Strain-Modulated Magnetism in MoS$_2$

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Abstract: Since the experiments found that two-dimensional (2D) materials such as single-layer MoS$_2$ can withstand up to 20% strain, strain-modulated magnetism has gradually become an emerging research field. However, applying strain alone is difficult to modulate the magnetism of single-layer pristine MoS$_2$, but applying strain combined with other tuning techniques such as introducing defects makes it easier to produce and alter the magnetism in MoS$_2$. Here, we summarize the recent progress of strain-dependent magnetism in MoS$_2$. First, we review the progress in theoretical study. Then, we compare the experimental methods of applying strain and their effects on magnetism. Specifically, we emphasize the roles played by web buckles, which induce biaxial tensile strain conveniently. Despite some progress, the study of strain-dependent MoS$_2$ magnetism is still in its infancy, and a few potential directions for future research are discussed at the end. Overall, a broad and in-depth understanding of strain-tunable magnetism is very necessary, which will further drive the development of spintronics, straintronics, and flexible electronics.

Keywords: straintronics; spintronics; web buckles; thickness-dependence

1. Introduction

Since Geim et al. [1] successfully peeled off stable monolayer graphene in 2004, 2D materials have gradually entered the vision of scientific researchers. While pristine graphene is diamagnetic, introducing defects and strains is an effective way to obtain long-range magnetic ordering [2–8]. Very recently, ferromagnetism (FM) has also been found in multilayer graphene [9], graphene nanoribbons [10], graphene open-shell nanostructures [11], twisted bilayer graphene [12–15], and graphene moiré superlattice [16]. Except for graphene, MoS$_2$ [17–21] has also attracted extensive attention. Interestingly, many experimental studies show that the defective MoS$_2$ nanostructures [18,19,22–47] also exhibit FM.

Notably, strain engineering [3–6,48–72] is also an effective way to mediate the magnetism of 2D materials. However, most of the previous work mainly focused on theoretical calculations. We have first introduced biaxial strain into the MoS$_2$ film through spontaneous buckling and found that biaxial strain can enhance its room-temperature FM (RTFM) [72–74]. As a whole, an extensive and in-depth understanding of strain-mediated magnetism in MoS$_2$ is needed, which would provide new avenues for spintronics and straintronics.

Here, we will give an overview of the timeline of strain-modulated magnetism in MoS$_2$ (Figure 1). We first review theoretical progress in various MoS$_2$ systems, such as nanoribbons (NRs) [17,48,49,51,75–82], hydrogenated [53,67] or nitrogen-doped [70,83] systems, defective systems [27,57,60,61,63,84–94] and 3d transition metal ion-doped systems [55,58,68,89–103]. Then, we outline the methods of introducing strain, such as using pre-stretched substrates [104,105], bending flexible substrates [106–114], utilizing lattice mismatch [115,116] or thermal mismatch [72,73,113,117–121], alloying [122], creating buckles [72,73,104,105,114,121,123,124], using patterned substrates [125–130], bubbles [131–133], atomic force microscopy (AFM) tip [134,135], or piezoelectric stretching [136]. Among all the methods, creating buckles is suitable for detecting and studying the magnetism conveniently. Furthermore, we emphasize...
the roles played by web buckles, which induce biaxial tensile strain. Despite some progress, the study of strain-dependent MoS₂ magnetism is still in its infancy and a few potential directions for future research are discussed at the end.

![Timeline showing key developments of strain-modulated magnetism in MoS₂.](image)

**Figure 1.** Timeline showing key developments of strain-modulated magnetism in MoS₂. Black font represents the theoretical progress; yellow font represents the experimental progress.

**2. Progress in Theoretical Calculations of Strain-Mediated Magnetism**

**2.1. Nanoribbons**

Similar to ZnO [80,137,138] and graphene [4,10] NRs with zigzag-terminated edges, zigzag MoS₂ NRs also exhibit FM [17,80] independent of NRs width and thickness due to the edge atoms. In contrast, armchair NRs show non-magnetism (NM). Interestingly, introducing adatoms can enhance the net magnetic moment of armchair NRs, but the FM of zigzag NRs is inhibited by the defects caused by adatoms [75]. Because the edge atoms are passivated, their spin polarization at the Fermi level is suppressed. Furthermore, an external static electric field can also reduce the energy gap of armchair NRs [76]. In detail, this electric field will drive metal-insulator phase transformation, which modulates or even suppresses FM.

In addition, monolayer and bilayer MoS₂ are also sensitive to tensile strain but cannot produce the long-range magnetic order in Figure 2. However, the magnetic moment in zigzag NRs is nearly doubled by 10% strain [51], as shown in Figure 2B, which may be related to the magnetic coupling from different edge atoms. As shown in Figure 2B–E, the variation is generally not monotonous [48,49,51].

Interestingly, applying tensile strain and an electric field in the zigzag direction can cause the reversible modulation of FM [48]. The applied strain is within the elastic limit of the material, which achieves the reversibility of regulation. Even for zigzag Janus MoSSe NRs, the magnetism shows a multi-stage change with the increase in strain, which is closely related to the electronic phase transition. After the electric field is applied again, the magnetism can be regulated more effectively [81].

However, this modulation is obviously different from that of the zigzag MoS₂ NRs shown in Figure 2E–G. Indeed, the difference in local spin density distribution determines the different modulation results of zigzag MoS₂ NRs and zigzag Janus MoSSe NRs.
Figure 2. Strain-dependent magnetism in zigzag MoS$_2$ NRs. (A,B) Energy difference and magnetic moment of the zigzag nanoribbons under uniaxial tensile strain along its axis. (Reprinted/adapted with permission from Ref. [51]. Copyright 2012, American Chemical Society). (C) Tensile strain along-dependent magnetic moment of MoS$_2$ nanoribbons and the internal electric field across the edges of the ribbon (Reprinted/adapted with permission from Ref. [48]. Copyright 2012, American Chemical Society). (D) Magnetic moment on the edge Mo atoms versus strain. (Reprinted/adapted with permission from Ref. [48]. Copyright 2012, American Chemical Society). (E) Magnetic moment evolution of the strained MoS$_2$ nanoribbon under electric fields. (Reprinted/adapted with permission from Ref. [48]. Copyright 2012, American Chemical Society). (F) 3D view of the combined effects of strain and external electric field on magnetic moment. (Reprinted/adapted with permission from Ref. [81]. Copyright 2018, Elsevier). (G) Magnetic moment versus the strained nanoribbon with different external electric fields (Reprinted/adapted with permission from Ref. [81]. Copyright 2018, Elsevier).
2.2. Hydrogenated or Nitrogen-Doped Systems

Even after applying the biaxial tensile strain from about −8% to 8%, pristine monolayer and bilayer 2H-MoS$_2$ [49] are NM, indicating that no spin polarizations are aligned to form FM. However, other dichalcogenides materials, such as pristine VS$_2$ and VSe$_2$, exhibit FM [50], and the FM will increase rapidly when the strain increases from −5% to 5%. Metallic materials such as pristine 1T-MoS$_2$ [33,37,41,67,139,140], VS$_2$ [50,141,142] and VSe$_2$ [50,141–145] monolayer are more likely to form spontaneous magnetization.

In addition, the contribution of V atoms to magnetism is much greater than that of S or Se atoms [50]. In contrast, unstrained NbS$_2$ and NbSe$_2$ monolayers [52] are NM but can produce between 0.50 and 0.61 µB per unit cell after applying 5% biaxial tensile strain. This novel magnetic behavior of NbS$_2$ and NbSe$_2$ monolayers is related not only to the bond length increased by strain but also to the metallic properties.

In fact, the self-exchange of populations between 4d orbitals of Nb atoms can lead to spin splitting [52,56]. Overall, V or Nb 4d states contribute mainly to the metallic state near the Fermi energy level [50,52,56]. By applying strain, the Curie temperature of the materials may be raised above room temperature [52], which will accelerate the spintronic application of 2D magnetic materials. However, MoS$_2$, WS$_2$, MoSe$_2$, and WSe$_2$ have no intrinsic magnetism [52] due to their characteristic band structures.

Hydrogen atoms [53,67] can modify the electronic structure of pristine 2H-MoS$_2$, but cannot produce spontaneous magnetism under <3% tensile strain [53], as shown in Figure 3A. With the increase in biaxial tensile strain, the magnetic moment and stability will be enhanced, as shown in Figure 3B. When the strain reaches 6.6%, the supercell obtains the most stable FM state, and the magnetic moment reaches 0.57 µB per unit cell. In addition, its Curie temperature (T$_c$, ~232 K) is much higher than that of the transition metal (TM)-doped system (T$_c$, ~40 K) [84].

![Figure 3. Strain-dependent magnetism in hydrogenated monolayer MoS$_2$. (A) Contour plots of the spin density of hydrogenated monolayer 2H-MoS$_2$ under the biaxial tensile strain of 6%. (Reprinted/adapted with permission from Ref. [53]. Copyright 2013, American Physical Society). (B) Energy difference per](image-url)
Mo atom for 2H-MoS\(_2\)H and the magnetic moment of Mo \(d\) orbitals per Mo as a function of strain (Reprinted/adapted with permission from Ref. [53]. Copyright 2013, American Physical Society). (C) Monolayer 1T-MoS\(_2\) model without and with hydrogen adsorption (Reprinted/adapted from Ref. [67] with permission from the Royal Society of Chemistry). (D) The function of magnetic moments of Mo atom in 1T-MoS\(_2\) as tensile strain (Reprinted/adapted from Ref. [67] with permission from the Royal Society of Chemistry). Note that: The 2H phase structure with space group Pm\(_2\) has hexagonal symmetry and the primitive unit cell of the single-layer has three atoms. The S atom is with trigonal prismatic coordination around Mo atoms; The 1T phase is also with hexagonal symmetry and the primitive unit cell of the single-layer has three atoms. In the 1T phase with space group Pm1, the S atom is with octahedral coordination around Mo atoms.

However, 1T-MoS\(_2\) and 1T-MoS\(_2\)H show FM behaviors, as shown in Figure 3C. Unlike 2H-MoS\(_2\), the relationship between magnetic moments and strain is linear, as shown in Figure 3D [67]. The crystal field makes a great contribution to the magnetism of the system.

Similarly, the biaxial tensile strain can also modulate the magnetism of nitrogen-doped 2H-MoS\(_2\) [70]. When the strain gradually increases to 17.09\%, a single nitrogen doping structure (NMo\(_{16}\)S\(_{31}\)) shows different magnetic phases. However, the magnetic moment of a dense nitrogen doping structure (NMo\(_{4}\)S\(_{7}\)) steps from 0 up to 1 \(\mu_B\) under 14\% strain. In detail, unpaired electrons doped with nitrogen atoms will induce magnetic order. When the doped nitrogen atoms are too dense, the magnetic order will be weakened. However, the biaxial tensile strain has a good modulation effect on these two structures.

### 2.3. Defective Strained Systems

Inspired by the magnetism caused by conductive electrons in defective graphene. Many research groups tried to introduce single vacancies into the MoS\(_2\) monolayer [57,94]. Experimentally, atomic single vacancies [91] (V\(_{\text{Mo}}\): mono-molybdenum vacancy; V\(_{\text{S}}\): mono-sulfur vacancy; V\(_{2\text{S}}\): disulfur vacancy), vacancy complexes (V\(_{\text{MoS3}}\): vacancy complex of Mo and nearby three sulfur; V\(_{\text{MoS6}}\): vacancy complex of Mo nearby three disulfur pairs) and antisite defects [61,63] (S\(_2\text{Mo}\): an S\(_2\) column substituting a Mo atom; Mo\(_{\text{S}}\): a Mo atom substituting an S column; Mo\(_{2\text{S}}\): a Mo atom substituting an S\(_2\) column) have been observed in CVD (chemical vapor deposition)-grown MoS\(_2\) monolayer by atomic-resolution annular dark field (ADF) imaging on an aberration-corrected scanning transmission electron microscope (STEM) [86]. Through first-principles calculations shown in Table 1, it is found that pristine [60,94] and single vacancy [57,60,94]-MoS\(_2\) monolayer are NM. Notably, when 19\% biaxial tensile strain is applied to the pristine MoS\(_2\) monolayer, 4 \times 4 supercells produce a magnetic moment of 5 \(\mu_B\). However, the uniaxial strain cannot cause a magnetic phase transition regardless of the applied direction.

Interestingly, unstrained MoS\(_2\) monolayers with V\(_{\text{Mo}}\) [60,94], V\(_{\text{S}}\) [57,60], V\(_{2\text{S}}\) [57,60,94], V\(_{\text{MoS}}\) [60], V\(_{\text{MoS3}}\) [57], S\(_{2\text{Mo}}\) [61] and MoS\(_2\) [61] are NM, as shown in Figure 4, while unstrained MoS\(_2\) monolayers with V\(_{\text{MoS2}}\) [46,60,146], V\(_{\text{MoS6}}\) [57] and MoS\(_{2}\) [63] are magnetic. In detail, the charge transfer and Mo atoms around the defects contribute mainly to magnetism. Furthermore, spin reorientation and the largest magnetic moment occur in the V\(_{2\text{S}}\)-MoS\(_2\) monolayer [60], as shown in Figure 4A,B, which is related to magneto-crystalline anisotropy. With the increase in the tensile strain, FM-NM-FM phase transformation has been observed in V\(_{\text{S}}\)-MoS\(_2\). Li et al. [91] have also drawn the magnetic phase diagram caused by strain and external electric field, as shown in Figure 4C,D. After applying strain, the charge sulfur vacancy defect shows rich magnetic responses.
Table 1. Strain-dependent magnetism of single-layer MoS\(_2\) with various defects.

| System   | Supercell Size | Maximum Strain | Magnetic Moment | Remarks                  |
|----------|----------------|----------------|----------------|--------------------------|
| Pristine | 4 × 4          | 11%            | 0 \(\mu_B\)    | NM (0–11%), biaxial      |
| Pristine | 4 × 4          | 20%            | 5 \(\mu_B\) (19%) | NM (0–20%), biaxial      |
| Pristine | 4 × 2\(\sqrt{3}\) | 20%           | 0 \(\mu_B\)    | NM (0–20%), x-axis       |
| Pristine | 4 × 2\(\sqrt{3}\) | 20%           | 0 \(\mu_B\)    | NM (0–20%), y-axis       |
| \(V_{Mo}\) [94] | 4 × 4          | 11%            | >2 \(\mu_B\) (7–11%) | NM (<7%), biaxial        |
| \(V_{Mo}\) [60] | 4 × 4          | 20%            | 2.02 \(\mu_B\) (14.5%) | NM (<6.5%), biaxial      |
| \(V_{Mo}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | 2.02 \(\mu_B\) (7.5–20%) | NM (0–7.5%), x-axis      |
| \(V_{Mo}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | 2.02 \(\mu_B\) (7.5–20%) | NM (0–7.5%), y-axis      |
| \(V_S\) [57] | 6 × 6          | 10%            | 2.0 \(\mu_B\) (9%) | NM (<9%), biaxial        |
| \(V_S\) [60] | 4 × 4          | 20%            | 0.07 \(\mu_B\) (14.5%) | NM (0–15%), biaxial      |
| \(V_S\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | ~2.07 \(\mu_B\) (20%) | NM (0–15%), x-axis       |
| \(V_S\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | ~2.07 \(\mu_B\) (20%) | NM (0–15%), y-axis       |
| \(V_S\) [91] | 4 × 4          | 16%            | ~3 \(\mu_B\) (12%) | NM (0–10%), biaxial      |
| \(V_S\) [91] | 4 × 4          | 16%            | 2.0 \(\mu_B\) (12%) | NM (0–6%), biaxial       |
| \(V_S\) [91] | 4 × 4          | 16%            | 2.0 \(\mu_B\) (12%) | NM (0–6%), biaxial       |
| \(V_{2S}\) [94] | 4 × 4          | 11%            | >2 \(\mu_B\) (>10%) | NM (<9%), biaxial        |
| \(V_{2S}\) [57] | 6 × 6          | 10%            | 5.5 \(\mu_B\) (9%) | NM (<9%), biaxial        |
| \(V_{2S}\) [60] | 4 × 4          | 22%            | 7.45 \(\mu_B\) (13.5%) | NM (<9.5%), biaxial      |
| \(V_{2S}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | ~3.0 \(\mu_B\) (20%) | NM (0–15%), x-axis       |
| \(V_{2S}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | ~1.0 \(\mu_B\) (20%) | NM (0–15%), y-axis       |
| \(V_{MoS}\) [60] | 4 × 4          | 20%            | 4.04 \(\mu_B\) (13%) | NM (<5.5%), biaxial      |
| \(V_{MoS}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | ~1.7 \(\mu_B\) (10%) | NM (<10%, 15%), x-axis   |
| \(V_{MoS}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | 0 \(\mu_B\)    | NM (0–20%), y-axis       |
| \(V_{MoS}\) [60] | 4 × 4          | 20%            | ~5.9 \(\mu_B\) (20%) | ~2 \(\mu_B\) (<5%), biaxial |
| \(V_{MoS}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | 0 \(\mu_B\)    | NM (<4%), x-axis         |
| \(V_{MoS}\) [60] | 4 × 2\(\sqrt{3}\) | 20%           | ~2 \(\mu_B\) (0–20%) | y-axis                   |
| \(V_{MoS}\) [57] | 6 × 6          | 10%            | 4.0 \(\mu_B\) (10%) | NM (<10%), biaxial       |
| \(V_{MoS}\) [57] | 6 × 6          | ~12%           | 12.0 \(\mu_B\) (9%) | NM (~12%), biaxial       |
| \(S_{2Mo}\) [61] | 6 × 6          | 8%             | 2.0 \(\mu_B\) (8%) | NM (<8%), biaxial        |
| \(MoS_2\) [61] | 6 × 6          | 8%             | 2.0 \(\mu_B\) (8%) | NM (<8%), biaxial        |
| \(MoS_3\) [63] | 4 × 4          | 7%             | 2.0 \(\mu_B\) (7–4%) | NM (5–7%), biaxial       |

Since Zhou et al. [86] and Jin et al. [147] found the antisite defects in the MoS\(_2\) monolayer by STEM imaging in 2013, researchers have been trying to understand their magnetic characteristics in Figure 4E–H. In detail, the defect is an intrinsic structural defect. After applying 8% biaxial tensile strain, the system will produce long-range magnetic order [61]. Overall, the spin density is mainly distributed in the sulfur atom and its nearest or second neighbor, the Mo atom. However, the antisite-doped monolayer exhibits a high spin state under the biaxial strain from −7% to 4%. With the further increase in tensile strain, magnetism will vanish. The position of the antisite atom is related to the magnetism of the system. In addition, it is found that strained VS can greatly improve the hydrogen evolution activity of MoS\(_2\) basal planes [148]. The sulfur vacancy will become a new active site and tune the adsorption-free energy of the hydrogen atom.
2.4. 3d Transition Metal (TM) Ion-Doped Systems

Doping engineering [149–157] is a traditional way to control the properties of materials, especially for 2D materials. Recently, it has been confirmed experimentally [149,150,158–162] that 3d TM doping can induce ferromagnetism in nonmagnetic MoS$_2$, ...
that 3d TM doping can induce ferromagnetism in nonmagnetic MoS$_2$, which can be combined with strain engineering to tune the magnetism, as shown in Table 2.

Table 2. Strain-dependent magnetism of TM-doped single-layer MoS$_2$.

| Dopant | Supercell Size | Maximum Strain | Magnetic Moment/µ$_B$ | Remarks                   |
|--------|----------------|----------------|---------------------|--------------------------|
| V      | 5 x 5          | 20%            | 0 µ$_B$ (−20–20%)   | AFM (3% or −2%)          |
| V      | 4 x 4          | 5%             | 0.81 µ$_B$ (0%)     | 0 (−20%); 2.8 µ$_B$ (20%)|
| Mn     | 5 x 5          | 20%            | 1.0 µ$_B$ (0%)      | 3.0 µ$_B$ (6%); biaxial  |
| Mn     | 4 x 4          | 6%             | 1.0 (−10–9%)        | be almost independent on the size of supercell, no matter under a tensile or compressive strain |
| Mn     | 4 x 4          | −10%           | 1.0 (−10–9%)        | AFM (3% or −2%)          |
| Mn     | 5 x 5          | −10%           | 1.0 (−10–9%)        | AFM (−20%); 2.8 µ$_B$ (20%)|
| Mn     | 6 x 6          | −10%           | 1.0 (−10–9%)        | AFM (−20%); 4.2 µ$_B$ (20%)|
| Mn     | Unit cell      | 9%             | 1.0 µ$_B$ (0–3%)    | 3.0 µ$_B$ (4–9%); biaxial |
| Fe     | 5 x 5          | 20%            | 2.0 µ$_B$ (0%)      | 0 (−20%); 4.2 µ$_B$ (20%)|
| Fe     | 4 x 4          | 6%             | 2.04 µ$_B$ (0%)     | 4.0 µ$_B$ (3.5–6%); spin reorientation |
| Co     | 5 x 5          | 9%             | 2.0 µ$_B$ (0–5%)    | 4.0 µ$_B$ (6–9%); biaxial |
| Co     | Unit cell      | 9%             | 3.0 µ$_B$ (0–7%)    | 3.4 µ$_B$ (8%); biaxial  |
| Ni     | 5 x 5          | 20%            | 5.0 µ$_B$ (10%)     | 0 (−20%); 2.0 µ$_B$ (20%)|
| Ni     | Unit cell      | 9%             | 4.0 µ$_B$ (0–8%)    | 3.7 µ$_B$ (9%); biaxial  |
| Cu     | 5 x 5          | 20%            | 5.0 µ$_B$ (0%)      | 0 (−20%); 0 µ$_B$ (20%)  |
| Zn     | 5 x 5          | 20%            | 3.0 µ$_B$ (10%)     | 0 (−20%); 0 µ$_B$ (20%)  |

Interestingly, TM-doped systems show different magnetic responses. Except for V, Cr, Ti, and Sc atoms [88], the TM-doped systems without strain are nonmagnetic, and no matter how much biaxial strain is applied, there will be no long-range magnetic order. Arguably, Ma et al. [100] reported that V-doped monolayer MoS$_2$ exhibits magnetic half-metal at zero strain. After 2% compressive strain or 3% tensile strain is applied, the system will change from an FM state to an antiferromagnetic state.

Notably, the magnetic properties of Co/Ni/Cu/Zn-doped molybdenum disulfide show nonlinear changes with strain. After applying 20% compressive strain, the system is nonmagnetic. When the applied tensile strain reaches a specific value, the system will obtain a high spin state (2.8 µ$_B$ for the Co-doped; 5 µ$_B$ for the Ni-doped; 5 µ$_B$ for the Cu-doped; 3 µ$_B$ for the Zn-doped). However, the magnetic moment will reduce to 0 under 20% tensile strain, except for the Co-doped system (3 µ$_B$).

The linear monotonicity of magnetism with strain has also been found in Mn-doped and Fe-doped MoS$_2$ systems, which is similar to those of 1T-MoS$_2$ and 1T-MoS$_2$H. In detail, the systems are NM under a 20% compressive strain. Applying 20% tensile strain, the systems have obtained high spin states (2.8 µ$_B$ for Mn-doped; 4.3 µ$_B$ for Fe-doped).

In general, strain engineering is an effective method to control the magnetism of the TM-doped molybdenum disulfide system.

3. Experimental Progress of Strain-Mediated Magnetism

3.1. Methods of Applying Strain

Since the experiments revealed that 2D materials can withstand up to 20% strain, strain-modulated magnetism has gradually become an emerging research field. However, it is difficult to apply strain directly in suspended 2D materials in Table 3.
Table 3. The range and types in strained MoS$_2$ systems by different inducing methods. HOPG: Highly oriented pyrolytic graphite; PMN-PT: [Pb(Mg$_{1/3}$Nb$_{2/3}$)O$_3$]$_{0.7}$-[PbTiO$_3$]$_{0.3}$. $\delta_{\text{mem}}$: the deflection of the membrane.

| Methods                      | Substrates          | Layers | Ranges          | Remarks               |
|------------------------------|---------------------|--------|-----------------|-----------------------|
| Pre-stretches substrate      | Gel-film [104]      | 3−5 L  | 0.2−2.5%        | Uniaxial              |
| Pre-stretches substrate      | PDMS [105]          | 2−10 L | 20% (PDMS)      | Uniaxial              |
| Flexible substrate           | Polyvinyl chloride  | 1−2 L  | 0−2.2%          | Uniaxial              |
| Flexible substrate           | Polymer [107]       | 1, few | 0−0.8%          | Uniaxial              |
| Flexible substrate           | Ag-coated PET [108] | 20−80 nm | 0−0.02%        | Uniaxial              |
| Flexible substrate           | PET [109]           | 1 L    | −0.7−0.7%       | Uniaxial              |
| Flexible substrate           | Polyimide [111]     | 1−2 L  | 0−0.32%         | Uniaxial              |
| Flexible substrate           | Polyimide [112]     | 2 L    | 0−1.19%         | Biaxial               |
| Flexible substrate           | PDMS [113]          | 1 L    | 0−4.8%          | Uniaxial              |
| Flexible substrate           | PDMS [114]          | 2−10 L | −2.2%           | Uniaxial              |
| Lattice mismatch Si/SiO$_2$  | 1 L                 | ~1.24% | Intrinsic tensile |
| Lattice mismatch HOPG        | 1 L                 | ~1.76% | Anisotropic tensile |
| Thermal mismatch Si/SiO$_2$  | 1 L                 | ~1.0%  | Intrinsic tensile |
| Thermal mismatch Si/SiO$_2$  | 1 L                 | ~0.4%  | Intrinsic tensile |
| Thermal mismatch Si/SiO$_2$  | 2 L                 | ~0.34% | Intrinsic compressive |
| Thermal mismatch Sapphire   | 1 L                 | 0.15%  | Intrinsic tensile |
| Thermal mismatch Si/SiO$_2$  | 1 L                 | ~0.8%  | Intrinsic tensile |
| Thermal mismatch Mica        | 1 L                 | ~0.8%  | Intrinsic tensile |
| Thermal mismatch PDMS        | 1 L                 | <0.2%  | Biaxial compressive |
| Thermal mismatch Al$_2$O$_3$ | ~60 nm              | ~0.29−0.45% | Biaxial compressive |
| Thermal mismatch m-quartz    | 1 L                 | ~0.776% | Uniaxial compressive |
| Alloying MoS$_2$Se$_2$(1−x) | 1 L                 | <4%    | Biaxial tensile |
| Creating buckles Gel-film   | 3−5 L               | 0.2−2.5% | Uniaxial tensile |
| Creating buckles PDMS       | 2−10 L              | −2.2%  | Uniaxial          |
| Creating buckles PDMS       | 2−10 L              | ~1−2%  | Uniaxial compressive |
| Creating buckles Al$_2$O$_3$ | ~60 nm              | −0.45−1.7% | Biaxial |
| Creating buckles m-quartz   | 1 L                 | 0.14−1.58% | Uniaxial tensile |
| Creating buckles Au films   | 1 L                 | −1.16−2.04% | Uniaxial |
| Creating buckles Si/SiO$_2$  | 10−21 nm            | 0.32−1.11% | Uniaxial tensile |
| Patterned substrate Holey Si$_3$N$_4$ | 2 L | ~1.8% | Biaxial tensile |
| Patterned substrate Ripped Si/SiO$_2$ | 4 L | ~0.5% | Uniaxial tensile |
| Patterned substrate SiO$_2$ nanocones | 1 L | ~0.565% | Biaxial tensile |
| Patterned substrate SiO$_2$ nanopillars | 1 L | ~2% | Uniaxial tensile |
| Patterned substrate Cone-Al$_2$O$_3$ | 2 L | ~0.04% | Tensile/compressive |
| Patterned substrate Pyramid-Al$_2$O$_3$ | 2 L | ~0.05% | Tensile/compressive |
| Patterned substrate ZnO rods | 1 L | 0−0.6% | Periodic biaxial |
| Bubbles PDMS                 | 1, few              | 2.9−3.5% | Biaxial tensile |
| Bubbles h-BN [132]           | 1 L                 | ~2%    | Gradient tensile |
| Bubbles Si/SiO$_2$ cavity [133] | multi-             | −0.8−1.5% | Biaxial, >5.6% |
| AFM tip Si/SiO$_2$ [134]     | 1-3 L               | $\delta_{\text{mem}}$: ~33 nm | Isotropic |
| AFM tip Si/SiO$_2$ [135]     | 1 L                 | 4.7 x 10$^{-5}$ F | Isotropic |
| Piezoelectric substrate PMN-PT [136] | 3 L | 0−0.2% | Biaxial compressive |

In 2013, Andres et al. [104] created wrinkles in few-layer MoS$_2$ by pre-stretching the gel-film substrate, resulting in uniaxial tensile strain up to 2.5%. In the same year, uniaxial tensile strain (0−2.2%) was also applied in the MoS$_2$/polycarbonate system by using four-point bending equipment [106]. Since then, many research groups have tried to apply strain through a variety of flexible substrates, including polymers [107], polyethylene terephthalate (PET) [108,109], polystyrene alcohol (PVA) [110], polyimide (PI) [111,112] and polydimethylsiloxane (PDMS) [113,114].

In addition, the researchers have found that the intrinsic tensile strain (0.15−1.37%) was also introduced in CVD grown-monolayer MoS$_2$ [113,115,117−119,122]. This intrinsic tensile strain is
caused by the mismatch of thermal expansion coefficients [72,73,113,115–117,121]. Interestingly, whether through flexible substrate [104] or thermal mismatch [72,73], the strain state of MoS$_2$ materials can be further mediated by creating buckles [72,73,104,105,114,121,123,124].

Recently, it has also been experimentally found that the strain can be introduced into the materials through patterned substrates such as holey Si$_3$N$_4$ [125], rippled Si/SiO$_2$ [126], SiO$_2$ nanocones [127], SiO$_2$ nanopillars [128], pyramid/cones Al$_2$O$_3$ [129], ZnO nanorods arrays [130], nanodots arrays, and so on. During the transfer of MoS$_2$ samples, bubbles [131–133] are often formed to introduce large strains into the samples. Notably, most of the methods required additional equipment to provide external stimulation, such as an AFM tip [134,135], an electromechanical device [74], or a focused laser beam [136]. Because scanning superconducting quantum interference device (SQUID) needs to be conducted in a cryogenic temperature and vibration environment, it is difficult to detect the strained material system. So far, material systems that can spontaneously form buckles [72–74] are more suitable for magnetic study.

3.2. Spontaneous Formation of Web Buckles

Spontaneous buckling [163,164] is frequently observed in the film system of traditional materials. When the residual strain in the film reaches its critical value, it will drive the film to delamination from the substrate and from spontaneous wrinkles [72–74]. Interfacial adhesion [73,165] is one of the key factors in determining whether buckling is formed or not. Relatively low adhesion is conducive to the formation and propagation of buckles. Because there is no hanging bond on the surface of 2D materials such as MoS$_2$, the van der Waals (vdW) force is the interaction between the material and the substrate, and its interface adhesion is relatively low. Since then, MoS$_2$ films are very likely to become the perfect platform for understanding the phenomena of spontaneous buckling [75].

Recently, our group prepared ultra-smooth MoS$_2$ films [72,73] by polymer-assisted deposition (PAD), as shown in Figure 5. When the thickness of the film is about 400 nm, its roughness is about 1 nm. In the laboratory environment, MoS$_2$ films will also spontaneously form buckles due to external disturbance. Inspired by this experimental observation, we have used a tungsten probe close to the touch film to apply a point load. Once the probe touches the film, web buckles will be formed and further spread to the whole film surface. The formed large-area film with web buckles is very suitable for the SQUID test. Surprisingly, there is no obvious damage to the web buckle’s structure after the magnetic test.

3.3. Web Buckle-Mediated RTFM

Strain engineering [6,49,51,52,56–58,61,72,73,166] is a straightforward way to mediate the magnetism of MoS$_2$. However, most of the previous work [48–53,55,57,58,60,61,63,67,68,70,81,88,90,91,94,97,98,100] mainly focused on theoretical calculations. In the experiment, it was very difficult to apply biaxial strain directly to 2D materials. In order to clarify the strain-mediated FM in MoS$_2$, the following problems must be solved: (1) how to quantitatively determine the strain in the system experimentally; (2) how to select two suitable strain states to study their ferromagnetism; (3) how to measure ferromagnetism in different zones of web buckles.

Since Ferrari et al. [167] successfully measured the uniaxial and biaxial strain in graphene samples in 2009, Raman spectroscopy has become a powerful tool to characterize the strain deformation of two-dimensional materials. Soon after 2013, the strain-tunable energy gap was studied in mono-, bi-, and tri-layer MoS$_2$ [104,106,136,168,169]. Notably, Yagmurcukardes et al. [170] studied how the strain modulated the Raman characteristics of single-layer materials by first-principle calculation. Therefore, we used Raman spectroscopy to quantify the strain in web buckles (Figure 6) [72–74]. In detail, it is estimated by Raman mapping that about 68% of the region in the flat film has strain variations.
Figure 5. Formation of large-area web buckles. (A) Schematic illustration of the growth of a MoS$_2$ thin film with PAD and the triggering of buckles by a probe touching. (B–G) In situ observation of large area web buckles formed on an as-grown MoS$_2$ thin film with a thickness of 370 nm. Scale bar, 100 µm. (H,I) Propagating distances and velocities of buckles along four different branches as labeled in (G), as a function of time, respectively. (J) AFM 3D topography of a buckled MoS$_2$ thin film with a thickness of 230 nm. Scale bar, 20 µm. (K) Two height-profile lines crossing the middle of a telephone cord (line A) and a node position (line B) as shown in the inset. (L,M) Statistical histograms of lengths and widths of buckles. Reprinted/adapted with permission from Ref. [73]. Copyright 2019, American Chemical Society.

So far, we cannot distinguish the magnetism from different buckled areas. Although traditional magnetic force microscopy can be obtained, we believe that there are too many impurity signals to identify the information in the samples. Hopefully, the newly emerging magnetic imaging technologies will provide technical support for further research.
Figure 6. Native strain variations in MoS$_2$ web buckles. (A) Optical image of MoS$_2$ web buckles. (B,C) Raman position mapping in the E$_{12g}$ and A$_{1g}$ modes. (D,E) Strain mapping of MoS$_2$ web buckles is estimated by the response of Raman-active modes to the applied biaxial strain for single-layer MoS$_2$. (F-I) Raman intensity mapping in E$_{12g}$ (between 373.7 cm$^{-1}$ and 375.5 cm$^{-1}$) and A$_{1g}$ (between 398.6 cm$^{-1}$ and 400.4 cm$^{-1}$). Scale bars: 5 µm. (Reprinted/adapted with permission from Ref. [72]. Copyright 2020, American Institute of Physics).

Figure 7. Ferromagnetism of MoS$_2$ thin films and web buckles. M-H curves (A), $M_s$–$T$ (B), FL excitation spectra (C), and FL emission spectra (D) of MoS$_2$ thin films and web buckles. (E,F) $M_s$–$T$ of MoS$_2$ thin films and web buckles. (Reprinted/adapted with permission from Ref. [72]. Copyright 2020, American Institute of Physics).
4. Conclusions and Outlook

In this review, we have summarized the recent developments in strain-dependent magnetism in MoS$_2$. First, we reviewed the progress of the theoretical study. Then, we compared the experimental methods of introducing strain and their effects on the ferromagnetism. We emphasized the roles played by web buckles since they could induce biaxial tensile strain conveniently for further tests, including magnetic measurements. Obviously, despite some progress, the study of strain-dependent MoS$_2$ magnetism is still in its infancy.

Although RTFM has been enhanced experimentally by biaxial strain [72] induced by web buckles, the magnetism contributions from different zones cannot be distinguished experimentally. Since most conventional magnetic probes [171] require the sample area to be at the millimeter level, magnetic testing of the micron wrinkled area is a great challenge. Very recently, magnetic imaging techniques have emerged as important tools for investigating 2D materials, such as magnetic force microscopy (MFM) [172–178], SQUID [179,180], magneto-optical Kerr effect (MOKE) [181,182] and scanning nitrogen-vacancy center microscopy (SNVM) [183–187]. These techniques make it possible to detect the magnetism of the wrinkled area.

Since the modulation effect of uniaxial strain on the properties of materials is weaker than that of biaxial strain, whether the RTFM of molybdenum disulfide can be regulated by uniaxial strain has always been a mystery, which is worthy of further exploration. In addition, the substrates commonly used in experiments are isotropic, so it is relatively easy to introduce isotropic strain (such as biaxial strain) into 2D materials. Recently, anisotropic substrates such as $m$-quartz [121,188] have been used in experiments, which provides a new idea for introducing uniaxial strain into MoS$_2$. We believe that the regulation of uniaxial strain on FM can be explained clearly by combining nanoscale magnetic detection instruments.

Overall, an extensive and in-depth understanding of strain-mediated magnetism in MoS$_2$ is needed, which would provide new avenues for spintronics [189–197] and straintronics [198–202].

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References

1. Novoselov, K.S.; Geim, A.K.; Morozov, S.V.; Jiang, D.; Zhang, Y.; Dubonos, S.V.; Grigorieva, I.V.; Firsov, A.A. Electric field effect in atomically thin carbon films. Science 2004, 306, 666. [CrossRef]
2. Yazyev, O.V. Emergence of magnetism in graphene materials and nanostructures. Rep. Prog. Phys. 2010, 73, 056501. [CrossRef]
3. Huang, B.; Yu, J.; Wei, S.H. Strain control of magnetism in graphene decorated by transition-metal atoms. Phys. Rev. B 2011, 84, 075415. [CrossRef]
4. Kou, L.; Tang, C.; Guo, W.; Chen, C. Tunable magnetism in strained graphene with topological line defect. ACS Nano 2011, 5, 1012–1017. [CrossRef]
5. Ma, Y.; Dai, Y.; Guo, M.; Niu, C.; Yu, L.; Huang, B. Strain-induced magnetic transitions in half-fluorinated single layers of BN, GaN and graphene. Nanoscale 2011, 3, 2301–2306. [CrossRef] [PubMed]
6. Santos, E.J.G.; Ayuela, A.; Sanchez-Portal, D. Strain-tunable spin moment in Ni-doped graphene. J. Phys. Chem. C 2012, 116, 1174–1178. [CrossRef]
7. Santos, E.J.G.; Ayuela, A.; Fagan, S.B.; Mendes Filho, J.; Azevedo, D.L.; Souza Filho, A.G.; Sánchez-Portal, D. Switching on magnetism in Ni-doped graphene: Density functional calculations. Phys. Rev. B 2008, 78, 195420. [CrossRef]
8. Boukhvalov, D.W.; Katsnelson, M.I. sp-electron magnetic clusters with a large spin in graphene. *ACS Nano* **2011**, *5*, 2440–2446. [CrossRef]
9. Swain, A.K.; Bahadur, D. Deconvolution of mixed magnetism in multilayer graphene. *Appl. Phys. Lett.* **2014**, *104*, 242413. [CrossRef]
10. Magda, G.Z.; Jin, X.; Hagymási, I.; Vancsó, P.; Osváth, Z.; Nemes-Incze, P.; Hwang, C.; Bíró, L.P.; Tapasztó, L. Room-temperature magnetic order on zigzag edges of narrow graphene nanoribbons. *Nature* **2014**, *514*, 608. [CrossRef]
11. Li; S.; S.; Corso, M.; Choi, D.J.; Peña, D.; Frederiksen, T.; Pascual, J.I. Single spin localization and manipulation in graphene open-shell nanostructures. *Nat. Commun.* **2019**, *10*, 200. [CrossRef]
12. Sharpe, A.L.; Fox, E.J.; Barnard, A.W.; Finney, J.; Watanabe, K.; Taniguchi, T.; Kastner, M.A.; Goldhaber-Gordon, D. Emergent ferromagnetism near three-quarters filling in twisted bilayer graphene. *Science* **2019**, *365*, 605–608. [CrossRef] [PubMed]
13. Liu, X.; Hao, Z.; Khalaf, E.; Lee, J.Y.; Ronen, Y.; Yoo, H.; Haei Najafabadi, D.; Watanabe, K.; Taniguchi, T.; Vishwanath, A.; et al. Superconductors, orbital magnets and correlated states in magic-angle bilayer graphene. *Nature* **2019**, *574*, 653–657. [CrossRef]
14. Lu, X.; Stepanov, P.; Yang, W.; Xie, M.; Aamir, M.A.; Das, I.; Urgell, C.; Watanabe, K.; Taniguchi, T.; Zhang, G.; et al. Tunable spin-polarized correlated states in twisted double bilayer graphene. *Nature* **2020**, *583*, 221–225. [CrossRef] [PubMed]
15. Zhou, H.; Holleis, L.; Saito, Y.; Cohen, L.; Huynh, W.; Patterson Caitlin, L.; Yang, F.; Taniguchi, T.; Watanabe, K.; Young, A.F. Isospin magnetism and spin-polarized superconductivity in bernal bilayer graphene. *Science* **2022**, *375*, 774–778. [CrossRef]
16. Chen, G.; Sharpe, A.L.; Fox, E.J.; Zhang, Y.-H.; Wang, S.; Jiang, L.; Lyu, B.; Li, H.; Watanabe, K.; Taniguchi, T.; et al. Tunable correlated Chern insulator and ferromagnetism in a moiré superlattice. *Nature* **2020**, *579*, 56–61. [CrossRef]
17. Li, Y.; Zhou, Z.; Zhang, S.; Chen, Z. MoS$_2$ nanoribbons: High stability and unusual electronic and magnetic properties. *J. Am. Chem. Soc.* **2008**, *130*, 16739–16744. [CrossRef] [PubMed]
18. Jaglicic, Z.; Jeromen, A.; Trontelj, Z.; Mihailovic, D.; Arcon, D.; Remskar, M.; Mrzel, A.; Dominko, R.; Gaberscek, M.; Martinez-Aguado, J.M.; et al. Magnetic properties of MoS$_2$ nanotubes doped with lithium. *Polyhedron* **2003**, *22*, 2293–2295. [CrossRef]
19. Mihailovic, D.; Jaglicic, Z.; Arcon, D.; Mrzel, A.; Zorko, A.; Remskar, M.; Kabanov, V.V.; Dominko, R.; Gaberscek, M.; Gomez-Garcia, C.J.; et al. Unusual magnetic state in Lithium-doped MoS$_2$ nanotubes. *Phys. Rev. Lett.* **2003**, *90*, 146401. [CrossRef] [PubMed]
20. Vojvodic, A.; Hinnemann, B.; Norrskov, J.K. Magnetic edge states in MoS$_2$ characterized using density-functional theory. *Phys. Rev. B* **2009**, *80*, 125416. [CrossRef]
21. Shidpour, R.; Manteghian, M. A density functional study of strong local magnetism creation on MoS$_2$ nanoribbon by sulfur vacancy. *Nanoscale* **2010**, *2*, 1429–1435. [CrossRef] [PubMed]
22. Gao, D.; Shi, S.; Tao, K.; Xia, B.; Xue, D. Tunable ferromagnetic ordering in MoS$_2$ nanosheets with fluorine adsorption. *Nanoscale* **2015**, *7*, 4211–4216. [CrossRef] [PubMed]
23. Chacko, L.; Swetha, A.K.; Anjana, R.; Jayaraj, M.K.; Aneesh, P.M. Wasp-waisted magnetism in hydrothermally grown MoS$_2$ nanoflakes. *Mater. Res. Express.* **2016**, *3*, 116102. [CrossRef]
24. Gao, G.H.; Chen, C.; Xie, X.B.; Su, Y.T.; Kang, S.D.; Zhu, G.C.; Gao, D.Y.; Trampert, A.; Cai, L.T. Toward edges-rich MoS$_2$ nanoribbon by sulfur induced by antiferromagnetic proximity of yttrium iron garnet. *Adv. Quantum Technol.* **2021**, *4*, 2000104. [CrossRef]
36. Gao, D.; Si, M.; Li, J.; Zhang, J.; Zhang, Z.; Yang, Z.; Xue, D. Ferromagnetism in freestanding MoS\textsubscript{2} nanosheets. *Nanoscale Res. Lett.* 2013, 8, 129. [CrossRef]

37. Yan, S.M.; Qiao, W.; He, X.M.; Guo, X.B.; Xi, L.; Zhong, W.; Du, Y.W. Enhancement of magnetism by structural phase transition in MoS\textsubscript{2}. *Appl. Phys. Lett.* 2015, 106, 012408. [CrossRef]

38. Park, C.-S.; Chu, D.; Shon, Y.; Lee, J.; Kim, E.K. Room temperature ferromagnetic and ambipolar behaviors of MoS\textsubscript{2} doped by manganese oxide using an electrochemical method. *Appl. Phys. Lett.* 2017, 110, 222104. [CrossRef]

39. Yang, Z.; Gao, D.; Zhang, J.; Xu, Q.; Shi, S.; Tao, K.; Xue, D. Realization of high curie temperature ferromagnetism in atomically thin MoS\textsubscript{2} and WS\textsubscript{2} nanosheets with uniform and flower-like morphology. *Nanoscale* 2015, 7, 650–658. [CrossRef] [PubMed]

40. Kumar, A.; Pawar, S.; Sharma, S.; Kaur, D. Bipolar resistive switching behavior in MoS\textsubscript{2} nanosheets fabricated on ferromagnetic shape memory alloy. *Appl. Phys. Lett.* 2018, 112, 262106. [CrossRef]

41. Xie, B.R.; Liu, P.T.; Liu, Y.G.; Gao, D.Q.; Xue, D.S.; Ding, J. Re doping induced 2H-1T phase transformation and ferromagnetism in MoS\textsubscript{2} nanosheets. *Appl. Phys. Lett.* 2018, 113, 013101. [CrossRef]

42. Shirokura, T.; Muneta, I.; Kakushima, K.; Tsutsui, K.; Wakabayashi, H. Strong edge-induced ferromagnetism in sputtered MoS\textsubscript{2} film treated by post-annealing. *Appl. Phys. Lett.* 2019, 115, 192404. [CrossRef]

43. Duan, H.; Li, G.; Tan, H.; Wang, C.; Li, Q.; Liu, C.; Yin, Y.; Li, X.; Qi, Z.; Yan, W. Sulfur-vacancy-tunable interlayer magnetic coupling in centimeter-scale MoS\textsubscript{2} bilayer. *Nano Res.* 2022, 15, 881–888. [CrossRef]

44. Mathew, S.; Gopinadhan, K.; Chan, T.K.; Yu, X.J.; Zhan, D.; Cao, L.; Rusydi, A.; Breese, M.B.H.; Dhar, S.; Shen, Z.X.; et al. Magnetism in MoS\textsubscript{2} induced by proton irradiation. *Appl. Phys. Lett.* 2012, 101, 102103. [CrossRef]

45. Tongay, S.; Varnoosfaderani, S.S.; Appleton, B.R.; Wu, J.; Hebard, A.F. Magnetic properties of MoS\textsubscript{2}: Existence of ferromagnetism. *Appl. Phys. Lett.* 2012, 101, 123105. [CrossRef]

46. Han, S.W.; Hwang, Y.H.; Kim, S.H.; Yun, W.S.; Lee, J.D.; Park, M.G.; Ryu, S.; Park, J.S.; Yoo, D.H.; Yoon, S.P.; et al. Controlling ferromagnetic easy axis in a layered MoS\textsubscript{2} single crystal. *Phys. Rev. Lett.* 2013, 110, 247201. [CrossRef]

47. Wang, Y.; Tseng, L.-T.; Murmu, P.P.; Bao, N.; Kennedy, J.; Ionesc, M.; Ding, J.; Suzuki, K.; Li, S.; Yi, J. Defects engineering induced room temperature ferromagnetism in transition metal doped MoS\textsubscript{2}. *Mater. Des.* 2017, 121, 77–84. [CrossRef]

48. Kou, L.; Tang, C.; Zhang, Y.; Heine, T.; Chen, C.; Frauenheim, T. Tuning magnetism and electronic phase transitions by strain and electric field in zigzag MoS\textsubscript{2} nanoribbons. *J. Phys. Chem. Lett.* 2012, 3, 2934–2941. [CrossRef]

49. Lu, P.; Wu, X.J.; Guo, W.L.; Zeng, X.C. Strain-dependent electronic and magnetic properties of MoS\textsubscript{2} monolayer, bilayer, nanoribbons and nanotubes. *Phys. Chem. Chem. Phys.* 2012, 14, 13035–13040. [CrossRef]

50. Ma, Y.D.; Dai, Y.; Guo, M.; Niu, C.W.; Zhu, Y.T.; Huang, B.B. Evidence of the existence of magnetism in pristine VX\textsubscript{2} monolayers (X = S, Se) and their strain-induced tunable magnetic properties. *ACS Nano* 2012, 6, 1695–1701. [CrossRef]

51. Pan, H.; Zhang, Y.W. Tuning the electronic and magnetic properties of MoS\textsubscript{2} nanosheets by strain engineering. *J. Phys. Chem. C* 2012, 116, 11752–11757. [CrossRef]

52. Zhou, Y.G.; Wang, Z.G.; Yang, P.; Zu, X.T.; Yang, L.; Sun, X.; Gao, F. Tensile strain induced ferromagnetism in layered NbS\textsubscript{2} and NbSe\textsubscript{2}. *ACS Nano* 2012, 6, 9727–9736. [CrossRef] [PubMed]

53. Shi, H.; Pan, H.; Zhang, Y.-W.; Yakobson, B.I. Strong ferromagnetism in hydrogenated monolayer MoS\textsubscript{2} tuned by strain. *Phys. Rev. B* 2013, 88, 205305. [CrossRef]

54. Guo, H.; Lu, N.; Wang, L.; Wu, X.; Zeng, X.C. Tuning electronic and magnetic properties of early transition-metal dichalcogenides via tensile strain. *J. Phys. Chem. C* 2014, 118, 7242–7249. [CrossRef]

55. Qi, J.S.; Li, X.; Chen, X.F.; Hu, K.G. Strain tuning of magnetism in Mn doped MoS\textsubscript{2} monolayer. *J. Phys. Condens. Matter* 2014, 26, 256003. [CrossRef] [PubMed]

56. Xu, Y.; Liu, X.; Guo, W. Tensile strain induced switching of magnetic states in NbSe\textsubscript{2} and NbS\textsubscript{2} single layers. *Nanoscale* 2014, 6, 12929–12933. [CrossRef]

57. Zheng, H.L.; Yang, B.S.; Wang, D.D.; Han, R.L.; Du, X.B.; Yan, Y. Tuning magnetism of monolayer MoS\textsubscript{2} by doping vacancy and applying strain. *Appl. Phys. Lett.* 2014, 104, 132403. [CrossRef]

58. Chen, Z.P.; He, J.J.; Zhou, P.; Na, J.; Sun, L.Z. Strain control of the electronic structures, magnetic states, and magnetic anisotropy of Fe doped single-layer Mo\textsubscript{2}. *Comp. Mater. Sci.* 2015, 110, 102–108. [CrossRef]

59. Manchanda, P.; Sharma, V.; Yu, H.B.; Sellmyer, D.J.; Skomsksi, R. Magnetism of Ta dichalcogenide monolayers tuned by strain and hydrogenation. *Appl. Phys. Lett.* 2015, 107, 032402. [CrossRef]

60. Yun, W.S.; Lee, J.D. Strain-induced magnetism in single-layer MoS\textsubscript{2}: Origin and manipulation. *J. Phys. Chem. C* 2015, 119, 2822–2827. [CrossRef]

61. Zheng, H.L.; Yang, B.S.; Wang, H.X.; Chen, Z.Y.; Yan, Y. Strain induced modulation to the magnetism of antisite defects doped monolayer MoS\textsubscript{2}. *J. Magn. Magn. Mater.* 2015, 386, 155–160. [CrossRef]

62. Chen, P.; Zhao, X.; Wang, T.X.; Dai, X.Q.; Xia, C.X. Electronic and magnetic properties of Ag-doped monolayer WS\textsubscript{2} by stain. *J. Alloy. Compd.* 2016, 680, 659–664. [CrossRef]

63. Sahoo, M.P.K.; Wang, J.; Zhang, Y.J.; Shimada, T.; Kitamura, T. Modulation of gas adsorption and magnetic properties of monolayer-MoS\textsubscript{2} by antisite defect and stain. *J. Phys. Chem. C* 2016, 120, 14113–14121. [CrossRef]

64. Yang, Y.; Fan, X.L.; Zhang, H. Effect of strain on the magnetic states of transition-metal atoms doped monolayer WS\textsubscript{2}. *Comp. Mater. Sci.* 2016, 117, 354–360. [CrossRef]
65. Zhang, W.; Guo, H.T.; Jiang, J.; Tao, Q.C.; Song, X.J.; Li, H.; Huang, J. Magnetism and magnetocrystalline anisotropy in single-layer PtSe$_2$. Interplay between strain and vacancy. J. Appl. Phys. 2016, 120, 013904. [CrossRef]
66. Luo, M.; Shen, Y.H. Effect of strain on magnetic coupling in Ga-doped WS$_2$ monolayer: Ab initio study. J. Supercond. Nov. Magn. 2018, 31, 1801–1805. [CrossRef]
67. Xu, W.; Yan, S.M.; Qiao, W. Magnetism in monolayer 1T-MoS$_2$ and 1T-MoS$_2$H tuned by strain. RSC Adv. 2018, 8, 8435–8441. [CrossRef][PubMed]
68. Zhu, Y.; Liang, X.; Qin, J.; Deng, L.; Bi, L. Strain tunable magnetic properties of 3d transition-metal ion doped monolayer MoS$_2$: A first-principles study. AIP Adv. 2018, 8, 055917. [CrossRef]
69. Cortés, N.; Ávalos-Ovando, O.; Rosales, L.; Orellana, P.A.; Ulloa, S.E. Tunable Spin-Polarized Edge Currents in Proximitized Transition Metal Dichalcogenides. Phys. Rev. Lett. 2019, 122, 086401. [CrossRef][PubMed]
70. Nie, S.; Li. Z. Strain effect on the magnetism of N-doped molybdenum disulfide. Phys. Status Solidi B 2019, 256, 1900110. [CrossRef]
71. Yang, H.P.; Ouyang, W.G.; Yan, X.X.; Li, Z.C.; Yu, R.; Yuan, W.J.; Luo, J.; Zhu, J. Bilayer MoS$_2$ quantum dots with tunable magnetism and spin. AIP Adv. 2018, 8, 115103. [CrossRef]
72. Ren, H.T.; Zhang, L.; Xiang, G. Web buckle-mediated room-temperature ferromagnetism in strained MoS$_2$ nanoribbons. Phys. Rev. Lett. 2019, 122, 086401. [CrossRef][PubMed]
73. Ren, H.T.; Xiong, Z.X.; Wang, E.Z.; Yuan, Z.Q.; Sun, Y.F.; Zhu, K.L.; Wang, B.L.; Wang, X.W.; Ding, H.Y.; Liu, P.; et al. Watching dynamic self-assembly of web buckles in strained MoS$_2$ thin films. ACS Nano 2019, 13, 3106–3116. [CrossRef]
74. Ren, H.T.; Xiong, G.; Lu, J.T.; Zhang, X.; Zhang, L. Biaxial strain-mediated room temperature ferromagnetism of ReS$_2$ web buckles. Adv. Electron. Mater. 2019, 5, 1900814. [CrossRef]
75. Ataca, C.; Sahin, H.; Akturk, E.; Ciraci, S. Mechanical and electronic properties of MoS$_2$ nanoribbons and their defects. J. Phys. Chem. C 2011, 115, 3934–3941. [CrossRef]
76. Dolui, K.; Das Pemmaraju, C.; Sanvito, S. Electric field effects on armchair MoS$_2$ nanoribbons. ACS Nano 2012, 6, 4823–4834. [CrossRef]
77. Pan, H.; Zhang, Y.W. Edge-dependent structural, electronic and magnetic properties of MoS$_2$ nanoribbons. J. Mater. Chem. 2012, 22, 7280–7290. [CrossRef]
78. Wen, Y.N.; Gao, P.F.; Chen, X.; Xia, M.G.; Zhang, Y.; Zhang, S.L. Width-dependent structural stability and magnetic properties of monolayer zigzag MoS$_2$ nanoribbons. Mol. Phys. Lett. B 2017, 31, 1750017. [CrossRef]
79. Chen, K.Y.; Ding, J.K.; Ding, X.D.; Sun, J.; Yang, S.; Liu, J.Z. Ferromagnetism of 1T-′MoS$_2$ nanoribbons stabilized by edge reconstruction and its periodic variation on nanoribbons width. J. Am. Chem. Soc. 2018, 140, 16206–16212. [CrossRef][PubMed]
80. Liu, Y.C.; Ren, H.T.; Gao, P.F.; Zhang, Y.; Xia, M.G.; Zhang, S.L. Flexible modulation of electronic and magnetic properties of zigzag H-MoS$_2$ nanoribbons by crack defects. J. Phys. Condens. Matter 2018, 30, 283502. [CrossRef][PubMed]
81. Wang, M.; Pang, Y.; Liu, D.Y.; Zheng, S.H.; Song, Q.L. Tuning magnetism by strain and external electric field in zigzag Janus MoSSe nanoribbons. Comp. Mater. Sci. 2018, 146, 240–247. [CrossRef]
82. Vancso, P.; Hagymasi, I.; Castenetto, P.; Lambin, P. Stability of edge magnetism against disorder in zigzag MoS$_2$ nanoribbons. Phys. Rev. Mater. 2019, 3, 094003. [CrossRef]
83. Chen, M.Y.; Hu, C.; Luo, X.F.; Hong, A.J.; Yu, T.; Yuan, C.L. Ferromagnetic behaviors in monolayer MoS$_2$ introduced by nitrogen-doping. Appl. Phys. Lett. 2016, 106, 073102. [CrossRef]
84. Cheng, Y.C.; Zhu, Z.Y.; Mi, W.B.; Guo, Z.B.; Schwingenschlogl, U. Prediction of two-dimensional diluted magnetic semiconductors: Doped monolayer MoS$_2$ systems. Phys. Rev. B 2013, 87, 100401. [CrossRef]
85. Najmaei, S.; Liu, Z.; Zhou, W.; Zou, X.L.; Shi, G.; Lei, S.D.; Yakobson, B.I.; I drobo, J.C.; Ajayan, P.M.; Lou, J. Vapour phase growth and grain boundary structure of molybdenum disulphide atomic layers. Nat. Mater. 2013, 12, 754–759. [CrossRef][PubMed]
86. Zhou, W.; Zou, X.; Najmaei, S.; Liu, Z.; Shi, Y.; Kong, J.; Lou, J.; Ajayan, P.M.; Yakobson, B.I.; Idrobo, J.C. Intrinsic structural defects in monolayer molybdenum disulfide. Nano Lett. 2013, 13, 2615–2622. [CrossRef][PubMed]
87. Zhou, Y.; Yang, P.; Zu, H.; Gao, F.; Zu, X. Electronic structures and magnetic properties of MoS$_2$ nanoribbons: Atomic defects, nanoholes, nanodots and antidots. Phys. Chem. Chem. Phys. 2013, 15, 10385–10394. [CrossRef][PubMed]
88. Zhou, Y.G.; Su, Q.L.; Wang, Z.G.; Deng, H.Q.; Zu, X.T. Controlling magnetism of MoS$_2$ sheets by embedding transition-metal atoms and applying strain. Phys. Chem. Chem. Phys. 2013, 15, 18464–18470. [CrossRef]
89. Najmaei, S.; Yuan, J.T.; Zhang, J.; Ajayan, P.; Lou, J. Synthesis and defect investigation of two-dimensional molybdenum disulphide atomic layers. Acc. Chem. Res. 2015, 48, 31–40. [CrossRef][PubMed]
90. Zhang, H.; Fan, L.; Yang, Y.; Xiao, P. Strain engineering the magnetic states of vacancy-doped monolayer MoSe$_2$. J. Alloy. Compd. 2015, 635, 307–313. [CrossRef]
91. Li, A.; Pan, J.; Yang, Z.; Zhou, L.; Xiong, X.; Ouyang, F. Charge and strain induced magnetism in monolayer MoS$_2$ with S vacancy. J. Magn. Magn. Mater. 2018, 451, 520–525. [CrossRef]
92. Yang, H.P.; Ouyang, W.G.; Yan, X.X.; Li, Z.C.; Yu, R.; Yuan, W.J.; Luo, J.; Zhu, J. Bilayer MoS$_2$ quantum dots with tunable magnetism and spin. AIP Adv. 2018, 8, 115103. [CrossRef]
93. Bourissant, A.; Layadi, A.; Maghraoui-Meherzi, H. Experimental study of the diamagnetism and the ferromagnetism in MoS$_2$ thin films. Appl. Phys. A 2020, 126, 93. [CrossRef]
94. Tao, P.; Guo, H.; Yang, T.; Zhang, Z. Strain-induced magnetism in MoS$_2$ monolayer with defects. J. Appl. Phys. 2014, 115, 054305. [CrossRef]
95. Kang, K.; Fu, S.C.; Shayan, K.; Anthony, Y.; Dadras, S.; Yuzan, X.; Kazunori, F.; Terrones, M.; Zhang, W.; Stefan, S.; et al. The effects of substitutional Fe-doping on magnetism in MoS$_2$ and WS$_2$ monolayers. Nanotechnology 2021, 32, 095708. [CrossRef] [PubMed]
96. Zhao, C.Y.; Jin, C.H.; Wu, J.L.; Ji, W. Magnetism in molybdenum disulphide monolayer with sulfur substituted by 3d transition metals. J. Appl. Phys. 2016, 120, 144305. [CrossRef]
97. Li, H.X.; Huang, M.; Cao, G.Y. Magnetic properties of atomic 3d transition-metal chains on S-vacancy-line templates of monolayer MoS$_2$. Effects of substrate and strain. J. Mater. Chem. C 2017, 5, 4557–4564. [CrossRef]
98. Miao, Y.P.; Huang, Y.H.; Bao, H.W.; Xu, K.W.; Ma, F.; Chu, P.K. Tunable magnetic coupling in Mn-doped monolayer MoS$_2$ under lattice strain. J. Phys. Condens. Matter 2018, 30, 215801. [CrossRef]
99. Zhang, S.F.; Li, Z.Q.; Li, J.; Hao, G.L.; He, C.Y.; Ouyang, T.; Zhang, C.X.; Tang, C.; Zhong, J.X. Strain effects on magnetic states of monolayer MoS$_2$ doped with group IIIA to VA atoms. Physica E 2019, 114, 113609. [CrossRef]
100. Miao, Y.P.; Bao, H.W.; Fan, W.; Ma, F. Modulation of the electronic structure and magnetism performance of V-doped monolayer MoS$_2$ by strain engineering. J. Phys. Chem. Solids 2020, 142, 109459. [CrossRef]
101. Yue, Y.L.; Jiang, C.; Han, Y.L.; Wang, M.; Ren, J.; Wu, Y.K. Magnetic anisotropies of Mn-, Fe-, and Co-doped monolayer MoS$_2$. J. Magn. Magn. Mater. 2020, 496, 165929. [CrossRef]
102. Gao, B.; Huang, C.; Zhu, F.; Ma, C.L.; Zhu, Y. Magnetic properties of Mn-doped monolayer MoS$_2$. Phys. Lett. A 2021, 414, 127636. [CrossRef]
103. Han, X.P.; Benkraouda, M.; Amrane, N. S vacancy enhanced ferromagnetism in Mn-doped monolayer MoS$_2$: A hybrid functional study. Chem. Phys. 2021, 541, 111043. [CrossRef]
104. Castellanos-Gomez, A.; Roldan, R.; Cappelluti, E.; Buscema, M.; Guinea, F.; van der Zant, H.S.J.; Steele, G.A. Local strain engineering in atomically thin MoS$_2$. Nano Lett. 2013, 13, 3561–3566. [CrossRef]
105. Iguiniz, N.; Frisenda, R.; Bratschitsch, R.; Castellanos-Gomez, A. Revisiting the buckling metrology method to determine the Young’s modulus of 2D materials. Adv. Mater. 2019, 31, 1807150. [CrossRef]
106. Conley, H.J.; Wang, B.; Ziegler, J.I.; Haglund, R.F.; Pantelides, S.T.; Bolotin, K.I. Bandgap engineering of strained monolayer and bilayer MoS$_2$. Nano Lett. 2013, 13, 3626–3630. [CrossRef] [PubMed]
107. Rice, C.; Young, R.J.; Zan, R.; Bangert, U.; Wolverson, D.; Georgiou, T.; Jalil, R.; Novoselov, K.S. Raman-scattering measurements and first-principles calculations of strain-induced phonon shifts in monolayer MoS$_2$. Phys. Rev. B 2013, 87, 081307. [CrossRef]
108. Lee, J.H.; Jang, W.S.; Han, S.W.; Baik, H.K. Efficient hydrogen evolution by mechanically strained MoS$_2$ nanosheets. Langmuir 2014, 30, 9866–9873. [CrossRef]
109. Pak, S.; Lee, J.; Lee, Y.W.; Jang, A.R.; Ahn, S.; Ma, K.Y.; Cho, Y.; Hong, J.; Lee, S.; Jeong, H.Y.; et al. Strain-mediated interlayer coupling effects on the excitonic behaviors in an epitaxially grown MoS$_2$/WS$_2$ van der Waals heterobilayer. Nano Lett. 2017, 17, 5634–5640. [CrossRef]
110. Li, Z.; Lv, Y.; Ren, L.; Li, J.; Kong, L.; Zeng, Y.; Tao, Q.; Wu, R.; Ma, H.; Zhao, B.; et al. Efficient strain modulation of 2D materials via polymer encapsulation. Nat. Commun. 2020, 11, 1151. [CrossRef]
111. John, A.P.; Thenapparambil, A.; Thalakulam, M. Strain-engineering the Schottky barrier and electrical transport on MoS$_2$. Nanotechnology 2020, 31, 275703. [CrossRef]
112. Thai, K.Y.; Park, I.; Kim, B.J.; Hoang, A.T.; Na, Y.; Park, C.U.; Chae, Y.; Ahn, J.-H. MoS$_2$/Graphene photodetector array with strain-modulated photoresponse up to the near-infrared regime. ACS Nano 2020, 15, 12836–12846. [CrossRef] [PubMed]
113. Liu, Z.; Amani, M.; Najmaei, S.; Xu, Q.; Zou, X.; Zhou, W.; Yu, T.; Qiu, C.; Birdwell, A.G.; Crowne, F.J.; et al. Strain and structure heterogeneity in MoS$_2$ atomic layers grown by chemical vapour deposition. Nat. Commun. 2014, 5, 5246. [CrossRef]
114. Brennan, C.J.; Nguyen, J.; Yu, E.T.; Lu, N.S. Interface adhesion between 2D materials and elastomers measured by buckle delaminations. Adv. Mater. Interfaces 2015, 2, 1500176. [CrossRef]
115. Amani, M.; Chin, M.L.; Mazzoni, A.L.; Burke, R.A.; Najmaei, S.; Ajayan, P.M.; Lou, J.; Dubey, M. Growth-substrate induced performance degradation in chemically synthesized monolayer MoS$_2$ field effect transistors. Appl. Phys. Lett. 2014, 104, 203506. [CrossRef]
116. Zhang, C.; Li, M.-Y.; Tersoff, J.; Han, Y.; Su, Y.; Li, L.-J.; Muller, D.A.; Shih, C.-K. Strain distributions and their influence on electronic structures of WS$_2$–MoS$_2$ laterally strained heterojunctions. Nat. Nanotechnol. 2018, 13, 152–158. [CrossRef]
117. Chae, W.H.; Cain, J.D.; Hanson, E.D.; Murthy, A.A.; Dravid, V.P. Substrate-induced strain and charge doping in CVD-grown monolayer MoS$_2$. Appl. Phys. Lett. 2017, 111, 143106. [CrossRef]
118. Luo, S.W.; Cullen, C.P.; Guo, G.C.; Zhong, J.X.; Duesberg, G.S. Investigation of growth-induced strain in monolayer MoS$_2$ grown by chemical vapor deposition. Appl. Surf. Sci. 2020, 508, 145127. [CrossRef]
119. Yu, Y.; Jung, G.S.; Liu, C.; Lin, Y.-C.; Rouleau, C.M.; Yoon, M.; Eres, G.; Duscher, G.; Xiao, K.; Irele, S.; et al. Strain-induced growth of twisted bilayers during the coalescence of monolayer MoS$_2$ crystals. ACS Nano 2021, 15, 4504–4517. [CrossRef]
120. Plechinger, G.; Castellanos-Gomez, A.; Buscema, M.; van der Zant, H.S.J.; Steele, G.A.; Kuc, A.; Heine, T.; Schüller, C.; Korn, T. Control of biaxial strain in single-layer molybdenite using local thermal expansion of the substrate. 2D Mater. 2015, 2, 015006. [CrossRef]
121. Wang, J.; Han, M.; Wang, Q.; Ji, Y.; Zhang, X.; Shi, R.; Wu, Z.; Zhang, L.; Amini, A.; Guo, L.; et al. Strained epitaxy of monolayer transition metal dichalcogenides for wrinkle arrays. ACS Nano 2021, 15, 6633–6644. [CrossRef]
175. Moser, A.; Xiao, M.; Kappenberger, P.; Takano, K.; Weresin, W.; Ikeda, Y.; Do, H.; Hug, H.J. High-resolution magnetic force microscopy study of high-density transitions in perpendicular recording media. J. Magn. Magn. Mater. 2005, 287, 298–302. [CrossRef]

176. Mattiat, H.; Rossi, N.; Gross, B.; Pablo-Navarro, J.; Magén, C.; Badea, R.; Berezovsky, J.; De Teresa, J.M.; Poggio, M. Nanowire magnetic force sensors fabricated by focused-electron-beam-induced deposition. Phys. Rev. Appl. 2020, 13, 044043. [CrossRef]

177. Jeffery, M.; Van Duizer, T.; Kirtley, J.R.; Ketchen, M.B. Magnetic imaging of moat-guarded superconducting electronic circuits. Appl. Phys. Lett. 1995, 67, 1769–1771. [CrossRef]

178. Sheng, Z.; Feng, Q.; Zhou, H.; Dong, S.; Xu, X.; Cheng, L.; Liu, C.; Hou, Y.; Meng, W.; Sun, Y.; et al. Visualization of electronic multiple ordering and its dynamics in high magnetic field. Evidence of electronic multiple ordering crystals. ACS Appl. Mater. Inter. 2018, 10, 20136–20141. [CrossRef]

179. Kirtley, J.R.; Paulius, L.; Rosenberg, A.J.; Palmstrom, J.C.; Holland, C.M.; Spanton, E.M.; Schiessl, D.; Jermain, C.L.; Gibbons, J.; Fung, Y.K.K.; et al. Scanning SQUID susceptometers with sub-micron spatial resolution. Rev. Sci. Instrum. 2016, 87, 093702. [CrossRef] [PubMed]

180. Vool, U.; Hamo, A.; Varnavides, G.; Wang, Y.; Zhou, T.X.; Kumar, N.; Dovzhenko, Y.; Qiu, Z.; Garcia, C.A.C.; Pierce, A.T.; et al. Scanning SQUID susceptometers with sub-micron spatial resolution. Rev. Sci. Instrum. 2016, 87, 093702. [CrossRef] [PubMed]

181. Rasaili, P.; Sharma, N.K.; Bhattarai, A. Comparison of ferromagnetic materials: Past work, recent trends, and applications. Adv. Mater. Horiz. 2021, 9, 2004533. [CrossRef] [PubMed]

182. Jeffery, M.; Van Duizer, T.; Kirtley, J.R.; Ketchen, M.B. Magnetic imaging of moat-guarded superconducting electronic circuits. Appl. Phys. Lett. 1995, 67, 1769–1771. [CrossRef]

183. Thiel, L.; Zhang, W.; Tschudin, M.A.; Rohner, D.; Gutiérrez-Lezama, I.; Ubrig, N.; Gibertini, M.; Giannini, E.; Morpurgo, A.F.; Maletinsky, P. Probing magnetism in 2D materials at the nanoscale with single-spin microscopy. Science 2019, 364, 973–976. [CrossRef] [PubMed]

184. Chang, K.; Eichler, A.; Rhensius, J.; Lorenzelli, L.; Degen, C.L. Nanoscale imaging of current density with a single electron spin sensitivity. Nat. Nanotechnol. 2013, 8, 639–644. [CrossRef]

185. Vool, U.; Hamo, A.; Varnavides, G.; Wang, Y.; Zhou, T.X.; Kumar, N.; Dovzhenko, Y.; Qiu, Z.; Garcia, C.A.C.; Pierce, A.T.; et al. Scanning SQUID susceptometers with sub-micron spatial resolution. Rev. Sci. Instrum. 2016, 87, 093702. [CrossRef] [PubMed]

186. Vool, U.; Hamo, A.; Varnavides, G.; Wang, Y.; Zhou, T.X.; Kumar, N.; Dovzhenko, Y.; Qiu, Z.; Garcia, C.A.C.; Pierce, A.T.; et al. Scanning SQUID susceptometers with sub-micron spatial resolution. Rev. Sci. Instrum. 2016, 87, 093702. [CrossRef] [PubMed]

187. Vool, U.; Hamo, A.; Varnavides, G.; Wang, Y.; Zhou, T.X.; Kumar, N.; Dovzhenko, Y.; Qiu, Z.; Garcia, C.A.C.; Pierce, A.T.; et al. Scanning SQUID susceptometers with sub-micron spatial resolution. Rev. Sci. Instrum. 2016, 87, 093702. [CrossRef] [PubMed]

188. Wang, J.; Luo, Y.; Cai, X.; Shi, R.; Wang, W.; Li, T.; Wu, Z.; Zhang, X.; Peng, O.; Amini, A.; et al. Multiple regulation over growth walls in a collinear antiferromagnet. Nano Lett. 2020, 20, 094426. [CrossRef] [PubMed]

189. Hossain, M.; Qin, B.; Li, B.; Duan, X.D. Synthesis, characterization, properties and applications of two-dimensional magnetic semiconductors. InfoMat 2020, 2, 639–655. [CrossRef]

190. Guo, Y.L.; Wang, B.; Zhang, X.W.; Yuan, S.J.; Ma, L.; Wang, J.L. Magnetic two-dimensional layered crystals meet with ferromagnetic semiconductors. InfoMat 2020, 2, 639–655. [CrossRef]

191. Liu, Y.P.; Zeng, C.; Zhong, J.H.; Ding, J.N.; Wang, Z.M.; Liu, Z.W. Spintronics in two-dimensional materials. Nano-Micro Lett. 2020, 12, 93. [CrossRef] [PubMed]

192. Xu, J.J.; Li, W.; Hou, Y.L. Two-dimensional magnetic nanostructures. Trends in Chem. 2020, 2, 163–173. [CrossRef]

193. Jiang, X.; Liu, Q.X.; Xing, J.P.; Liu, N.S.; Guo, Y.; Liu, Z.F.; Zhao, J.J. Recent progress on 2D magnets: Fundamental mechanism, structural design and modification. Appl. Phys. Rev. 2021, 8, 031305. [CrossRef]

194. Zhang, S.F.; Wu, H.; Yang, L.; Zhang, G.J.; Xie, Y.M.; Zhang, L.; Zhang, W.F.; Chang, H.X. Two-dimensional magnetic atomic crystals. Mater. Horiz. 2021, 9, 559–576. [CrossRef]

195. Hossain, M.; Qin, B.; Li, B.; Duan, X.D. Synthesis, characterization, properties and applications of two-dimensional magnetic materials. Nano Today 2022, 42, 101338. [CrossRef] [PubMed]

196. Wang, Y.; Wang, C.; Liang, S.J.; Ma, Z.; Xu, K.; Liu, X.; Zhang, L.; Admasu, A.S.; Cheong, S.W.; Wang, L.; et al. Strain-sensitive magnetization reversal of a van der Waals magnet. Adv. Mater. 2020, 32, 2004533. [CrossRef] [PubMed]

197. Miao, F.; Liang, S.J.; Cheng, B. Straintronics with van der Waals materials. NPJ Quantum Mater. 2021, 6, 59. [CrossRef]

198. Yan, Y.L.; Ding, S.; Wu, X.N.; Zhu, J.; Feng, D.M.; Yang, X.D.; Li, F.F. Tuning the physical properties of ultrathin transition-metal dichalcogenides via strain engineering. RSC Adv. 2020, 10, 39455–39467. [CrossRef] [PubMed]

199. Zhao, Z.Y.; Liu, K.; Liu, Y.W.; Guo, Y.L.; Liu, Y.Q. Intrinsically flexible displays: Key materials and devices. Natl. Sci. Rev. 2022, nwac090. [CrossRef]

200. Liu, R.Y.; Wang, Z.L.; Fukuda, K.; Someya, T. Flexible self-charging power sources. Nat. Rev. Mater. 2022, 1–17. [CrossRef]