5-18-2022

Review of applications and research of 2D TMDCs (WS2 & MoS2)

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1. Abstract:

Monolayers of 2D transition metal dichalcogenides (TMDC) have promising applications due to their unique properties, from optoelectrical to piezoelectric properties. When combined stacked to create heterostructures, they have the potential to greatly improve current sensors, mainly photodetectors and related sensors, and strain sensors. However, there are many obstacles that prevent further understanding. These obstacles depend on the application and properties being sought. This paper aims to review existing literature on TMDC applications and TMDC heterostructures to further understanding of this growing field.

2. Introduction:

Transition metal dichalcogenides (TMDCs) are being increasingly studied due to their unique physical, chemical, and optoelectrical properties [1]. Commonly studied TMDCs are WS_2 & MoS_2. TMDC structures are layered, with a transition metal between two chalcogen atoms (hence dichalcogenide) [1]. An example is given below in Fig. 1, with MoS_2.

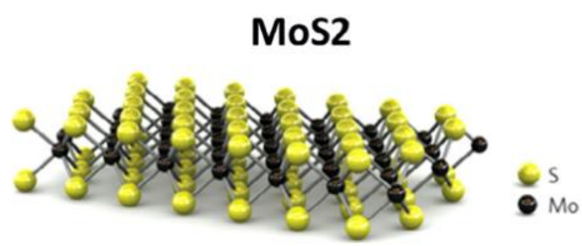

Fig. 1 MoS_2 Structure [1].

From the figure we can see that Mo is the transition metal, and S is the chalcogen. Interactions between layers of these monolayers (or in heterostructures) are governed by van der Waals interactions [1].

TMDCs are often studied for their optoelectrical properties. For example, WS_2 has high absorption coefficients, broad absorption spectra, tunable bandgaps, and long carrier diffusion lengths [2]. TMDcs also have an indirect-to-direct bandgap transition in monolayer form, making it useful in photodetectors and transistors [1]. When combined into heterostructures these properties can be further tailored. For example, TMDCs with different bandgaps could be tailored to absorb a larger range of the solar spectrum [1]. TMDCs studied for their optoelectrical properties have the potential to be applied to things such as photodetectors, LEDs, lasers, and solar cells. TMDCs can be synthesized by a wide variety of methods: chemical vapor deposition (CVD), mechanical exfoliation, and liquid isolation [1].

3. Review

A number of papers have worked to further clarify and understand TMDCs and their properties as 2D materials, especially with regards to integrating TMDCs into heterostructures. Their findings also give insight into the wide variety of potential applications.

3.1 Perovskites

3.1.1

A study by Ufuk et al.l focused on integrating WS_2 into 2D perovskite heterostructures, with the intent to further understand TMDC heterostructures for potential optoelectrical properties [2]. Ufuk et al. specifically investigated organic-inorganic perovskites due to their good optoelectrical properties [2]. Perovskites being materials with the same crystal structure as $CaTiO_3$[3], with a general formula of ABX_3, where A & B are cations and X is an anion [3]. An example crystal is shown below in Fig. 2.

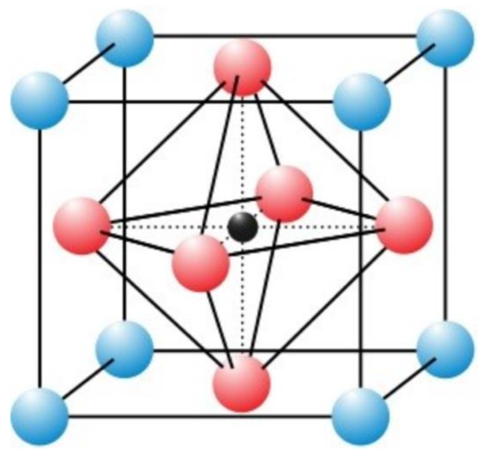

Fig. 2 Perovskite Structure [3].

In this image, the blue dots are the A cation, the red are the X anion, and the black is the B cation [3]. Ufuk et al. sought to create perovskite/TMDCs heterostructures by using CVD to produce monolayer WS_2, vapor-phase selective deposition of 2D PbI_2, and conversion of PbI_2 to the organic-inorganic perovskite $CH_3NH_3PbI_3$[2]. They then produced photodetectors with the resulting heterostructure [2]. Ufuk et al. found that TDMCs could be successfully integrated into a large-area perovskite heterostructure that could be patterned without damaging the structure [2]. Furthermore, optical studies showed good interactions between the TMDC WS_2 monolayer and the perovskite [2]. Specifically, they observed large PL (photoluminescence) quenching and fast PL decay [2].

3.1.2

Wang et al. conducted another study regarding WS_2 monolayer 2D perovskite heterostructures [4]. More specifically, Wang et al. sought to further understand the optoelectrical properties of van der Waals vertical heterostructures [4]. This study was motivated by the advantages that 2D Ruddlesden-Popper perovskites over 3D perovskites, mainly due to their better ambient stability [4]. Wang et al. believed that 2D perovskites would be superior, as they have hydrophobic organic barriers that enhance moisture stability, a necessity for practical application [4]. In this study they primarily focused on the photovoltaic effect and photodetection performance [4]. The schematic crystal structure of the heterostructure studied is shown below in Figure 3.

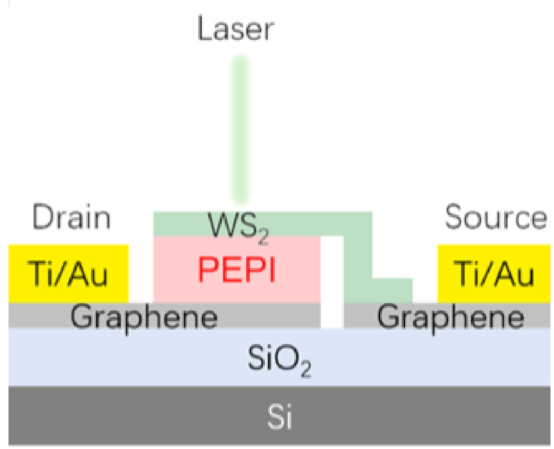

Fig. 3 Studied Heterostructure [4].

To characterize the heterostructures, they fabricated self-driven photodetectors using the synthesized heterostructures, and measured the on/off ratio, the photoresponsivity, and external quantum efficiency [4]. Wang et al. concluded that the heterointerface's photoresponsivity was significantly better than the TMDC monolayer, and had good EQE (external quantum efficiency), suggesting that 2D perovskites, particularly TMDC-perovskite heterostructures, are good candidates for optoelectronic applications [4].

3.1.3

Interlayer excitons in 2D perovskite/monolayer TMDCs were studied by Chen et al. In this work, they sought to understand interlayer excitons in TMDC heterobilayers [5]. Understanding interlayer excitons (IXs) is important as they depend on local atomic registry & coupling strength; and can have an effect on the complexity of device fabrication [5]. Heterostructures were created by placing a 2D perovskite microplate over a monolayer TMDC [5]. They speculated that 2D perovskite/monolater TMDC heterostructures will have robust coupling and efficient charge transfer [5]. They found pronounced IX emissions independent of alignment and stacking sequence, and that the IX emissions dominate the emission spectrum at low temperatures and showed a blue shift with increasing excitation power [5]. This paper provides good insights into interlayer excitons in perovskite/monolayer TMDC heterostructures.

3.1.4

Kang et al. reported a high-performance photodetector using a perovskite-TMDC heterostructure. Their paper was motivated by the desire to maximize high quantum efficiency of TMDCs, and minimize the drawbacks, one of which is the difficulty of TMDC layers to absorb light because they are so thin [6]. Kang et al. thereby suggested inserting an absorption layer with high absorption rate and high efficiency [6]. Kang et al. also reviewed several papers in which the authors explored similar approaches to mitigating the absorption issues of TMDCs [6]. These reviews make this paper a fairly comprehensive view into the creation of high-performance photodetectors, and what challenges might still remain. Some of these issues were issues with photoresponsivity, and issues with avoiding dark current [6]. Kang et al. fabricated a photodetector with an MoS_2 monolayer, and measured photoluminescence, rigorous couple-wave analysis, and assessed optoelectrical performance by measuring photoresponsivity, detectivity, and photoswitching under light and dark conditions [6]. They also were concerned with stability and took steps to measure this [6]. They observed that the photocurrent of perovskite/MoS2 was 8x that of conventional MoS2 device, suggesting that this is an effective way to create an ultra-sensitive photodetector [6].

3.1.5

Song et al. also reported additional enhanced photodetectors using MoS_2/perovskite heterostructures. In this work, they integrated all-inorganic CsPbBr3 photodetectors to take advantage of absorption coefficients, and high quantum efficiency of perovskites [7]. Song et al sought to mitigate the currently limited applications of TMDCs, noting that their exceptional qualities have only been observed under special conditions, such as being measured in a vacuum [7]. Song et al. created MoS_2/CsPbBr3 hybrid structures, fabricated photodetectors, and investigated output properties, measuring current-voltage (I-V) characteristics under light and dark conditions [7]. They reported a quenching and shortened lifetime of PL, and state that this indicates an efficient charge transfer between layers [7]. They also found good responsivity and high EQE values, which they attribute to large light absorbance and interfacial charge separation [7]. They also note high response speed, which would be essential for application for photodetection [7]. Song et al.'s work presents a detailed insight into all-inorganic perovskites and their integration with TMDCs. It also confronts a major issue of TMDCs having exceptional qualities only under special conditions and could lead to wider applications.

3.1.6

In this work, Yang et al. reported a successful 2D TMDC/perovskite heterostructure using new techniques that yielded improved stability and optoelectrical properties [8]. They were motivated by the promising qualities of TMDCs and the desire to overcome performance issues and stability issues with 2D TMDC/perovskite heterostructures [8]. To do this, they created a TMDC and Ruddlesden-Popper hybrid 2D perovskite by exfoliating 2D perovskite and dry viscoelastic stamping WS_2 on a silicon substrate [8]. They applied Raman spectroscopy and measured PL [8]. They found that the heterostructure had improved PL by 2 orders of magnitude and had enhanced stability and emission [8]. This paper provides yet more insight into the strong potential of TMDC/perovskite heterostructures.

Conclusion

In this work, we reviewed existing literature on methods and experiments to further the understanding of TMDCs in heterostructures, and how they may be manipulated to address their shortcomings, mainly low stability, low absorption, and the issue that their exciting properties have not been observed frequently outside of idealized conditions. Using TMDCs in combination with perovskites has been demonstrated to have a positive effect and has mitigated some of the previous issues. However, more understanding is required before TMDC/perovskite heterostructures can become ubiquitous in optoelectronic applications.

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