Fabrication and characterization of MOS$_2$/WS$_2$ van der waal’s heterostructure

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Abstract

Ultrathin graphene-like two-dimensional (2D) transition-metal dichalcogenides (TMDCs) due to their fundamentally intriguing properties, have attracted a wide range of research interest in recent days. Combining different materials to obtain the elite properties of each compound and tuning them according to the prerequisite has been the grounds for the successful fabrication of a number of novel devices. In such a manner, various 2D materials can be combined to concoct new devices for various applications. MoS$_2$ and WS$_2$ are two such TMDCs with excellent electronic and optical properties. Since these are atomically thin layered materials and are held by a weak van der Waals force, it is easier to peel them apart to form thin sheets, and hence the combined arrangement of different materials is named as van der Waals heterostructure. Our motive is to use the mechanical exfoliation technique, which can yield a highly crystalline, atomically thin layer of TMDCs (MoS$_2$ and WS$_2$). These layers are stacked one above the other to form van der Waals heterostructure, whose fundamental properties are studied in detail. The morphological and topographical properties are investigated using several microscopic techniques’ data. Its optical and vibrational properties are scrutinized from various spectroscopic techniques. The data we acquired from optical imaging and Raman scattering gives an insight into the thickness and edge effects of the flake. The absorption spectrum of MoS$_2$, WS$_2$, and their heterostructure reveal several interesting properties of the electronic band structure. These properties can then be explored and incorporated practically in several fields to fabricate energy storage devices, flexible and transparent electronics, thin electronics, switching devices, photodetectors, etc.

Keywords: Two-Dimensional Material, Transition-metal Dichalcogenide, Heterostructures, van der Waals force, Molybdenum Disulfide, Tungsten Disulfide.

Introduction

After the revelation of graphene by Novoselov et al. (2004) for which they were granted the Nobel Prize in 2010, the transition metal dichalcogenide (TMDC) materials experienced a resurrection. Graphene possesses excellent electronic and thermal conductivity making it an ideal material for a large group of applications and eventually sparked significant interest in other two–dimensional materials (2D) materials. 2D TMDCs can be easily exfoliated, show extremely intriguing electrical and optical properties, and open up novel opportunities for developing thin devices (Joensen et al., 1986; Frindt, 1966; Ramakrishna Matte et al., 2010). When compared to their 3D equivalent, 2D materials have vastly different mechanical, chemical, optical, and morphological characteristics such as the 2D material-like graphene behaves as a zero–overlap semimetal, Niobium diselenide (NbSe$_2$) behaves as a metal, Molybdenum disulfide (MoS$_2$), Tungsten disulfide (WS$_2$) behaves as a semiconductor whereas the Hexagonal Boron Nitride (h–BN) possess insulating properties (Novoselov et al., 2016).

One of the important properties of 2D materials is their transparent and mechanically deformable nature. Graphene is reported to possess high transparency of 97.7% transmittance in the visible spectrum (Wassei and Kaner, 2010; Li and Zhu, 2015). In graphene, the valence and the conduction band are symmetrical about the Dirac point (Koroteev et al., 2011). Hence the Fermi surface lies at the point of intersection of valence and conduction bands, making it a zero–bandgap material ((Novoselov et al., 2004; Soldano et al., 2010). This property contributes to the high electrical conductivity of graphene but simultaneously limits
its application in switching devices, which contributes to modern-day electronics. So, there arises a need to find the existence of similar 2D materials that are transparent and flexible possessing a considerable band gap overcoming the shortcomings of graphene (Ganatra and Zhang, 2014). Several transition–metal dichalcogenides materials can fulfil this requirement.

Transition metal compounds like molybdenite (MoS$_2$) are abundantly occurring compounds on the earth’s crust. The TMDCs in their bulk form will exhibit an indirect band gap while their 2D form will possess a direct bandgap. This bandgap shift from near-infrared to the visible range makes it suitable for various optoelectronic and switching applications (Jariwala et al., 2014).

Each 2D material possesses excellent electrical, thermal, and optical properties, therefore, can be used in a wide range of applications. For making certain devices with enhanced performance, the best of the materials can be combined together, such combinations are called heterostructures. 2D materials provide a platform to create such heterostructures with a variety of properties (Zhang et al., 2020). Since each layer in the TMDCs is held together by a weak van der Waals force, it is easier to exfoliate the layers of different materials and make heterostructures, hence the name van der Waals heterostructures. Since MoS$_2$ and WS$_2$ have outstanding electrical, optical, mechanical, and thermal capabilities, they are employed to create van der Waals heterostructures. Because heterostructures of 2D materials in diverse combinations are employed in a variety of applications, there is a need for fundamental characterization of both individual 2D materials and their heterostructures. MoS$_2$ is a semiconductor having an indirect band gap of 1.23 eV in its bulk form and a direct bandgap of 1.85 eV in its single-layer form (Ellis et al., 2007). WS$_2$ undergoes a similar bandgap transition, i.e. the bandgap shifts from indirect 1 eV to direct 1.8 eV (Zhao et al., 2013a). Due to this property, MoS$_2$ and WS$_2$ absorb and emit light, making them unique materials for optoelectronic devices and photodetectors. The electronic band structure changes when the heterostructures are formed with 2D MoS$_2$/WS$_2$. Both MoS$_2$ and WS$_2$ monolayers are direct bandgap semiconductors with the valence band maximum and the conduction band minimum located at K–points, but MoS$_2$/WS$_2$ heterostructures exhibit an indirect band gap of about 1.45 eV (Hill et al., 2016). The conduction band minimum, contributed by MoS$_2$, is located at the K–point and the valence band maximum, contributed by WS$_2$, is located at the K–point in the heterostructure (Feng et al., 2019; Wang et al., 2022).

The fundamental characterization for homogenous MoS$_2$, WS$_2$, and their heterostructures are done distinctly. The morphology and topography of the heterostructure flakes formed from mechanical exfoliation are studied using various imaging techniques, while its vibrational properties are studied using Raman spectroscopy and their optical properties are studied using absorption spectroscopy.

**Fabrication**

MX$_2$ is the typical form for TMDCs, where M signifies the transition metal and X indicates the chalcogen. Despite the similar behavior of WS$_2$, MoSe$_2$, and WSe$_2$, the availability and good electrical, thermal, and optical characteristics of MoS$_2$ in the 2D regime makes it the most intensively researched TMDC (Kuc, 2014; Chhowalla et al., 2013). The intralayer bonding (i.e. the bonding between X and M within a layer) is covalent, whereas the interlayer bonding (i.e., the bonding between two different TMDC layers) is a van der Waals force that is much weaker than the intralayer covalent bonds. Hence, it is simpler to exfoliate the layers from a bulk TMDC crystal (Dong and Kuljanishvili, 2017).

**Mechanical Exfoliation**

Our aim is to exfoliate and construct the MoS$_2$/WS$_2$ heterostructures and investigate their morphological, optical, vibrational, and electrical properties. Mechanical exfoliation is the approach we use to exfoliate the appropriate 2D material from its bulk crystal. Because the interlayer bonding is formed by the weak van der Waals force, the layers may be readily separated by manually peeling the bulk crystals repeatedly using an adhesive tape. Other exfoliation techniques like liquid and chemical are also widely used for fabricating large-scale devices. However, these possess a disadvantage by incorporating chemicals, which results in the modification of certain behavioral properties of the material, while mechanical exfoliation techniques can yield a pure form of 2D material that is highly crystalline with thin atomic layers. As this method provides thin high-quality flakes it can be used for the fundamental characterization of the 2D materials.

The Thermal release adhesive tape is used owing to the exclusive property of its glue. The exfoliated sample is then transferred to a substrate, and the glue in the tape will be removed after applying elevated temperatures (~100°C). This leaves the exfoliated sample onto the substrate without contamination from the glue. The thermal release tape is hence used extensively to exfoliate the 2D materials. The mechanical exfoliation of 2D materials from their bulk counterparts is illustrated in Figure 1.

**Results and Discussions**

The layered TMDCs thus obtained individually are restacked to form the desired van der Waals heterostructure. The TMDC heterostructure is then characterized using various microscopic and spectroscopic experimental techniques to investigate the morphology, optical properties, vibrational properties, etc. The characterization results of the heterostructures are further compared with the results of individual 2D materials. This fundamental characterization
helps in the detailed study of changes in the behavioral properties in the 2D forms of MoS$_2$ and WS$_2$ and the constructed MoS$_2$/WS$_2$ heterostructure, which can be then used in various applications.

**Morphology Characterization**

Although mechanical cleaving is a widely used technique to form highly crystalline atomically thin flakes, the larger proportion of thicker flakes present in the samples makes it difficult to detect the thinner ones. Scanning probe microscopy can in principle, give an insight into the thickness of the exfoliated flakes. However, the lower concentration of thinner flakes makes this technique almost impractical/difficult to carry out. In such a scenario, optical imaging can give a global view of the sample surface, its morphology, and, to an extent, the information of flake thickness.

The initial morphology study for the exfoliated MoS$_2$, WS$_2$, and heterostructure flakes has been carried out using an optical microscope. The visibility of the flakes on the Si wafer highly depends on the native SiO$_2$ thickness and illumination condition (Ottaviano et al., 2017). The 2D/dielectric/Si sandwich produces multiple reflections of light at the air–2D, 2D–dielectric, and dielectric–Si interfaces that give rise to the observed optical contrast which is a function of the thickness of the flake (Li et al., 2018). In our case, the samples (MoS$_2$, WS$_2$, and WS$_2$/MoS$_2$) were prepared on 280nm SiO$_2$/Si substrate. The optical microscope images taken with 100x magnification revealed the presence of few-layer thin flakes (all samples) distributed on top of bulk thicker flakes which is evident from the varying contrast in the image. This contrast, according to the definition of Michelson (Ottaviano et al., 2017; Michelson, 1927) can be quantified as in the equation (1),

$$\text{Contrast} = \frac{I_{\text{sub}} - I_{\text{mat}}}{I_{\text{sub}} + I_{\text{mat}}}$$  \(1\)

where $I_{\text{sub}}$ denotes the substrate intensity and $I_{\text{mat}}$ denotes the material intensity.

The contrast difference can be obtained from equation (2),

$$C_D = C - C_S$$  \(2\)

$C_D$ is defined as the contrast difference which is obtained by subtracting the optical contrast of the substrate ($C_S$) from the optical contrast of the nanosheets ($C$) (Li et al., 2013; Kolobov, 2018).

The analysis of optical images is done using the free software ImageJ.

Figure 2 shows the optical images of (a) MoS$_2$, (b) WS$_2$, and (c) WS$_2$/MoS$_2$ heterostructures obtained over a 280nm SiO$_2$/Si substrate under white light illumination. These images were captured with a 100X objective lens, which is the maximum magnification possible in optical microscopes with a resolution of 10µm. This gives an idea of the flakes’ morphology and provides information about their lateral size. The lateral size of the flakes in all the images is more or less equal to 20 µm with respect to the mentioned scale. We can clearly see the color differences at different positions on the same flake from the images obtained. This color/contrast difference can be attributed to the fact that the layers with varying thicknesses got stacked in such a fashion that one lies above the other bigger flake during the exfoliation process. There would be little or no force between such restacked flakes hence the difference in contrast. As the number of flakes varies, the height of the flake will also vary accordingly, thus it gives rise to the contrast difference during the reflection of the incident white light (Wang et al., 2012).

Figure 2 (d, e, and f) gives the corresponding profiles taken along the lines marked in (a), (b), and (c). The step-like features in the profiles indicate the flakes’ thickness change. As we claimed before, it is now well evident from the profiles that indeed, there occurs a stacking of flakes one upon the...
other. At this point, a comparative study can be carried out regarding the relation between optical contrast and the thickness of the flakes. For reference, we have considered the work done by Li et al. (2013) where a systematic study of optical images was carried out and the contrast values were compared with the height of the flakes obtained from AFM. By comparing the optical contrast from our image with the reported values, it can be concluded that we have flakes with thicknesses down up to 10 monolayers. The pinkish region in our optical images showed the minimum number of layers (10 monolayers) whereas the brighter ones have 12–14 monolayers.

From the optical images, we obtained the lateral size of the flakes and a quantitative idea about the flake height. To obtain more detailed information about the morphology of a sample, it is viewed under a scanning electron microscope (SEM) which provides a magnification of about 150000X with a maximum resolution of 0.5µm. Figure 3 shows the SEM images obtained for MoS$_2$, WS$_2$, and their heterostructures, respectively. The SEM images will have more magnification than the optical microscopy images, thus providing detailed information of stacking in the flakes. From the images, we can clearly see that the layers do not have smooth surfaces indicating that the layers are stacked one above the other as marked in white square regions in Figure 3. In Figure 3.c, a number of flakes are lying one above the other. The edges of the underlying flakes are visible in the SEM images revealing the transparent nature of the 2D flakes since the bulk crystals, unlike 2D flakes, are not transparent (Georgiou et al., 2013). As we discussed already from the optical images, the contrast difference over the flakes is due to the difference in the number of staked layers, from these SEM images, it is evident that a single flake that we see is actually a stack of layers with a smaller lateral dimension.

A closer look at the exfoliated samples can be made using Atomic Force Microscope (AFM), which can provide much higher magnification, even up to atomic regime. The AFM line scan over a heterostructure flake along with the height profile is provided in Figure 4.

The previous microscopic techniques we have seen will provide only the 2–dimensional information about the flakes formed (i.e. the morphology of the flakes), whereas this microscopic technique provides us 3–dimensional information about the flakes formed. These will contain details about the height of each flake at different positions. This AFM has a higher resolution than the optical and scanning electron microscopes. The maximum height obtained in Figure 4.b is approximately 6.25 nm. A single MoS$_2$ flake will have a thickness of about 0.65nm, hence it is obvious that there is a maximum of about 10 layers in this particular flake. The stacking also is clearly visible in the profile where the small step-like feature represents a bilayer MoS$_2$ flake (with monolayer height 0.65nm) (Cong et al., 2014).

An interesting feature that we noticed is the presence of periodic steps on top of the exfoliated flake. We have chosen the particular heterostructure flake and the profile taken on top of the flake is shown in Figure 5. The periodicity which was hidden in the image can now be clearly visible in the line profile in Figure 5b. The height of each step was calculated to be 0.86nm matching with the monolayer thickness. We have checked all the flakes and found a similar behavior everywhere. Thus our claim of the layers getting stacked while exfoliation is now confirmed beyond doubt from the AFM image height profiles.

**Spectroscopic Techniques**

**Optical Properties**

Even at the few atomic layer limitations, the TMDC materials exhibit significant optical characteristics. This is remarkable because the tiny layers, only a few angstroms thick, are predicted to be optically clear and devoid of any electron–photon interaction. This remarkable occurrence is thought to be the result of “band nesting”. Band nesting occurs in materials with band topologies containing regions of energy parallelism between the conduction and valence bands. This means that when such a material absorbs a photon, the generated carriers, namely electrons and holes, propagate at the same but opposite velocities. The combined density of states in two-dimensional materials diverges as a result of band nesting, resulting in extraordinarily high optical conductivity (Carvalho et al., 2013; Sumesh, 2019).

![Figure 3: Scanning electron microscope images of a) MoS$_2$ b) WS$_2$ and c) heterostructure](image)

![Figure 4: a) Atomic Force microscope images of MoS$_2$ b) Height profile of the particular flake](image)

![Figure 5: a) Atomic Force microscope images of Heterostructure b) Height profile of the particular flake](image)
The optical property is investigated using UV–Vis absorption spectroscopy for our mechanically exfoliated samples. Figure 6 provides the absorption spectrum of all three distinctly. The sharp peak at 636 nm (1.95 eV) of MoS₂ and the peak at 674 nm (1.84 eV) of MoS₂ arise from A-exciton resonances. However, we could see a slight shift in the heterostructure in these peak positions. The A excitonic peak for MoS₂ has undergone a slight red shift whereas the WS₂ peaks show a blue shift in the heterostructure compared to the individual samples. This shift could be attributed to the interlayer coupling between the layers (Chen et al., 2016; Savjani et al., 2014).

The excitonic transition from valance band split states in MoS₂, the B peak is observed at 619 nm with a difference of ~55 nm (0.16 eV split) from the A excitonic peak, matching with the spin-orbit splitting reported earlier for MoS₂ (Visic et al., 2011; Frey, 1998). The B excitonic peak for WS₂ is reported to be observed at 525 nm, however, in our case (Figure 6b), both the A and B excitonic peaks are overlapped to form the broader peak centered at 636 nm. From Figure 6b the C and D excitonic transitions can be attributed to the modest peak onset at 460 nm and the low-intensity wide peak at 413 nm, respectively. The 2H phase of MoS₂ may also exhibit the twisted C, D excitonic peaks between 400 and 500 nm (Reshmi et al., 2017). We ascribe the peak feature at 492 nm due to the C, D excitonic transitions responsible for the 2H phase of MoS₂ (Reshmi et al., 2017; Zhu et al., 2015). In the three spectrums above, an additional prominent peak observed between 200 to 250 nm, which we attribute to the high-energy excitonic transition (Eda et al., 2011).

The A & B excitonic peaks arise due to the direct transitions at the K point of the Brillouin zone, the C & D peaks arise due to transitions between the deep valance band to the conduction band (Chua, n.d.).

The A and B peaks of MoS₂ and the A peak of WS₂ are retained in the heterostructure spectrum in Figure 6c. Due to increased absorbance, the C peaks of both materials have been combined to provide an enhanced peak at 472 nm. It can also be observed from that the absorbance of heterostructure samples is more around the A, B excitonic peaks. This can be explained with the help of type II band alignment existing in the MoS₂/WS₂ combination heterostructure. In the type II band alignment, the conduction band minima and valance band maxima reside in two different materials (Niu and Li, 2015). This is due to the formation of interlayer excitons in the heterostructure arising from the bonding between electrons and holes of opposing layers by a Coulomb force. Even without any applied bias, electrons and hole will relax to distinct layers during photoexcitation and thus facilitating increased carrier collection and absorbance. This causes a decrease in optical band of the obtained heterostructure.

### Vibrational Properties

Each atom or molecule in the material will exhibit a distinct vibrational mode when excited with a laser. These distinct vibrational modes are studied using Raman spectroscopy to determine the type of material present in the sample.

Figure 7 shows the Raman spectrum recorded for our mechanically exfoliated MoS₂, WS₂, and heterostructure samples excited with a 532 nm laser beam. For MoS₂, the A and B peaks appear at 383 cm⁻¹ and 409 cm⁻¹ respectively and for WS₂, it appears at 352 cm⁻¹ and 420 cm⁻¹. In the micro mechanically exfoliated and restacked 2D hetero layers, the resulting structures can show the combined properties of individual materials comprising the heterostructure. Hence, the MoS₂/WS₂ heterostructure shows the 4 peaks corresponding to in-plane and out-of-plane vibrations of both MoS₂ and WS₂ individually. However, we could see a shift in the peak positions as both MoS₂ and WS₂ were combined to form the heterostructure (Reshmi et al., 2017; Liang and Meunier, 2014).

The small onset (marked with black arrows in Figure 7b and Figure 7c) of WS₂ around 340 cm⁻¹ can be attributed to the longitudinal acoustic mode which arises at the M point of the Brillouin zone (Berkdemir et al., 2013).

### Edge Effects

The structure of few-layer TMDCs and their heterostructure varies spatially and the most prominent changes are visible at the edge of the flakes. We captured the Raman spectra of a particular flake at the center and edge to investigate such edge effects for our mechanically exfoliated MoS₂, WS₂, and heterostructure samples.

Figure 8 shows the Raman spectra obtained for our samples along with the optical image of the corresponding flake. The points at which the spectrum was acquired are marked in the optical image (Figure 8 a, c, and e). There is a slight shift in the peak positions towards the edge of the flakes. The shift is recorded for the individual samples of both MoS₂ and WS₂ as well as for the heterostructure flakes.

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**Figure 6:** Absorption spectrum of a) MoS₂, b) WS₂, and c) Heterostructure

**Figure 7:** Raman spectrum of a) MoS₂, b) WS₂, and c) Heterostructure
For MoS$_2$ and WS$_2$ peaks, we could observe a slight red shift in wavelength once we move towards the edge of the flake as is clearly visible in Figure 8 b, d and f.

In the heterostructure flakes however, the peaks corresponding to WS$_2$ undergo a blue shift and the peaks corresponding to MoS$_2$ undergo a red shift. This type of shift occurs only when there is a considerable spatial variation in the electronic structure. Unlike the center of the flakes, the edges will possess unsaturated bonds, thus giving rise to two types of edges: armchair and zig-zag edges. This will give rise to the spatial variation in their electronic structure, resulting in the blue or red shift in their vibrational mode edge peaks from the center of the flakes. There is another factor that contributes to these edge effects, its strain. The edges will be easily subjected to a strain since that is the spot where the flakes are split to form boundaries (Mitioglu et al., 2014).

**Thickness Determination**

The change in number of layers of the 2D material will be evident in the peak position of the vibrational modes of Raman spectroscopy. The number of layers present the occurrence of red and blue shifts respective to the change in number of layers and their frequency differences can be used to identify the number of layers (Tuschel, 2015; Tan, 2019). Similar thickness dependence of frequencies of and modes has been observed for both MoS$_2$ and WS$_2$ (Lee et al., 2010; Zhao et al., 2013b).

Figure 9 shows the Raman spectra acquired for our samples on different flakes where a clear shift in the peak position is evident for both as well as modes, indicating a variation in the layer thickness. We can notice that the shift in peak is more prominent than the shift in peak, this is because corresponds to out–plane vibration, in other words, the vibration of S (challogen) atoms present at either side of the transition metal atom perpendicular to the atomic plane. This interacts directly with the adjacent layers which is not the case in mode where the vibration is in–plane.

There is a small low intense peak around 310 cm$^{-1}$ in WS$_2$ apart from the shift in both the in-plane vibration mode and out-of-plane vibration mode, which could be considered as an indicator to qualitatively understand the flake height. The presence of a vibrational mode at ~310 cm$^{-1}$ was reported (Zhao et al., 2013b). They observed that this particular weak Raman mode consistently appears in multilayer WS$_2$ flakes but is absent in the monolayer regime. Though the origin of this mode is unknown, it has been concluded that the absence of this peak in monolayers may indicate that it is related to the rigid layer shear mode (Eda et al., 2011). The large frequency pattern inferred from this peak could also result from combining two or more low–frequency modes (Zhao et al., 2013b; Zhao et al., 2013c).

Figure 10 shows the variation in the peak onset around 310nm in the Raman spectrum for different WS$_2$ flakes. It is noted that this peak intensity reduces with respect to the other two adjacent peaks at 297 and 323 nm, respectively if the number of layers reduces. This will almost be absent for a monolayer flake. In Figure 10a the peak is seen very prominent at 309 nm, whereas it softens gradually and is least present in Figure 10d indicating that the number of layers present is very less in the last flake, which can be of few layers.
Conclusion

The morphological details like the lateral size of the flakes and their distribution, are obtained from the optical microscopic images. These SEM images reveal the transparent nature as well as the stacking of the MoS\(_2\), WS\(_2\), and heterostructure flakes. As the transparent nature is evident, its application can be extended in the emerging field of transparent and flexible electronics.

The topographical information like the height profile of the flakes exfoliated, is obtained from the AFM images. Along with the height profile of the flake at a particular point, it also gives an insight into the stacking of layers on a single flake, as is evident from the step-like profile obtained across the flake.

The optical properties of the MoS\(_2\), WS\(_2\), and the heterostructure flakes are explored by means of UV–Vis spectroscopy, as it provides the absorption spectrum of the exfoliated sample. This spectrum reveals various excitonic peak positions which are attributed to the different excitonic transitions in the 2D regime with respect to the electronic band structures reported from previous work of theoretical models. This provides insight into the electronic band nature, the transition type of each material, and the formed heterostructures.

The vibrational properties of the exfoliated material are studied from the Raman spectrum with a 532nm excitation. This provides a clear idea of various vibrational modes, giving rise to the corresponding peaks. This technique can be used to ensure the formation of heterostructure as it is highly uncertain with the use of mechanical exfoliation technique. Since mechanical exfoliation gives rise to a statistical distribution of flakes with varying thicknesses, Raman fingerprints can give qualitative insight into the thickness variations throughout the sample. The strain developed in the system during the mechanical peeling also affects the signature Raman peaks of the material. These studies were done elaborately to understand the basic science behind such observations.

In summary, the fundamental characterization for MoS\(_2\), WS\(_2\), and their heterostructures are carried out using various experimental techniques. Exploring these fundamental properties is important as it provides the basis knowledge about various intriguing properties of the 2D MoS\(_2\), WS\(_2\), and their heterostructures so that it can be extended to various technological applications. The class of 2D materials offers a platform for the creation of heterostructures with diverse properties. Plenty of opportunities lays open once we start combining individual materials, held together by mere van der Waals forces, the bulk material can be bought to 2D regime quite effortlessly.

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