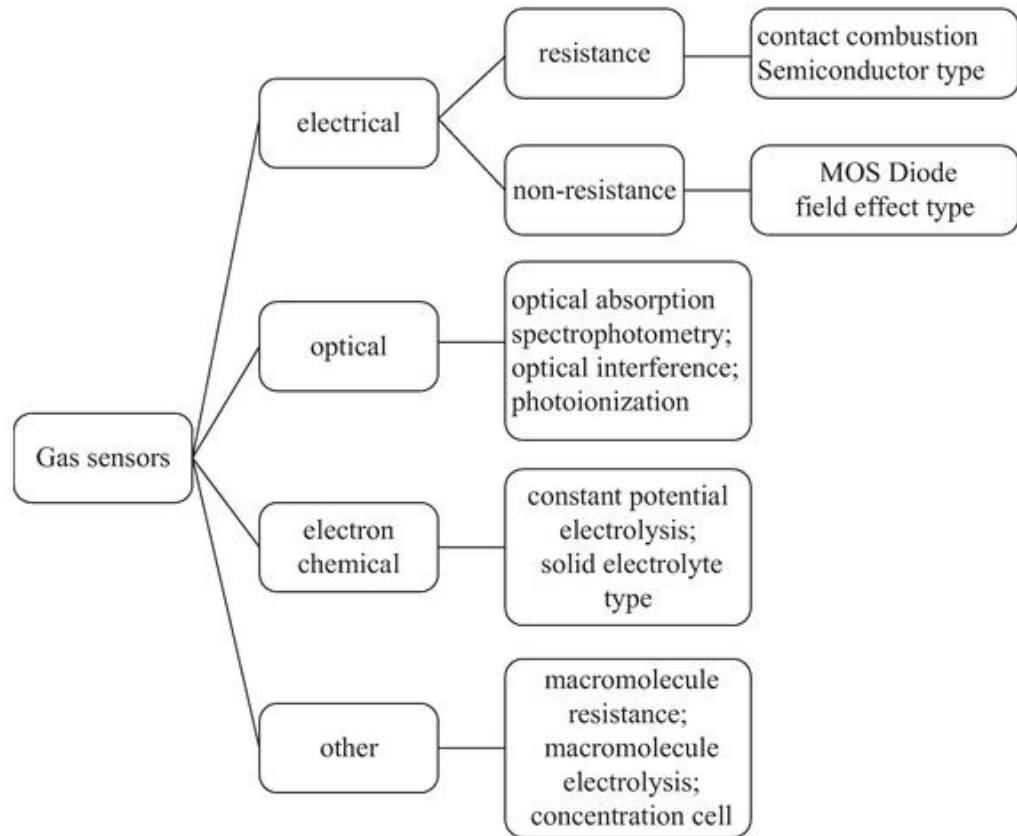


Figure 1.3: Classification of the gas sensor based on sensing operation principles. Reproduced with permission from ref (J. Tang et al., 2017).

1.2.4 Characteristics of Gas Sensor

These are following key gas sensor performance's parameters which are used for describing or comparing the gas sensing characteristics of the gas sensors. Here, all the parameters are described based on conductometric gas sensor which is used in this thesis work.

(a) Sensor Response/ Sensitivity

This parameter is called via two different names as sensitivity and sensor's gas response and here, in this thesis work, the relative response is used. Relative response/sensitivity is defined as the relative change in between resistance/voltage/current value of the sensor in target gas ambient and resistance/voltage/current value of the sensor in the air or before gas exposure. It is defined by the following expressions: - $(R_g - R_o)/R_o$, or $(V_g - V_o)/V_o$, or $(I_g - I_o)/I_o$ where R_g , I_g and V_g are the resistance, current and voltage in presence of target gas, respectively, and R_o , I_o and V_o are the resistance, current and voltage in presence of air or before target gas, respectively. Sensor response/Sensitivity of the gas sensor should be high.

(b) Response and Recovery Time

Sensor response time is that time at which sensor achieve a response from 10 % to 90% value of highest response under target gas ambient. Recovery time is that time at which sensor's response falls from 90 % to 10 % value of highest response during the gas desorption process. Response time and recovery time of the sensor should be low.

(c) Selectivity and Limit of Detection

The selectivity of the gas sensor is defined as the highest sensitivity to a particular gas against many other gases. Thus, the sensor would be selective to that particular gas. Sensor

should be highly selective to avoid any interference of other gases. Limit of detection of the gas sensor is the lowest concentration of a gas that can be detected by the sensor.

(d) Operating Temperature

It is a temperature at which sensor shows high and stable gas response even capable to detect the lowest concentration of the gas. Operating temperature of the sensor should be low.

1.3 Gas Sensing Mechanism of 2D Materials

The gas-sensing performance of a developed gas sensor strictly correlates to its sensing mechanism. Generally, the sensing mechanism of conventional metal oxide gas sensors depends on surface reaction performing in between target gas molecules and pre-adsorbed oxygen ions on the surface of metal-oxide [Nicolae Barsan et al., 2001]. Various kinds of oxygen ions (O_2^- , O^- and O^{2-}) are generated after extracting electrons from the conduction band of metal oxide by adsorbed atmospheric oxygen at different working temperatures [Wang et al., 2010; and Choopun et al., 2012]. In contrast, the sensing mechanism of 2D materials based gas sensors mainly depends on the charge transfer process in between target gas molecules and 2D materials [Yue et al., 2013; Ou et al., 2015; Huo et al., 2014; and Yu et al., 2015]. The direction of charge transfer depends on oxidizing or reducing nature of target gas analytes. In general, the oxidizing gas (NO_2) takes the electrons due to having an unpaired electron at its N atom, whereas reducing gas (NH_3) gives the electrons to materials because of one lone pair (Kong et al., 2000), as shown in Figure 1.4. Thereby, the electronic interaction of gas molecules and reactive sites of the material surface perturbs the charge carrier concentration, resulting in a change in conductivity (resistivity) of the 2D materials. Such a charge transfer process has already been verified by theoretical calculation (DFT) [Yue et al., 2013; and Shokri et al., 2016] and in-situ photoluminescence PL study [B. Cho et al., 2015].

Besides the direct charge transfer in between gas molecules and reactive sites, modulation of a Schottky barrier as well as built-in potential at the material/metal (electrode) interfaces upon exposure to gas also plays a crucial role for enhancing sensing performance [Wei et al., 2009]. In this case, a Schottky or an ohmic contact is formed at the interface of metal (electrode) and material, and which directly depends on the metal work function and electron affinity value of the material. For example, n-type MoS_2 (electron affinity ~ 4.2 eV) [Gong et al., 2013 and Fontana et al., 2013] and Au (work function ~ 5.1 eV) [Sze et al., 2007] form Schottky junction at their interface. Upon exposure to NO_2 , Fermi level of n-type MoS_2 moves towards the valence band because of electron extraction by NO_2 , thereby, built-in potential (V_{bi}) decreases. Meantime, a surface dipole layer forms at interface through negatively charged NO_2^- species and results in increase the Schottky barrier height, as shown in Figure 1.4 (ii) and results in decreased conductivity of the device [B. Liu et al., 2014]. That is vice-versa for the NH_3 adsorption.

On the other hand, incorporation of another material into 2D sensing material in terms of a hybrid or nanocomposite or van der Waals heterostructure makes a more complicated sensing mechanism. Apart from the above-mentioned sensing mechanism, integration of another material improves the sensing performance of the sensor through tuning of barrier height at the heterointerface between the constituent materials by adsorption of gas molecules [E. Lee et al., 2018]. For instance, Han et al. [Han et al., 2018] have proposed the sensing mechanism based on modulation of a developed heterojunction barrier potential at the ZnO/MoS_2 interface upon exposure to gas. The barrier potential was developed through formed depletion region at the interface, which was formed due to electron-hole diffusion for equilibrating the different Fermi levels of the ZnO and MoS_2 during contact formation, as shown in Figure 1.4 (iii).

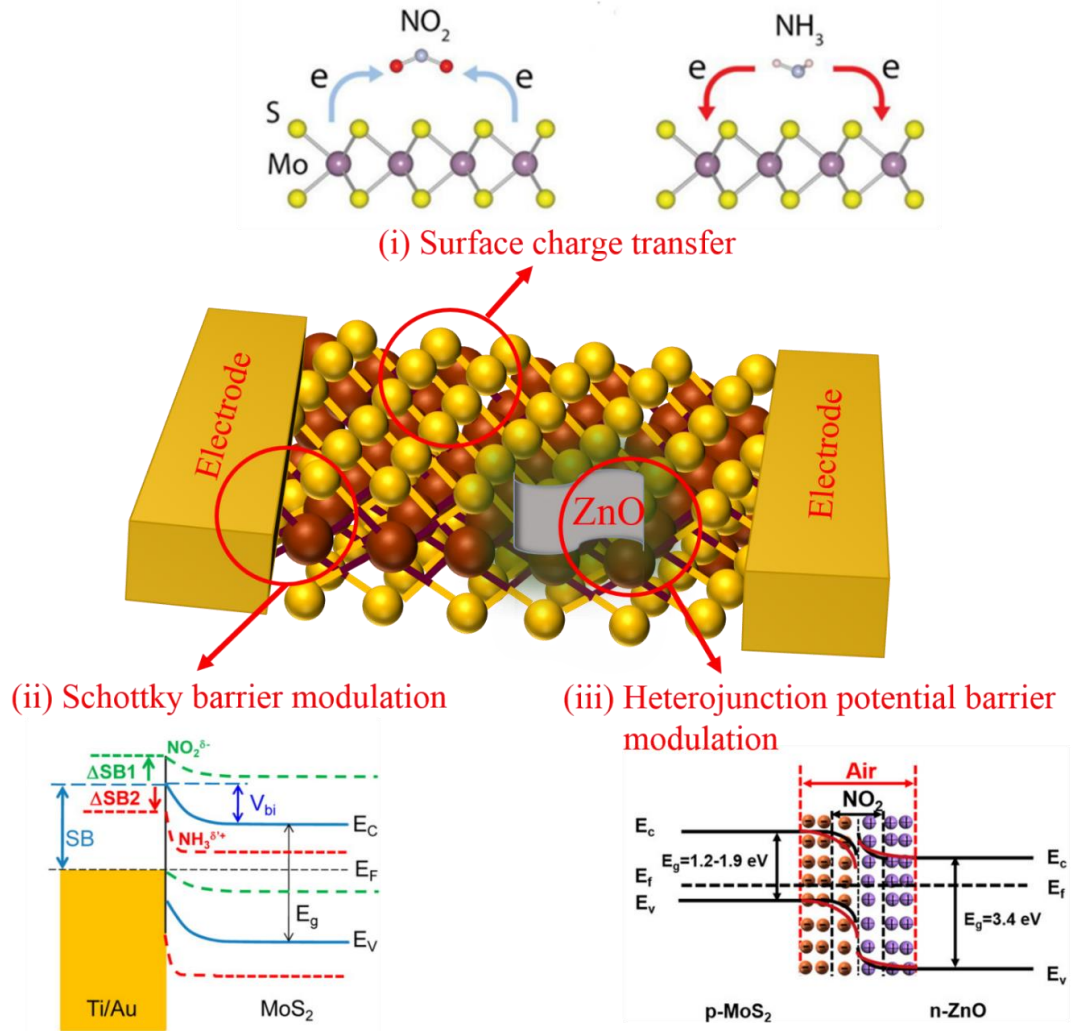


Figure 1.4: Schematic illustration of the gas sensing mechanism of 2D materials based gas sensor. (here, MoS₂ material, a famous member of the TMDCs family is only used for representation perspective) (i) Reproduced with permission from ref. (B. Cho et al., 2015). Published by Nature Publishing Group. (ii) Reproduced with permission from ref. (B. Liu et al., 2014). Copyright © 2014, American Chemical Society. (iii) Reproduced with permission from ref. (Yutong Han et al., 2018). Copyright © 2018, American Chemical Society.

The sensing mechanism of various mixed dimensional heterostructures of the TMDCs materials based on electronic and chemical sensitization can be read in more detail in Ref [E. Lee et al., 2018]. Proposed above all gas sensing mechanism for the 2D materials based gas sensors have been proved for improving the sensing performance via individual or synergistic effects. On the other hand, the discussion on the gas sensing mechanism of the different effects on gas sensing characteristics of the MoS₂ materials is given in detail in the following their respective sections.

1.4 Literature Review on MoS₂ Gas Sensor

The detection of a single gas molecule by the graphene gas sensor at room temperature motivated to explore the sensing ability of other 2D materials. Analogous to graphene, MoS₂ is most exploring 2D materials for gas sensing applications. In 2012, to explain the gas and MoS₂ interaction, Li et al. fabricated FET structure-based gas sensors from the single, bilayer, three-layer, and four-layer of the MoS₂ by using mechanical exfoliation. Upon exposure to NO gas, all MoS₂ sensors exhibited the decrease in current through charge transfer in between gas molecule and MoS₂, resulting in p-type doping effect for inherent n-type MoS₂. The high current response with a detection limit of 0.8 ppm NO gas of bilayer MoS₂ was similar to that of 3 and 4 layer

MoS₂. However, single-layer MoS₂ shown unstable current response over time. Likewise, to explain further the layer dependent sensing characteristic, Late et al. [Late et al., 2013] fabricated the FET gas sensor from single to multilayer MoS₂ using the same mechanical exfoliation method. They also observed a similar behavior unstable current overtime for monolayer and noted that gas sensing responses of three, four, and five-layer MoS₂ were comparable under exposure to NO₂ and NH₃ at room temperature. It was clear that five-layer MoS₂ exhibited higher sensitivity to gas than that of bilayer MoS₂. The resistance value of n-type MoS₂ was increased/decreased after adsorption of NO₂/NH₃ because the electron concentration of the MoS₂ was reduced/increased through the charge transfer mechanism. The oxidizing nature of the NO₂ with an unpaired electron on N atom helps to shift the Fermi level of the MoS₂ close to valance band through extracting the electron charge from the MoS₂. In contrast to NO₂ gas, NH₃ having a loan pair transferred the electron to MoS₂, however, there was no significant shift in the Fermi level of the MoS₂. Moreover, higher binding energy to NO₂ gas assists to more charge transfer between MoS₂ and NO₂ and less charge transfer in between MoS₂ and NH₃ owing to lower binding energy to NH₃. As a result, the MoS₂ sensor exhibited high sensitivity to NO₂ gas at room temperature. The charge transfer mechanism was elucidated by transfer characteristic (I_{DS} - V_{BG}) of the MoS₂ FET gas sensor. The exposure of the FET sensor with an increased concentration of NO₂ leads positive voltage shift in threshold voltage through extracting the electron from n-type MoS₂, resulting in high operating voltage for the transistor. However, increased concentration of NH₃ shifts the threshold voltage in a negative direction, and thus, the transistor will work at low voltage [B. Liu et al., 2014]. Furthermore, the charge transfer mechanism was also verified by performing in-situ PL experiment. The electronic interaction of NO₂ with MoS₂ converted the neutral exciton (A^0) into a quasi-particle trion (A^+) through creating hole after extracting an electron. However, NH₃ interaction dissociated the trion (A^+) into neutral excitons through rendering electron to MoS₂. Therefore, in PL spectra, A^+ peak intensity was increased/decreased after interacting the NO₂/NH₃ gas with MoS₂, respectively and vice versa for A^0 peak intensity [B. Cho et al., 2015]. In addition, the Raman experiment was performed before and after the gas exposure, which suggests no chemical reaction between gas molecules and MoS₂ through showing intact peak position of Raman active modes [B. Liu et al., 2014].

Further, Liu et al.[B. Liu et al., 2014] investigated that modulation of Schottky-contact between CVD grown monolayer MoS₂ and metal electrode (Ti/Au) under exposure to gases also plays a crucial role in enhancing the sensitivity of the MoS₂ sensor. Gas molecules produce surface dipole layer at the interface of electrode/semiconductor through exchanging the electron, resulting in modulation in the work function of both metal and semiconductor. Here, NO₂ took an electron from MoS₂ and formed NO₂^{δ-} charge, which increased the Schottky barrier height and reduced the built-in potential. They observed that Schottky contact-based MoS₂ sensor exhibited excellent sensitivity with detecting as low as 20 ppb NO₂ and 1 ppm NH₃ at room temperature. However, the MoS₂ gas sensor is unable to recover its initial base resistance value at room temperature, which restricts its use for practical applications. Room temperature energy is not suitable for giving energy above the threshold energy for desorbing gas molecules from the MoS₂ surface. Because, gas molecules such as NO₂, NH₃ have a strong binding with the MoS₂. So, an extra energy source such as optical or thermal is required for desorption of gas molecules. Moreover, several reports described that thermal energy is suitable to recover its initial base resistance value at the expense of sensitivity. Thermal energy increased the desorption rate of gas molecules by providing energy above the threshold value for accelerating the desorption process. Hence, high desorption and slow adsorption rate of gas molecules reduce the sensitivity of the MoS₂ at elevated temperature [B. Cho et al., 2015; Long et al., 2017; and B. Cho et al., 2015].

In addition to enhancing the sensitivity of the MoS₂ gas sensor, theoretical density functional theory (DFT) calculation inferred that charge transfer through electronic interaction is higher on edge sites compared to that of terrace sites of basal plane of the MoS₂. Edge sites, as

well as defect sites of the MoS₂, have a larger value of adsorption energy to gases [Yue et al., 2013; González et al., 2017; and Yu et al., 2015]. From that fact, to study of gas molecules interaction on different sites of the MoS₂, Cho et al. [Cho et al., 2015] fabricated horizontally and vertically aligned MoS₂ by rapid sulfurization of CVD process in 2015. They observed that vertically aligned MoS₂ shows five times higher sensitivity to NO₂ at room temperature than that of the horizontally aligned MoS₂. The exposed edge sites of vertically oriented MoS₂ assisted a large number of charge transfer in between gas molecules and MoS₂ through strong electronic interaction because of having high d-orbital electron density. However, growth of vertically oriented flakes on a substrate is a challenging task because edge sites on vertical flake have high surface energy. Agrawal et al. [Agrawal et al., 2017] fabricated the high-edge oriented 3D network of MoS₂ by using the particular arrangement 'tube in tube' CVD process. The interconnected edges behave as metallic wire, and sensor exhibited a fast response to hydrogen gas by detection at room temperature. To increase more numbers of edge sites, Li et al. [Y. Li et al., 2019] fabricated three different structures of the MoS₂, i.e., smooth, solid, and hollow sphere by using a hydrothermal method and evaluated the NO₂ sensing response. They observed that hierarchical hollow sphere of the MoS₂ exhibits higher sensitivity about 3.1 times than that of a smooth solid sphere. The high surface area and exposed active edge sites of hollow sphere enhanced the NO₂ gas response, as well as nanopores on the hollow sphere assist in diffusing NO₂ into deeper with reduced diffusion length. The deeper diffusion of NO₂ reduced the operating temperature and also enhanced the adsorption rate with increased NO₂ concentration.

Besides inorganic gas sensing, organic gas detection by the MoS₂ has also attracted attention on a chemical sensing platform. Perkins et al. [Perkins et al., 2013] evaluated the response of monolayer MoS₂ to a range of organic gas and provided a selective response mechanism for planar MoS₂. Weak n-type MoS₂ exhibited a higher and selective response to electron donors compared to low response to an electron acceptor. They explained the experimental result through molybdenum-sulfur hybridized orbitals in the monolayer MoS₂. In planar MoS₂ configuration, molybdenum Mo 3d_{xy} orbitals are responsible for forming Mo-S bond, and Mo 3d_{yz} are free in a perpendicular direction to the surface, while S 2p orbitals having localized lone pair are free above the surface plane. Because of different charge distributions, negatively charged Mo 3d_{yz} orbital was compensated by the positive charge of SiO₂ substrate, while a positive charge of S 2p was free for interactions with a strong affinity towards electron donor vapor.

On the other hand, besides inorganic and organic gas sensing, moisture detection by using the MoS₂ materials has also become an efficient tool for developing a humidity sensor for industry and our daily life applications. In past few years, humidity sensors were fabricated by using the MoS₂ nanosheets (2D MoS₂) and humidity sensing performance of the MoS₂ nanosheet was further enhanced via functionalizing MoS₂ nanosheet by platinum nanoparticle as well changing the morphology in terms of microsphere/flower through increasing specific surface area and surface active sites on MoS₂ nanosheet. To increase the more surface active sites and large edges to volume ratio, Yadav et al. [Yadav et al., 2019] fabricated the MoS₂ quantum dot (0D MoS₂) with an average size of ~5 nm via ultrasonication assisted liquid exfoliation technique and measured response at room temperature in relative humidity range (10-90 % RH). The sensor exhibited high response with fast response time and also showed high response even at low humidity with the negligible ageing effect. The humidity sensing performance of 0D MoS₂ was higher than that of 2D MoS₂ nanosheet because 0D MoS₂ provided more surface active sites for a large number of the interaction of water molecules through its large edges to volume ratio.

From the above gas sensing results, it is noticed that the gas sensing characteristic of the individual MoS₂ could be enhanced by morphology engineering. Different morphologies of the MoS₂ renders a various number of reactive sites and provide an opportunity to transfer a large

number of charge in between MoS₂ and gas molecules. However, individual MoS₂ still faces challenges of ultra-high sensitivity, fast response/recovery kinetics at room temperature as well as particularly, selectivity similar to metal oxide sensor through detecting more than one gas. So, to improve the selective sensing mechanism, many research efforts have been made for controlling the charge concentration with efficient doping of the MoS₂ by functionalization of novel metal nanoparticles [Suh et al., 2019; Cho et al., 2015; and Baek et al., 2017] and doping of transition metal nanoparticles [Zhang et al., 2017] as well as ligand conjugation [Kim et al., 2014]. Sarkar et al. [Sarkar et al., 2015] have demonstrated the electronic doping of the MoS₂ through functionalizing the surface of the MoS₂ with high or low work function metal nanoparticles. High work function noble metal (Au, Ag, Pt, and Pd) nanoparticles increased the p-type doping of innate n-type MoS₂ with increasing work function values, while low work function metal as yttrium (Y) induced n-type doping. The interfacing of metal nanoparticles tailors the charge concentration within the MoS₂ and also shows high affinity toward a particular gas, which leads to the selectivity of the MoS₂ sensor. Moreover, nanoparticles also enhance the sensitivity of the MoS₂ through the spillover effect. From this understanding, Kuru et al. [Kuru et al., 2015] reported a room temperature hydrogen gas sensor with fast response and recovery using a composite of the MoS₂ and Pd nanoparticles. Before H₂ exposure, high work function Pd increased the resistance value of the MoS₂ through inducing p-type doping, and after H₂ exposure, the work function of Pd was reduced by adsorption of H₂, thereby, this low work function of Pd leads to decrease the resistance value of the MoS₂ after recovering depleted electrons. Moreover, Pd functionalization increased the selectivity of the MoS₂ toward H₂ gas. Further, Cho et al. [Cho et al., 2017] reported that chemically exfoliated p-type MoS₂ shows a distinctly different response to organic vapors through controlled n-type doping effect of Au nanoparticles. It was observed that primitive p-type MoS₂ shown positive resistance change to all volatile organic compounds (VOC), while Au-doped MoS₂ exhibited positive resistance change to only hydrocarbon molecules and negative resistance change to oxygen-functionalized gases. Upon hydrocarbon molecules exposure, both p-type MoS₂, as well as Au-doped n-type MoS₂, exhibited small similar positive response due to dipole-induced scattering on the channel by the electron cloud of physisorbed VOC molecules [Cho et al., 2016; and Ma et al., 2012]. However, oxygen-functionalized VOC was chemisorbed on the MoS₂, and thereby hole concentration of p-type MoS₂ was impeded through the extraction of the hole by ethanol [Kim et al., 2014]. On the contrary, electron concentration was increased in n-type MoS₂ after injecting electron by the oxygen molecule of oxygen-functionalized VOC. As a result, different positive and negative responses to the same oxygen-functionalized VOC were observed by modulating the doping concentration of the MoS₂ by Au nanoparticles. Hence, decoration or doping of the MoS₂ by metal nanoparticles leads to an improvement in response and selectivity of the sensor.

From the above results, it is noticed that mostly gas sensing experiments were performed in inert ambient (Ar, N₂ environment), which restricts the MoS₂ for practical gas sensing in an air atmosphere. Because oxygen in air ambient strongly influenced the properties after adsorbing on the surface of the MoS₂ as well as leads to instability of the MoS₂ sensor [Park et al., 2013; and Qiu et al., 2012]. Besides the stability in air atmosphere, incomplete recovery at room temperature of the MoS₂ sensor was still an unresolved issue after functionalizing/doping of metal nanoparticles. To overcome these problems, Cui et al. [Cui et al., 2015] reported high-performance NO₂ sensing in an air atmosphere at room temperature by using MoS₂/SnO₂ nanohybrids. In this work, n-type SnO₂ nanoparticles distributed over the MoS₂ surface, which served as major gas adsorption centres as well as p-type dopants for the MoS₂, resulting in p-type behavior of the MoS₂/SnO₂ nano-hybrids. The sensor exhibited a stable response to NO₂ gas in air atmosphere and also shown complete recovery at room temperature without using any extra stimuli (light source or temperature). On the contrary, pristine MoS₂ shown unstable response and incomplete recovery to NO₂ in an air atmosphere at room temperature. As a result, the stability of the MoS₂ sensor in the air was achieved after decorating the SnO₂ nanoparticle because SnO₂ particles generated a passivation layer on the surface of the MoS₂,

which stop the interaction of oxygen with the MoS₂. Moreover, the MoS₂/SnO₂ nanohybrids sensor exhibited the excellent selectivity to NO₂ gas. In addition, the MoS₂/SnO₂ nanocomposite based sensor also showed ultrahigh sensitivity with ultrafast response and recovery time to humidity at room temperature [Zhang et al., 2016]. The unprecedented sensing performance of the MoS₂/SnO₂ nanocomposite was reported ten times higher than that of the conventional humidity sensor. This excellent sensing characteristic of the sensor was attributed to a synergistic effect of the MoS₂ and SnO₂, and in MoS₂/SnO₂ nanocomposite based sensor, SnO₂ nanocrystal served as adsorption centres for interacting more water molecules and MoS₂ acted as an anchor in nanocomposite as well as played an active role in eliciting humidity response.

Further, Han et al. [Han et al., 2018] demonstrated the NO₂ sensing of a MoS₂/ZnO hetero-nanostructures at room temperature in air ambient. A fabricated p-n type hetero-nanostructures of the MoS₂/ZnO shown an extraordinary sensitivity of 3050 % to 5 ppm NO₂ and detected as low as 50 ppb NO₂. Moreover, the sensor exhibited a stable response with reliable long-term stability and a fast response time of 40 s with complete recovery at room temperature. The gas-sensing performance was enhanced by a synergistic effect of the enlarged specific surface area of the MoS₂ by ZnO nanoparticles decoration and modulation of potential barriers at the interfaces of the MoS₂/ZnO under gas environment. In this work, MoS₂ and ZnO are p- and n-type semiconductors. Due to different Fermi levels, electron diffusion into the MoS₂ or hole diffusion into the ZnO form a depletion region at the interface for achieving equilibrium state of the Fermi levels. Upon NO₂ exposure, electrons were extracted from the ZnO surface and thereby, a disturbed electric field at the interface formed a new equilibrium through an accumulation of hole at the MoS₂. Accordingly, it contributes to a reduction of the width of the heterojunction barrier, which enhanced the conductivity of the MoS₂/ZnO hybrid.

Besides the two materials hybrid, several tri-materials hybrids such as PANI/MWCNT/MoS₂, [Zhang et al., 2018] Pd-TiO₂/MoS₂, [Zhang et al., 2018] Pt-TiO₂/MoS₂, [Luo et al., 2018] rGO-MoS₂-CdS, [Shao et al., 2019] and Ag-ZnO-MoS₂ [Zhang et al., 2017] have also used for enhancing the sensing performance of the MoS₂. Li et al. [Li et al., 2017] reported the enhanced trimethylamine (TEA) sensing of the MoS₂ by synthesizing tri-material hybrid as Au@SnO₂/MoS₂. In this work, SnO₂ nanoparticles were deposited on the MoS₂ flowers by a pulsed laser deposition process and later, Au nanoparticles were deposited on the SnO₂/MoS₂ flower via a sputtering. The Au@SnO₂/MoS₂ sensor shown higher sensitivity to TEA with fast response/recovery time compared to that of pristine MoS₂ and SnO₂/MoS₂ hybrid. The improved sensing performance of the designed Au@SnO₂/MoS₂ nanostructures was attributed to modulation of two different junction potentials as Schottky contact at Au@SnO₂ and n-n type heterojunction SnO₂/MoS₂ under gas environment.

Friedman et al. [Friedman et al., 2014] measured the responses to a variety of analytes based on a MoS₂ field-effect transistor (FET) device and studied the effect of illumination on the sensing response for the first time. The MoS₂ thin films were exfoliated from bulk using the scotch tape as the channel materials. Ti/Au was deposited as the large wire-bonding contacts, while the Au was deposited along to contact the MoS₂ and the optical image of the FET device. The device was exposed to a variety of chemical vapor compounds and found that it had the strongest response for triethylamine (TEA). In order to determine the effect of illumination on the sensitivity of MoS₂ sensors, they measured the sensing behavior with and without illumination. The results represented a 10-fold increase of the sensitivity with white light illumination. However, the mechanism of the sensing abilities enhancement of the device by illumination is still unclear. Therefore, more studies attempt to explain the reason for the light assisted enhancement of the gas sensor properties. In addition to NO₂ and TEA, MoS₂ gas sensor also has a good response to NO under light illumination. For example, Ramu et al. [Ramu et al., 2019] found that atomic MoS₂ sensor exhibit a response of about 25% at RT, and improved response (70%) was observed to NO gas under UV light ($\lambda=254\text{nm}$).

Although previous research reported an enhanced response and proposed sensing mechanism of MoS₂ on NO, NO₂ and TEA exposure with illumination throughout the sensing process, the recovery mechanism under illumination is still unclear. Kang et al. [Kang et al., 2019] proposed a recovery mechanism for MoS₂ under UV-LED illumination. On exposure of the sensor to NO₂ molecules, they captured electrons from MoS₂ and were preferentially absorbed in the NO₂ (ads.) form on the edge of MoS₂. They believed that the UV-LED illumination could generate the electron-hole pairs in MoS₂, and the photo-generated holes could react with absorbed NO_2^- . Resulting in NO₂ desorption from MoS₂ via a change in its chemical state from absorbed ion to gas. Agrawal et al. [Kumar et al., 2018] reported a photoactivated highly reversible and fast detection of NO₂ sensor at room temperature (RT) by using mixed in-plane and edge-enriched p-MoS₂ flakes. The mixed MoS₂ flakes were synthesized on a SiO₂/Si substrate by the modified atmospheric pressure chemical vapor deposition (APCVD) technique. Corresponding 3D schematic NO₂ gas sensor from mixed MoS₂ flakes. As is known, the interaction of the gas molecules completely depended on the adsorption energy on the surface. Another important parameter is the charge transfer and adsorption site between the gas molecule and the MoS₂ flakes. To understand their experimental finding, they used the density functional theory (DFT) calculation. The very high adsorption energy of the NO₂ gas at the H-site the T_M-site, and the B-site made the device faster, more sensitive, and more selective for the NO₂ gas molecules even at RT. In the case of MoS₂, the edges possessed highly active sites in the form of the S vacancy and oxygen adsorbed on the S vacancy and formed O²⁻ ions. When the device illuminated with the UV light, which revealed greater removal of the adsorbed O²⁻ ions due to the UV light and which lead to the availability of fresher sites increases NO₂ gas molecule adsorption, and thus the sensitivity is increased in the presence of the UV light at RT.

However, the sensitivity of above-mentioned gas sensors is still at ppm-level. To further improve the gas sensitivity, the structures of the materials need to be improved and some appropriate measures must be applied, such as morphological adjustment, surface modification, forming heterogeneous structures. At present, there are a series of studies on this aspect to realize the improvement of gas-sensitive properties to reach the ppb level. Chen et al. [Chen et al., 2019] by controlling the morphology and structure of MoS₂, for the first time, demonstrated an indoor light-activated 3D cone-shaped MoS₂ bilayer-based NO gas sensor with ppb-level detection operated at room temperature. This is the first report of manipulating a 3D structure as well as a photochemical reaction for advancing performance of a gas sensor. Compared with the flat structure, the 3D architecture MoS₂ combined the advantages of both enhanced light absorption and photo-desorption. As a result, the response of 3D architecture MoS₂ gas sensor is nearly twofold stronger than that of the flat sensor upon illumination with UV light of 365 nm wavelength. The results exhibited the gas sensor had the potential to detect ultra-diluted (0.06 ppm) NO gas with 200% response under UV light with a wavelength of 365 nm. Moreover, Zhou et al. [Zhou et al., 2018] reported a UV light-assisted, room-temperature, recoverable, sensitive and selective NO₂ gas sensing based on few-layer MoS₂ nanosheet-Au nanoparticle composites serving as the sensing layer. Better performance in terms of three-time enhanced response, full recovery and favourable repeatability was achieved in comparison with that in the dark case. In this work, their combined band diagram relationship with p-doping resulting from the foregoing formation of Au nanoparticles as well as an eventual exhibition of p-type properties, they inferred that p-doping predominated over n-doping. The incorporation of Au nanoparticles not only increased the number of active adsorption sites but also enhanced the diffusion and transfer rate of adsorbed species from an active site to inactive sites. When the sensor exposed to the UV light, Au nanoparticles trapped more incident lights. Furthermore, the mismatch of work functions between MoS₂ and Au was so tiny that the charge carriers readily transferred through the contact interfaces, thereby improving the recovery characteristics in terms of recovery speed and restoration degree. Hence, decoration or doping of the MoS₂ by metal nanoparticles changed the bandgap, resulting in an improvement in response and selectivity of the sensor under illumination.

Heterostructures, combining different materials, show bandgap offset and tunable electrical and optoelectrical properties, which play a crucial role in modern microelectronics and optoelectronics. However, there are few reports of photoelectric gas sensors based on MoS₂ heterogeneous structure and still in the initial stage. Zhou et al. [Zhou et al., 2018] reported a UV assisted ultrasensitive trace NO₂ gas sensor based on few-layer MoS₂ nanosheet-ZnO nanowire p-n junctions at room temperature. The sensing response attained 8.4 and 188, toward 50 ppb and 200 ppb NO₂ with a full recovery under UV illumination. At the meantime, the sensor exhibited a sensitivity of 0.93 ppb⁻¹ and a detection limit of 50 ppq. On the one hand, p-n heterojunctions improved the electron-hole separation under UV illumination. On the other hand, it would be formed a built-in field and the photoexcited electrons on the conduction band of the MoS₂ could readily transfer to that of the ZnO, while the exciting holes on the valence band of ZnO transferring to that of the MoS₂. Therefore, the photogenerated charge carriers could be separated efficiently at the interface, prolonging the lifetimes, hindering the recombination, and eventually improving the sensing capabilities.

Moreover, recent studies [Pham et al., 2019] on heterogeneous structure light-enhanced gas sensors formed between MoS₂ and graphene have a limit of detection ~100 ppt, creating a precedent for two-dimensional heterogeneous junction photoelectric gas sensors. They found that under red light illumination, Au/MoS₂/Au optoelectronic gas sensor showed a significant enhancement of the device sensitivity S toward ppb level of NO₂ gas exposure reaching $S=4.9\%/ppb$ (4900%/ppm). Contrast with Au/MoS₂/Au structure device, further optimization of the MoS₂ based optoelectronic gas sensor by using graphene (Gr) electrodes coated by Au forming Au/Gr-MoS₂-Gr/Au device, the limit of detection of NO₂ gas at the level of 0.1 ppb.

1.5 Motivation

The rapid growth of industry and road transportation in the past decades from an increasing human population has increased toxic gases into the atmosphere. Air pollution damages the human brain through impairing cognitive ability and results in problems for making a decision as well as performing daily errands [X. Zhang et al., 2018; and Zivin et al., 2012]. Moreover, millions of people die per year as a result of inhaling polluted air as quotes World Health Organisation. These facts have aroused vast attention for air quality monitoring in the past few years to save both humans and the environment. A gas sensor one of the vital electronic devices is needed for detecting hazardous inorganic (NO₂, NO, NH₃, H₂, CO₂, etc.) and organic (methane, triethylamine, benzene, etc.) gases [Timmer et al., 2005; Xianghong Liu et al., 2017; Binions et al., 2013; Xiao Liu et al., 2012; Stetter et al., 2008; and Hübert et al., 2011]. Moreover, the gas sensor has also shown its immense presence in various applications such as industry and agriculture processing, aerospace, military, and medical diagnosis [Kohl et al., 2001; Arshak et al., 2004; Yunusa et al., 2014; and Yamazoe et al., 2005]. For this motive, a variety of sensor technology such as conductometric, optical, electrochemical, thermoelectric, and acoustic have been utilized for gas sensing from the last 50 years [Korotcenkov et al., 2014; Baron et al., 2017; Bogue et al., 2015; Askim et al., 2013; Ifsa et al., 2014; Korotcenkov et al., 2009; Drafts et al., 2001; and Bănică et al., 2012]. Among these, semiconductor-based resistive/field-effect transistor (FET) sensor has prime potential in sensing technology because of its easy fabrication process, low cost, desired miniaturization, and integration with conventional integrated circuit technology [Balouria et al., 2013; Andringa et al., 2014; Kumar et al., 2017; Ramgir et al., 2013; and Chiu et al., 2013]. The key figures of merit, such as ultimate sensitivity and detection at room temperature in chemical sensors could easily be achieved by using atomically thin layered 2D materials. In particular, the detection of target gas molecules at room temperature removes the micro-heater from the conventional gas sensor and making them as energy-efficient materials after reducing the consumption power from several hundreds of mW to μ W level. The 2D materials have a great potential to substitute the matured metal oxide gas

sensor technology on a gas sensing platform owing to the detection of target gases at room temperature as well as their extraordinary flexible, transparent and stretchable properties.

1.6 Objective

Since the first metal oxide-based gas sensor in 1960, a metal oxide semiconductor has been becoming a core for propelling gas sensor technology [Ihokura et al., 2017]. Many reviews and some book chapters described the gas sensing behavior of the individual metal oxide semiconductor, heterostructure, surface functionalization and micro- and nanostructure of metal oxides [Sun et al., 2012; N. Barsan et al., 2007; C. Wang et al., 2010; Miller et al., 2014; Eranna et al., 2004; Eranna et al., 2016; Mazloom et al., 2014; and Jun Zhang et al., 2019]. Moreover, a metal oxide semiconductor has been exploited in gas sensing on the commercial application platforms. Despite, there are still some unresolved issues in this technology, which challenge the metal oxide-based gas sensor for its practical limitations. The operation of the gas sensor at high temperature ($>200\text{ }^{\circ}\text{C}$) is one of the significant issues, that restricts its utilization in a risky environment because of an explosion of combustible gases at elevated temperatures. That also increases the complexity, size and power consumption of the sensor through the integration of microheater with the sensing layer. Moreover, variation in the microstructure of the metal oxide at high temperature degrades the sensitivity and stability of the sensor. Some other issues, such as baseline resistance drift, poor selectivity, and humidity effect also observed in this type of sensors. Some research endeavours addressed these problems and motivated further developments through optimizing the material structure, surface modification of sensing material and using different fabrication techniques. It is important to note that all these processes stem from modification of quality of the sensing material. Thus, a design of a new novel sensing material and adopting reliable fabrication techniques for integrating into existing industry technologies, are primary for improving the 4S aspects of a gas sensor, i.e., sensitivity, selectivity, stability and speed (response/recovery time) as well as for detection of gas molecules at or close to room temperature. On the other hand, some other crucial aspects such as flexible, wearable, wireless, and small size have also demanded in recent years for the advent of Internet of Things and flexible electronics [Potyrailo et al., 2016]. Besides, recent progress of nanoscience and nanotechnology has sparked scientific and technological interest in gas sensing technology for miniaturizing the device with enhanced sensing performance using new low dimensional materials. From the energy point of view, the 2D TMDCs materials-based gas sensors consume less power in μW level compared to the commercially available metal oxide gas sensors (several tens of mW level). Besides reduced power consumption after removing the extra heating element from the sensor, this disintegration of the heater makes a simple design for chemiresistive gas sensor through minimizing complexity and also provides a simple and small footprint for the integration of the sensor into IC technology with CMOS compatibility. Moreover, low power consumption helps to reduce the thermal effects on the human body as well as increases long-term operation.

In this thesis work, the author aims to:

- Develop and optimize a CVD process for fabrication of different nanostructures or morphologies of MoS_2 in large scale area over the different substrate.
- Spectroscopic and microscopic characterizations of CVD grown different nanostructures or morphologies of MoS_2 at room temperature.
- Investigate the stability of the as-synthesized MoS_2 thin films on the substrate in air ambient for stability or lifetime of the device.
- Study of gas sensing characteristic of different adsorption sites on MoS_2 through forming different nanostructures such as horizontal, vertical and nanowires.

- Exploit defect and interface engineering in gas sensing field after fabricating a gas sensor by rGO functionalized vacancy containing MoS₂.
- Study the gas sensing performance of the fabricated gas sensor of the hybrid of the MoS₂.
- Detection of NO₂ gas at room temperature without using any extra heating element or light source in an air atmosphere.
- Explore the role of MoS₂ in light sensing.

1.7 Outline of Thesis

This thesis work includes gas and light-sensing applications of CVD grown MoS₂. Figure 1.5 illustrating the schematic diagram of several strategies which are adopted for developing a gas sensor using MoS₂ in this thesis work. In the last part of thesis, we also described the light-sensing application of the MoS₂. Outline of this thesis is described below.

Chapter 1: This chapter described a brief introduction about two-dimensional materials, in particular, MoS₂ for sensing applications. Firstly, gas sensors were explained with their comparison in the context of the operation principle, and sensing materials. The gas sensing mechanism of 2D materials was also elucidated. Then, brief literature review on MoS₂ gas sensors followed by motivation, objective and outline of the thesis was mentioned.

Chapter 2: This chapter involved deposition techniques and different characterization techniques for examining morphology and structural properties. In addition, gas and light-sensing characterization systems which are used in this thesis work are described.

Chapter 3: This chapter focused on exploring the role of different adsorption sites of the CVD grown MoS₂ in gas sensing application. In this regard, sensing behavior of different nanostructures such as horizontal, vertical aligned flakes and nanowires network of MoS₂ were studied at different temperatures.

Chapter 4: In this chapter, firstly, change in morphology and semiconducting properties of the MoS₂ after defect and interface engineering are explained. Later, defect and interface engineering effects in gas sensing of CVD grown MoS₂ are described with a proposed gas sensing mechanism.

Chapter 5: This chapter described the gas sensing behavior of MoS₂ gas sensor under UV-light irradiation. A comparative study of gas sensing characteristics of MoS₂ under light and thermal energy sources with proposed sensing mechanism is also introduced.

Chapter 6: This chapter focused on the fabrication of MoS₂-MoO₃ hybrid micro flower for sensing application. The growth mechanism of nucleation controlled one-step process to synthesize MoS₂-MoO₃ hybrid micro flowers using vapor transport process was described. The exact position of MoS₂ and MoO₃ in as-synthesized hybrid micro flower film was explained. Later, gas sensing behaviour of MoS₂-MoO₃ hybrid micro flower was studied for NO₂ gas at room temperature with explaining proper sensing mechanism.

Chapter 7: In this chapter, light-sensing behavior of the 2D MoS₂ in the visible range wavelengths was described by fabricating a vertical out-of-plane van der Waals heterojunction

of the MoS₂ and rGO. Moreover, light-sensing mechanism also proposed with the help of photoexcited enhanced carrier density and photogating effects.

Chapter 8: In this last chapter of the thesis, we summarized this thesis work and also described the future scope of this work. Moreover, challenges and future perspective in the emerging MoS₂ research in sensing applications were also explained.

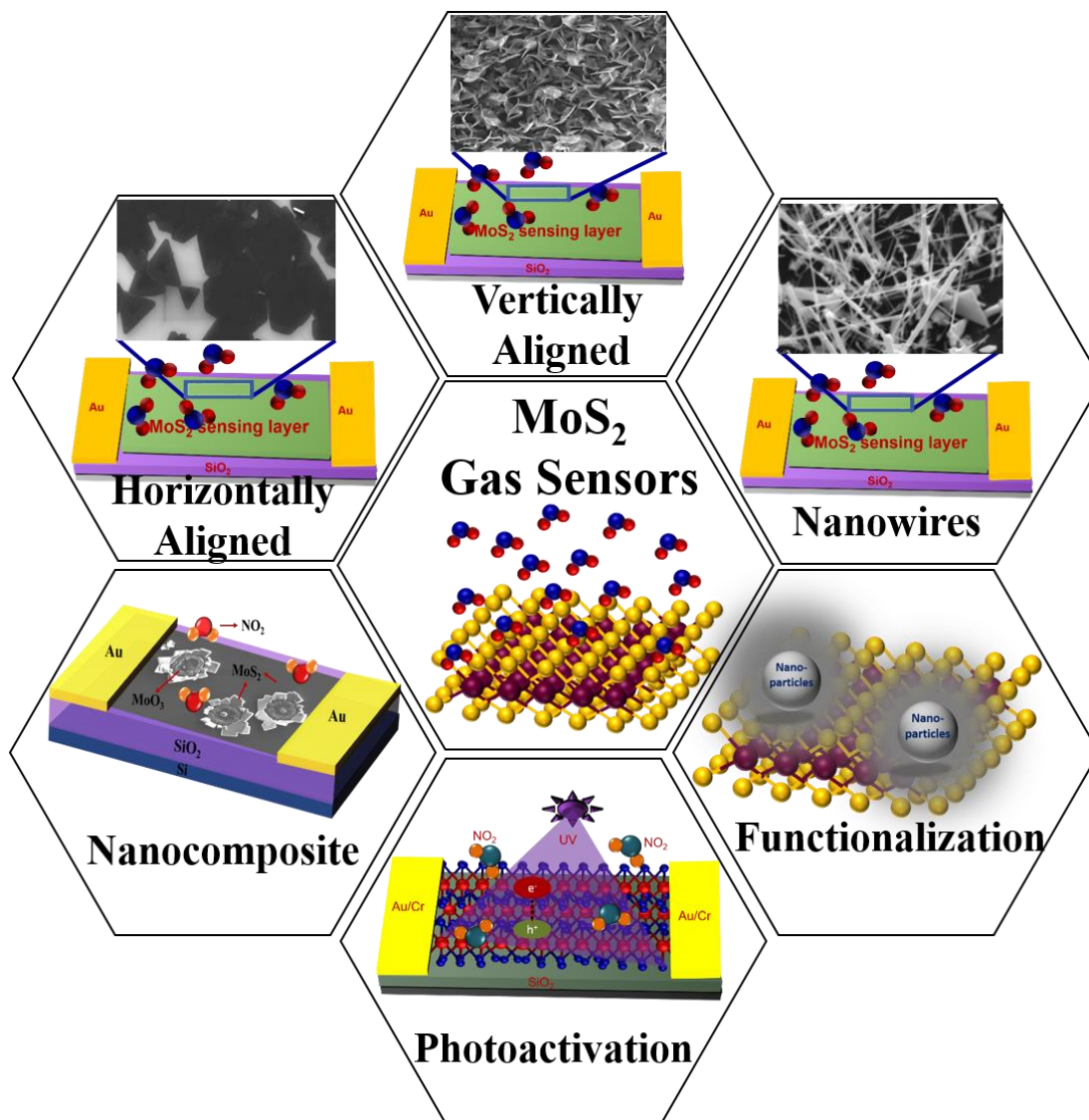


Figure 1.5: Schematic illustrating the several strategies adopted for developing a gas sensor using MoS₂ in this thesis work. First, Gas sensors were fabricated by using different nanostructures including Horizontal MoS₂, vertically aligned MoS₂ and MoS₂ nanowires networks. Second, rGO functionalized sulfur vacancy containing MoS₂ based sensor. Third, Photoactivated MoS₂ based sensor. Fourth, the Gas sensor was fabricated by CVD grown MoS₂-MoO₃ hybrid.

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