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Mini Review

Recent Progress in Ferromagnetism of Two-Dimensional Materials

Julienne Impundu[1,2], Tariq Abbas[3], Balla Diop Ngom[4*] and Sabir Hussain[5*]

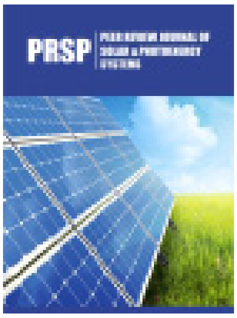
[1]CAS Key Laboratory of Nano system and Hierarchical Fabrication, CAS Center for Excellence in Nanoscience, National Center for Nanoscience and Technology, China

[2]University of Chinese Academy of Sciences, China

[3]Department of Chemistry, Division of Science and Technology, University of Education, Pakistan

[4]Department of Solid-State Physics and Engineering Science, University Cheikh Anta Diop of Dakar, Senegal

[5]Tyndall National Institute, University College Cork, 'Lee Maltings', Dyke Parade, Cork T12 R5CP, Ireland



***Corresponding author:** Balla Diop Ngom, Laboratory of Quantum Photonics, Energy and Nanofabrication, Department of Solid State Physics and Engineering Science, University Cheikh Anta Diop of Dakar, Senegal
Sabir Hussain, Tyndall National Institute, University College Cork, 'Lee Maltings', Dyke Parade, Cork T12 R5CP, Ireland

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Abstract

Two-dimensional (2D) materials are appealing for nanoelectronics due to their distinct physical characteristics and ultimate thickness dimension. Using these nanomaterials will be advantageous for many developing spintronic device designs and provide a more incredible method for controlling spin. Spintronics holds promise for the future of information technology, potentially replacing silicon-based complementary metal-oxide semiconductors that rely on charge manipulation. Still under investigation is the quest for discovering 2D materials with ferromagnetic properties, capable of generating, detecting, and controlling spin behavior. So, we are writing this mini-review to provide a concise summary of the recent advancements made in the field of ferromagnetism. Here we will summarize to encompass various aspects, such as the development of ferromagnetic 2D materials, their ability to produce, detect, manipulate spin behavior, and the implications of these findings in broader scientific and technological contexts.

Keywords: Ferromagnetic properties; Spintronics; Heterostructure; 2D Nanomaterials

Introduction

Ferromagnetism in 2D materials originates from the alignment of electron spins, resulting in a collective magnetic order where neighboring spins are parallel. This alignment can be achieved through various mechanisms, such as the presence of localized magnetic moments or the exchange interaction between itinerant electrons. The reduced dimensionality and unique properties of 2D materials play a crucial role in stabilizing ferromagnetic order at relatively high temperatures, which is not typically observed in bulk materials. Ferromagnetic 2D materials hold significant importance due to their potential applications in spintronic devices, magnetic sensors, and data storage [1,2].

Graphene, the first discovery of 2D material, developed in 2004 when Novoselov and Geim [3] succeeded in isolating a single layer of carbon atoms arranged in a honeycomb lattice with unique and fascinating physical properties. It opened up a new era in materials science and led to extensive research into 2D materials. It serves as a building block for constructing more complex 2D materials and has found applications in fields ranging from electronics and photonics to energy storage and biomedical devices [3].

Ferromagnetism has also been observed in several 2D materials beyond graphene. For instance, well know monolayer MoS_2, $MoSe_2$, WS_2 and so on have exhibited ferromagnetic behavior when subjected to certain conditions, such as strain, defects, or doping. Additionally, Van Der Waals (vdW) magnets like CrI_3 and Fe_3GeTe_2 have shown robust ferromagnetic properties in their 2D form. Moreover, combining different 2D materials in vdW heterostructures allows for the engineering of tailored magnetic properties and interlayer exchange interactions. The exploration of ferromagnetism in these diverse 2D materials and vdW heterostructures presents exciting prospects for advancing spintronics, magnetic storage, and other technological applications [4-6].

In this mini-review, research into the ferromagnetism in 2D materials has taken many directions, particularly in the field of spintronics, as shown in Figure 1. This evolution is due to a variety of techniques, some of which are purely technical, such as the increased use of Magnetic Force Microscopy (MFM), which is used to analyze the local magnetic behavior of nanomaterials [7]. This system functions in non-contact mode using a ferromagnetic tip as a local field sensor. As a result, images of the spatial variation of magnetic forces can be viewed on a sample surface, showing both its topography and magnetic properties. Moreover, the MFM provides the highest resolution and details regarding the magnetization process in general [8] and the magnetization reversal [9,10] of magnetic materials. Spintronics devices utilize the intrinsic spin property of electrons to manipulate and store information, enabling faster and more energy-efficient electronic devices. They hold promise for next-generation technologies such as magnetic memory, spin-based logic devices, and quantum computing. Additionally, a lot of research has gone into understanding the magnetization response that spintronics devices exhibit [10-14].

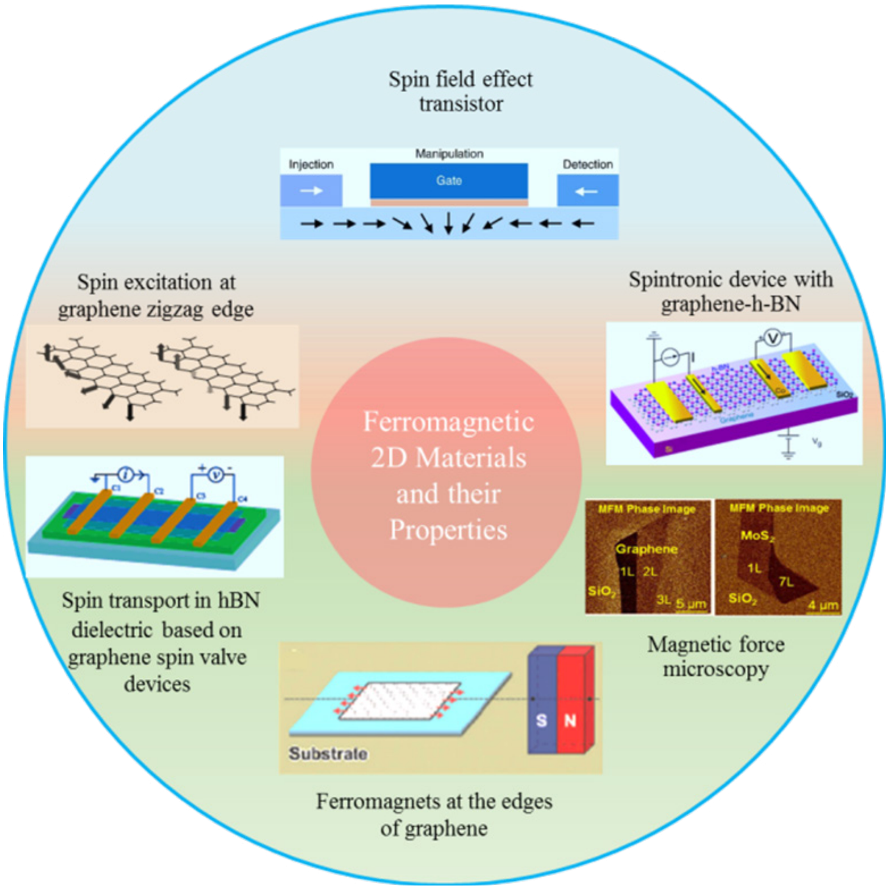

Figure 1: Structural properties, characterizations and device applications based on ferromagnetic 2D materials [2,10-14].

Central Concept of Ferromagnetic 2D Materials and Application

The paramagnetic behavior has been observed in 2D materials due to the presence of unpaired electrons and high density of states near the Fermi level. Where the favorable electronic structures and strong exchange interactions align the neighboring magnetic moments, resulting in a net magnetic moment. Kim et al. [15], Kou et al. [16], Yazyev and Helm [17] have predicted that magnetism (Figure 2) will result from both the edge states that develop around zigzag-shaped edges [15,16] and defects that either vacancy or hydrogen chemisorption [17,18]. Cervenka et al. [19], Zhou et al. [20] have revealed the presence of ferromagnetic localized on order at the edges of graphite and n-layer graphene [19,20]. In addition, the available literature from Zhou et al. [20] has shown that local magnetic moments exist at the edges of n-layer graphene and graphite with a Curie temperature above ambient temperature [11]. On the other hand, Yazyev et al. [21] have exposed that both transverse and longitudinal fluctuations of magnetic moments at the zigzag edges of graphene from the first principles have been studied as well. It has been found that due to the transverse fluctuations resulting from a high spin stiffness constant, the spin correlation length at ambient temperature is 1nm. Under the critical temperature, the spin correlation length increases significantly, while at temperatures exceeding 10K, the spin correlation length decreases due to weak magnetic anisotropy [21].

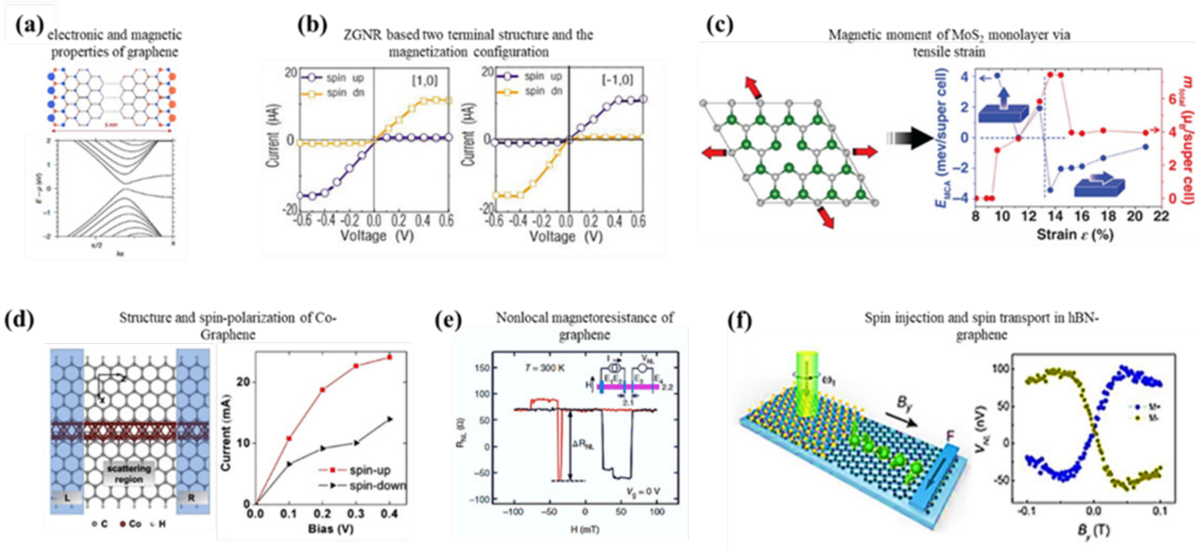

Figure 2: Structures and Graphs explain ferromagnetism of 2D nanomaterials. (a) Magda et al. [22] show the correlation between the electronic and magnetic properties of ZGNs. (b) Zeng [23] and colleagues determined the spin-dependent electron transport properties of 8-ZGNR. (c) Yun et al. [24] propose a diagrammatic representation of the magnetic moment of the MoS_2 monolayer induced by tensile strain. (d) Jiang et al. [25] establish the design of the two-probe model apparatus and its Spin-dependent I-V curves. (e) Measurement of nonlocal magnetoresistance on a graphene nonlocal spin valve with tunneling contacts done by Han [26] and his colleagues. (f) Sierra et al. [27] obtained optical spin injection and spin transport.

Further improvements in ferromagnetism behavior were observed when different research groups have conducted density functional theory calculations to investigate the strain-induced electronic and magnetic properties of single-layer MoS2 with vacancy defects [22-27]. It has been observed that the application of tensile strain induces ferromagnetic behavior and transforms the material into a metallic state [24]. They then used cobalt electrodes to demonstrate spin injection into graphene at ambient temperature. Where it is also possible to detect spin by contrasting the spin-up and spin-down local currents. Nevertheless, both weak spin-orbit coupling, and its zero bandgap prevent it from being used to create sophisticated spintronic devices like logic gates [28]. Now that straightforward experimental methods have been developed for coupling graphene with other atomically thin vdW crystals to generate heterostructures has made it possible to examine the characteristics of vdW heterostructures [29].

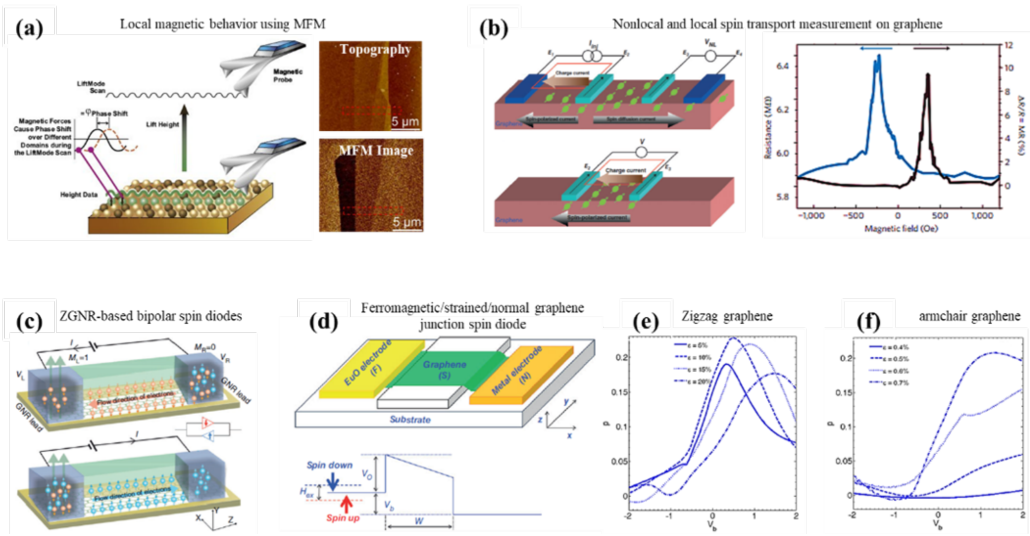

Figure 3: MFM and magnetic devices. (a) The topography and phase images of graphene nanosheets captured by AFM and MFM, respectively, are represented by Wang [10] and his colleagues. (b) Configurations for nonlocal and local spin transport measurement done by Han et al. [26] (c) Zeng et al. [23] proposed a schematic representation of bipolar spin diodes based on ZGNR. (d) Wang et al. [30] spin diode diagram. The spin diode comprises a junction of graphene that is ferromagnetic, strained, and normal. (e and f) Graph showing the relationship between spin polarization and the bias voltage Vb. The effects of the strain caused by the zigzag direction and the effects of the strain caused by the armchair's direction are represented respectively.

However, there are still numerous unanswered questions, and some of them are addressed in this mini-review. It is undoubtable that readers will come up with more to be added to the list. However, A new class of magnetic devices for magnetic storage, sensing, and data processing would be possible if 2D nanostructures could be used to effectively and reliably produce nanosized carbon materials that are magnetic. Eventually, these concerns are to enhance the innovative nature of the experimental study in this field and its promising future [30] (Figure 3).

Summary and Challenges

Recent progress in the field of ferromagnetism in 2D materials has shown great promise for various applications namely spintronics, magnetic memory devices, magnetic sensors, spin filters, magnetic heterostructures, and magnetic probes. Here we have described some techniques like doping, defect engineering, and proximity effects have been employed to induce and manipulate ferromagnetism in these materials. However, challenges still remain, including understanding spin relaxation in materials like graphene, studying magnetic interactions in graphene, addressing environmental effects and material degradation in TMDCs, overcoming limitations in achieving room temperature spintronic applications involving magnetic vdW materials, and developing diluted magnetic systems for TMDCs. Overcoming these challenges will be crucial to fully harness the potential of 2D ferromagnetic materials and realize their practical applications in various fields.

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