

## 2D MAGNETIC MATERIALS AND VAN DER WAALS HETEROSTRUCTURES: PROPERTIES, PHENOMENA, AND APPLICATIONS

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### Abstract

<p><b>Received:</b> 20/02/2024 <b>Revised:</b> 11/03/2024 <b>Accepted:</b> 25/04/2024</p> <p><b>DOI:</b> <a href="https://doi.org/10.12060/jet-ep-v27.i1-3">10.12060/jet-ep-v27.i1-3</a></p> <p><b>Funding:</b> This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.</p> <p><b>Copyright:</b> © 2025 The Author(s). This work is licensed under a Creative Commons Attribution 4.0 International License.</p> <p>With the license CC-BY, authors retain the copyright, allowing anyone to download, reuse, re-print, modify, distribute, and/or copy their contribution. The work must be properly attributed to its author.</p>	<p>Two-dimensional (2D) magnetic materials, such as CrI<sub>3</sub>, Cr<sub>2</sub>Ge<sub>2</sub>Te<sub>6</sub>, and Fe<sub>3</sub>GeTe<sub>2</sub>, have emerged as platforms for exploring low-dimensional magnetism and spin-dependent phenomena. Coupled with van der Waals heterostructures, these materials enable the design of atomically thin devices with tunable electronic, optical, and magnetic properties. This paper reviews the synthesis methods, magnetic properties, interlayer coupling, and spintronic applications of 2D magnets. Challenges related to stability, integration, and scalable fabrication are discussed, along with future directions for next-generation spintronic and quantum devices.</p> <p><b>Keywords:</b> 2D magnetic materials, van der Waals heterostructures, spintronics, interlayer coupling, low-dimensional magnetism.</p>
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### 1. INTRODUCTION

The isolation of graphene inspired the exploration of other 2D materials, including semiconductors, superconductors, and magnets. 2D magnets have attracted attention due to **intrinsic long-range magnetic ordering** in atomically thin layers, despite the Mermin-Wagner theorem predicting suppression of long-range order in purely 2D isotropic systems (Gong et al., 2017).

Van der Waals (vdW) heterostructures, formed by stacking different 2D materials, enable novel phenomena arising from interlayer interactions, proximity effects, and strain engineering. These systems offer promising applications in **spintronic devices, magneto-optical modulators, and quantum technologies**.

## 2. CRYSTAL STRUCTURE AND MAGNETIC PROPERTIES

### 2.1 Monolayer Magnetism

- **CrI<sub>3</sub>**: Exhibits ferromagnetic order down to monolayer thickness; interlayer coupling can be tuned from ferromagnetic to antiferromagnetic by external fields.
- **Cr<sub>2</sub>Ge<sub>2</sub>Te<sub>6</sub>**: Layered ferromagnet with strong anisotropy, enabling tunable spin orientations in thin flakes.
- **Fe<sub>3</sub>GeTe<sub>2</sub>**: Metallic ferromagnet suitable for spintronic devices due to high Curie temperature and spin polarization.

### 2.2 Magnetic Anisotropy

Magnetic anisotropy stabilizes 2D magnetism by providing an energy barrier against thermal fluctuations. Out-of-plane anisotropy is particularly important in monolayer magnets.

### 2.3 Interlayer Coupling

Interlayer exchange coupling in vdW heterostructures leads to tunable magnetic order. Layer stacking, twist angles, and proximity to nonmagnetic layers significantly affect the magnetic properties.

## 3. SYNTHESIS AND FABRICATION TECHNIQUES

### 3.1 Mechanical Exfoliation

Provides high-quality monolayers but is limited in scalability.

### 3.2 Chemical Vapor Deposition (CVD)

Enables large-area synthesis of 2D magnets on various substrates, suitable for device integration.

### 3.3 Molecular Beam Epitaxy (MBE)

Allows precise control of thickness and layer quality for heterostructure engineering.

## 4. ELECTRONIC AND SPINTRONIC PROPERTIES

### 4.1 Spin Transport

2D magnets exhibit spin-polarized currents, long spin diffusion lengths, and proximity-induced magnetism when integrated with graphene or TMDs.

### 4.2 Magnetoresistance Effects

Magnetoresistance in 2D magnets and heterostructures enables nonvolatile memory devices and spin valves. Tunnel magnetoresistance is observed in CrI<sub>3</sub>-based junctions.

### 4.3 Magneto-optical Phenomena

Kerr rotation and Faraday effects allow optical probing of spin dynamics and control of magnetization in vdW heterostructures.

## 5. DEVICE APPLICATIONS

### 5.1 Spintronic Devices

- **Spin valves:** 2D magnets as spin filters.
- **Magnetic tunnel junctions (MTJs):** High TMR ratios using CrI<sub>3</sub> barriers.
- **Spin-FETs:** Gate-controlled spin currents in hybrid 2D structures.

### 5.2 Quantum Information

2D magnets integrated with superconductors or topological insulators can host Majorana modes and enable spin-based qubits.

### 5.3 Magneto-optical Devices

Light-controlled magnetization switching in vdW heterostructures enables ultrafast optical modulators.

## 6. CHALLENGES AND FUTURE DIRECTIONS

- **Stability:** 2D magnets are sensitive to air and moisture; encapsulation is required.
- **Scalable Fabrication:** Large-area, uniform monolayers are needed for commercial applications.
- **Integration:** Combining 2D magnets with other functional materials in heterostructures poses interface engineering challenges.
- **Room-Temperature Magnetism:** Research focuses on increasing Curie temperature and achieving robust magnetism in monolayers.

Future directions include **twistronics in magnetic layers**, **proximity-induced effects in hybrid structures**, and **opto-spintronic devices** for quantum technologies.

## 7. CONCLUSION

2D magnetic materials, combined with van der Waals heterostructures, offer unprecedented opportunities for low-dimensional magnetism and spintronic applications. Advances in material synthesis, interface engineering, and device design will enable scalable, high-performance spintronic, magneto-optical, and quantum devices.

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