Magnetic proximity effect in two-dimensional van der Waals heterostructure

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Keywords: low-dimensional materials, magnetic proximity effect, interfacial phenomena, proximitized van der Waals heterostructure, spin-dependent behaviour

Abstract

The evolution of low-dimensional materials has frequently revolutionized new intriguing physical standards and suggests a unique approach to scientifically design a novel device. However, scaling down of spin-electronic devices entails in-depth knowledge and precise control on engineering interfacial structures, which unveils the exciting opportunity. To reveal exotic quantum phases, atomically thin two-dimensional van der Waals material, embraces control and tuning of various physical states by coupling with peripheral perturbation such as pressure, photon, gating, Moire pattern and proximity effect. Herein, we discuss the physical property of a pristine material which can be converted via proximity effects to attain intrinsic spin-dependent properties from its adjacent material like magnetic, topological or spin–orbit phenomena. Realizing magnetic proximity effect in atomically thin vdW heterostructure not only balance the traditional techniques of designing quality spin interface by doping, defects or surface modification, but also can overcome their restrictions for modelling and fabricate novel spin-related devices in nanoscale phases. The proximitized van der Waals heterostructure systems unveil properties, which cannot be realized in any integral component of considered heterostructure system. These proximitized van der Waals material provide an ideal platform for exploring new physical phenomena, which delivers a broader framework for employing novel materials and investigate nanoscale phases in spintronics and valleytronics.

1. Introduction

Atomically thin two-dimensional (2D) materials rarely show exciting features as we require them in pristine form. Instead, they offer new physical paradigm when these pristine materials were essentially modified by forming van der Waals (vdW) heterostructure. These modifications were achieved for 2D vdW crystals via rapid fabrication, which negotiates the controlled levels of chemical, physical, optical and electrical properties having applications from transistors and energy storage to environmental remediation [1–3]. Till date, the modifications in two-dimensional crystals like semiconductor, superconductor, semimetal, metals, topological insulators, the magnetic semiconductor is mostly seen via doping, introducing magnetic species or inducing defect, coupling with substrates, where extrinsically the impurities were introduced to amend and modify their properties [4–7]. These modifications suggest a new path to realize intrinsic magnetic behaviour in vdW heterostructure, where dynamics of spin are predicted to be significantly enhanced [8, 9]. Extrinsicly introduced dopants or defects in 2D vdW crystals have been commonly employed to alter the surface and interfacial phenomena leading to produce exciting outcomes. Pristine materials with low dopants or defects act like an insulator, with moderate dopants or defects are superconductors and at high dopants or defects concentration, it resembles traditional metals [10]. Combining 2D materials with dopants or defects with different functionalities has led to the formation of new and unique heterostructures for investigating novel physical phenomena for developing low-power nano-electronic devices.
Doping in usual semiconductors like hexagonal boron nitride (h-BN) by graphene quantum dots (GQDs) can infer unique physicochemical properties. The insertion of GQDs also enhances the crystal structure of h-BN, characteristics of semiconductor and bonding among carbon (C)–nitrogen (N), carbon (C)–boron (B) at the interface leads to manipulation of spin and also induces ferromagnetism in h-BN [11]. Essentially, this can be beneficial objectives to introduce a smooth incorporation for nanoelectronics, spin-logics, energy storages. Magnetic impurities such as Mn, Fe, Co and Ni-doped 2D layered materials provides controlled exchange interaction by altering the perpendicular magnetic anisotropy and Curie temperature, $T_C$ [12], also unveil the new techniques to check the direction of magnetization [13]. Coupling of 2D materials with the magnetic substrate is a promising material for inducing magnetism by modulating external perturbative effects like light [14], gating [15] and electric field [16]. However, after successfully examining the novel properties in vdW heterostructure by vacancies, adatoms, doping, defects, coupling with magnetic species or substrates [4–7], it is important to reconsider 2D vdW heterostructure and analyse long-range spin correlation using magnetic proximity effect (MPE). Thus, vdW materials, attributing atomic thicknesses and forming atomically sharp interfacial phenomena, are an attractive platform to engineer novel devices.

However, even with a successful realization and modifications of extrinsically induced phenomena in 2D atomic crystals, they have certain restrictions in the context of doping concentration, which results in disordered spins and notably reduces the mobility of electrons in 2D layered crystals [17]. Also, low solubility of dopant or defect concentration challenges the growth and agglomerates to nanocluster which complicates the determination of physical and chemical properties [18]. Moreover, externally induced magnetic moments in layered atomic crystals have been realized by doping, defects and coupling with magnetic substrates. In this scheme, it is challenging to induce long-range interaction between extrinsic injections of local spins via robust exchange interaction [5] and 2D materials coupling with magnetic substrate hinders the development of advanced spin related device by inhibiting vdW heterostructure.

To overcome the limitations of extrinsically induced phenomena, an extraordinary path for designing materials has emerged from proximity effects. Proximity effect is the most crucial tools required for manipulating spintronics [19, 20], superconductor [21, 22], topologically non-trivial phenomena [23, 24] and excitonic [25]. This effect is highly flexible to interfacial phenomena when two or more dissimilar materials are integrated and brought near to each other because of proximity effect. The culmination of MPE tends to modify functionalities and difference in the exchange interaction near the interface [26, 27]. Moreover, proximity effect broadly transforms a wide range of materials, where the effective Hamiltonian of the interface between the two monolayers has different functionalities than that of the two individual monolayers. The first instinct about proximity effect was realized from superconducting materials, known for 86 years [28]. The properties of superconducting materials can penetrate from one region into a usual neighbouring region, which may not have superconducting nature. Similarly, MPE was realized almost three decades ago by Zuckermann [29]. He explained theoretically that a thin film comprising weak intrinsic ferromagnetic behaviour brought in close vicinity to a thick film of a paramagnetic material and has observed non-zero Curie temperature. The method that was employed to understand MPE is by solving the Landau–Ginzburg theory of phase transition. The following equation scrutinize as

$$M(\vec{r}) = \int d^3r' U(\vec{r}) \chi(T(\vec{r}'; 0))M(\vec{r}') - U(\vec{r})M(\vec{r}) \sum_\omega G_p^0(\omega)$$  \hspace{1cm} (1)

where $M(\vec{r})$ depicts local magnetization at $\vec{r}$, $U(\vec{r})$ represents Hubbard exchange term, $\chi(T(\vec{r}; 0))$ is the static $\vec{r}$ dependent magnetic susceptibility of non-interacting conduction electrons and $G_p^0(\omega)$ depicts momentum propagator $p$ conduction electrons. However, this approach was appropriate for superconducting material and not reliable for magnetic interfaces. Therefore, to understand the exact theory Bergmann [30] in 1978 explained experimentally by depositing a thin film of Ni, Co and Fe over a paramagnetic metallic substrate (Pb,Bi). This interpretation implied that the magnetization value in the initial few FM layers nearest to the PM is considerably different from the bulk counterpart. Therefore, Bergmann’s experimental measurement was relevant for understanding the fundamental problem of the relation among magnetism and dimensionality, also verifies the existence of MPE. Till date, a plethora of studies have been explored and designed using an extrinsically modified parameter for various applications in spintronics and valleytronics but a synergy needs to be established between the optimized dimensionality with combining capabilities among the layers leading to vdW heterostructure.

In this review, we have explained a comprehensive view of proximity effects which resembles to modify broad variety of 2D vdW materials which has the possibility to surpass the restrictions of doping, defects, coupling with substrates, adatoms, grain boundaries, edge effects and chemical functionalization. Meanwhile, the MPEs involve transfer of an ordered state to the nearest neighbour region, where the
Figure 1. Displaying the scheme of MPE which can be realized, by keeping adjacent material in close vicinity via different mechanisms acquiring different functionalities applicable in designing various spin-electronic devices.

Electronic structure was not strongly affected initially at pristine form. Later, this terminology has pertained more extensively which includes proximity-induced spin–orbit interaction (SOI) or topologically non-trivial phases [31, 32]. Figure 1 gives an overview of the diverse area for interfacial engineering via MPE:

(a) The lattice perturbation in the interface changes the stacking configuration from in-plane to out-of-plane for tuning the magnetic behaviour in layered vdW heterostructure.

(b) The electron transfer in the interface varies the concentration of electrons and orbital nature in atomically thin vdW nanomaterials, leading to the variation in the electronic property.

(c) Lattice symmetry breaking tunes the orbital physics and subsequently the rearrangement of spin is induced in the interface due to MPE.

(d) The orbital hybridization in the interface due to MPE modifies the resultant magnetic property by influencing the electronic properties and orbital character of vdW heterostructure.

(e) The band structure in the interface may renormalize when one layer is kept in close proximity with a material of matching lattice constant. Band renormalization in atomically thin vdW heterostructure can be induced by the dielectric screening of neighbour material.

(f) The electrical control via gating plays an important role when 2D magnet will be in close vicinity with the nonmagnetic material, where interfacial polarization is intrinsically related to the vdW heterostructure.

2. From bulk to proximitized material

In general, the dimension in bulk structures widely attribute to large characteristic scales, where time-reversal symmetry naturally breaks in proximitized materials. In the bulk system, the phase transition appears at fixed temperature, while 1D material illustrates long-range behaviour, which is observed at absolute temperature. Being at the periphery between these two end points, the condition in atomically thin van der Waals crystals such as graphene, h-BN, transition metal dichalcogenides (TMDCs), magnetic semiconductors (chromium trihalides, FePS$_3$, and MnPS$_3$) [33, 34] is extremely complicated as it can destroy the intrinsic magnetism by strong thermal perturbation, even short-range MPE surpass their macroscopic length scale which vigorously modifies the transport and optical properties. For example, gapless and massless pristine graphene exhibit a linear dispersion near K point in the Dirac cone, exhibits negligible spin–orbit coupling (SOC) and spin-unpolarized density of states (DOS). Thereafter, proximity effects profoundly alter the characteristics of neighbouring material such that it can acquire spin-polarization [35], SOC [36, 37], magnetism [38], or superconductivity [39]. Sandwiching with magnetic insulators will lead to an ideal combination of vdW heterostructures, which can be advantageous for exchange interaction at the interface because of atomically active interfacial registry. In addition, proximity with magnets alters the changes in the electronic structure of atomically thin interfacial registry and can proceed for spin-selective
transmission across the interface. Therefore, scaling down of nanostructures and modified version of interfaces can ardently amend the properties of 2D atomic crystals through proximity effects.

However, in this review we have basically highlighted the outlined anatomy of MPEs along with external perturbative effect (SOC, electric field, gating, strain, etc) and their intriguing properties for their application in spintronics and valleytronics, which provides many other tantalizing opportunities. Thereof, MPE can be an exciting platform to model novel exotic quantum phenomena which reveal the universal properties of heterosystems impervious to disorganization of spin and local fluctuations which lead to the applications such as magnetic storage using magnetic skyrmions [40], or quantum computing [41].

3. Induced magnetism in non-magnetic layered materials

Since the discovery of graphene, efforts to generate magnetism in non-magnetic 2D materials have continued to gain enormous attention very quickly in proximitized materials. One of the conventional approaches is known by introducing defects or dopants or adding adatoms, coupling with metallic magnetic substrates or 3D materials [4–6]. Creating defects, dopants or coupling with magnetic substrates can extrinsically develop localized spin moments generated from unpaired electrons, which has the possibility of orbital hybridization at the interface through conduction electron in atomically thin vdW materials. However, efforts to arrange these electronic spins in an ordered fashion will be a challenging task in material preparation. In this line, the prior literatures, on the realization of long-range magnetic order in close proximity with non-magnetic layered material, no certain understanding in this regard has been reached yet [42, 43]. Flat band ferromagnetism has been introduced via inducing defects in the zigzag periphery of graphene nanoribbons or grain boundaries of atomically thin layered vdW heterostructure [44]. Such defects lead to inaccurate electronic band which signifies the large amount of DOS in a small energy regime, which generates stoner instability, tends to ferromagnetic phase. Moreover, these chemically dynamic defects are exposed to the penetration of exotic species with which long-range ferromagnetism cannot be acquired [45]. The ferromagnetic ordering in bilayer graphene was predicted by electronic band structure under the existence of electrical biasing [46] and doped gallium selenide [47].

The magnetic proximity induced effects have been studied in graphene–europium oxide (EuO) van der Waals heterostructure. The ab initio simulation shows the magnetic interaction in graphene-EuO van der Waals heterostructure which convince large exchange splitting in the electronic structure of about 36 meV (figure 2(b)) and polarization of spins in graphene π orbitals was found to be up to 24% shown in figure 2(a) [48]. The proximity effect on graphene-EuO van der Waals heterostructure has been successfully fabricated at the high temperature shown in a cross-sectional view of HAADF-STEM in figure 2(d). Figure 2(e) shows the fast Fourier transform pattern which recognizes the structure to be the rock-salt structure with EuO lattice. The magnetic nature in graphene demonstrates the vulnerability of $R_{xy}$ on magnetic field at $T = 2$ K which leads to linear nature for graphene and graphene-EuO (+Eu)-graphene structure, respectively. The linearity is observed due to over doping nature of Eu intercalation which does not exhibit any notable magnetic behaviour in figure 2(g). The graphene-EuO structure manifests nonlinearity, where the hall resistance in high magnetic field unveils the transfer of charge carriers from holes to electron caused due to EuO. The emergence of anomalous Hall effect (AHE) was found to be non-linear and this non-linearity strongly depends upon the effect of temperature as observed in figure 2(h). Figure 2(i) displays the AHE signals in graphene-EuO vdW heterostructure demonstrated an articulate hysteresis curve with a coercive field of around 40 Oe. Also, the finding of AHE marks evidence of SOC introduced in graphene because of proximity-induced phenomena [49]. Figure 2(j) shows the model system for graphene-magnetic substrate vdW heterostructure comprising two proximity induced magnetic leads with magnetizations $\mathbf{M}_1$ and $\mathbf{M}_2$, separated by distance $d$. The proximity magnetoresistance (PMR) in graphene vdW heterostructure can couple with magnetic substrates such as yttrium iron garnet (YIG), cobalt ferrite (CFO) and two europium chalcogenides (EuO and EuS). The percentage of PMR for YIG and CFO is 77% and 22% at ambient temperature whereas for the chalcogenide systems (EuO and EuS) are 100% at 16 K and 70 K as shown in figure 2(k). The PMR dependencies for YIG while altering the Rashba spin–orbit interaction shows SOC decreases about half while introducing big SOC strength shown in figure 2(l) [50].

The MPE is a scheme to magnetize non-magnetic monolayer system by prompting functionalities from adjacent magnetic materials. A pristine graphene monolayer has been transferred above YIG [51] or upon which WS$_2$ was kept [16], which manifests AHE and enhances the strength of SOC. The clear proof of the interfacial exchange phenomena based upon spin current transport, which was subsequently acquired in lateral graphene spin valves on YIG [52, 53]. Most importantly, a dephasing of spin can be observed because of spatiotemporal perturbation of interfacial exchange interaction [53], which focuses on a new angle of understanding the quality interface in spin related transport phenomena in proximity systems.
4. Interfacial engineering via MPE in vdW layered materials

The advantage of utilizing magnetic 2D nanostructures as a constituent of vdW heterostructures can basically fulfill two important goals. One is to extend the performance of vdW heterostructures suitable for carrying out experiments and to develop novel device applications. Additional way is to engineer standard interface evolving from proximity to nearby 2D vdW system as a tool to manipulate the magnetic behaviour of the magnetic layer themselves. 2D materials realize high spin and valley polarization which offers exciting opportunities for the development of efficient spintronics and valleytronics. Sandwiching 2D spintronic or valleytronic material via MPE with magnetic semiconductor or insulator can provide a plausible procedure to acquire spin or valley-polarized heterostructure. Moreover, coupling with magnetic insulators leads to seamless integration and interplay of interfacial exchange interaction at the atomically sharp interface. The main aim to employ spin degrees of freedom essentially require spin-dependent phenomena at proximitized material which is not present initially in bulk counterparts, such as spin-up and spin-down electrons (with respect to the direction of magnetization or an externally applied electric or magnetic field) which are no longer identical. Various heterostructure systems have been realized with MPE to tune the spin and valley-polarization phenomena which includes graphene on Bismuth Ferrite BiFeO$_3$ (BFO) [54], EuS on graphene [55], WSe$_2$ on EuS [56], graphene on CrI$_3$ [57] and graphene on h-BN [58].

MPE has been realized till date with various combined heterostructure such as ferromagnetic substrate-superconductor [59], nonmagnetic bilayer heterostructure [60], and the nonmagnet-ferromagnetic substrate [34]. However, coupling with magnetic conducting substrate limits the design in developing spin-switches via clearly short-circuiting the neighbour layer material. Moreover, the concept of spin-injection and topological behaviour from one layer to another neighbouring layer via proximity effect is presently a fascinating and emerging area of research. Thereafter, 2D layered nonmagnetic material is...
introduced and linked with two ferromagnetic layers for realizing the behaviour of vdW spin-valve, which have a different outlook from lateral heterostructure spin-valves, where the substantial section of the nonmagnetic layered system is not in correspondence with the ferromagnetic electrode. The relative orientations of spin in vdW spin-valves can show a robust impression on in-plane conductance predominant by spin proximity effect [61]. Topological phases in a 2D layered system can attract enormous attention due to the exciting physics and application prospect in spintronics and valleytronics [31, 62]. Topological edge states in case of quantum spin Hall effect inoculate by time-reversal symmetry, while the existence of exchange coupling can break time-reversal symmetry leading to quantum anomalous Hall effect (QAH) [63, 64]. QAH phases have been realized in graphene and graphene on Ising antiferromagnet MnPSe₂ via proximity effect. Topologically trivial states were realized by combining uniform and staggered spin–orbit and exhibit proximitized graphene edge states visualizing the magnetization orientation-dependent QAH phases [65]. The proximity exchange coupling can incorporate stronger and enhanced effects [14, 66] for realizing Zeeman coupling by introducing an extrinsically applied large magnetic field, without significantly varying the band structure. Therefore, the short-range behaviour of proximity effects leads to large exchange coupling within the 2D layer which is in close contact with magnetic material [67, 68]. More attempts have been made using chemical vapour deposition of Bi₂Te₃ on Cr₂Ge₂Te₆ [69] and MBE growth of Cr₂Ge₂Te₆ on (Bi, Sb)₂Te₃ [70]. Another cascade of focus toward QAH was recently toggled by the experimental realization in proximity-coupled YIG/graphene/h-BN heterostructure system [71]. Apart from SOC, other property can be approachable to graphene via proximity effect which can be relevant in spintronics.

Allocation of layered vdW magnets in close vicinity with nearby materials not only imparts the spin related nature to the neighbouring layer but also can alter the properties of vdW magnetic material by interfacial engineering. The typical magnetic phase is realized at EuS-Bi₂Se₃ interface which continued to survive beyond the room temperature [72]. Layer resolved MPE has been realized in vdW magnetic heterostructure by exploiting multiple magnetic alignments penetrable in layered antiferromagnetic (AFM) CrI₃. The magnetization in CrI₃ in every single layer was tuned by an extrinsically applied magnetic field and spin mediated relocation of charge in WSe₂–CrI₃ heterostructure was intimidat by CrI₃ layer whereas the proximity exchange phenomena were highly flexible to magnetic heterostructure entirely. By altering the spin–valley properties of WSe₂, visualization of the layered AFM domains in a vdW magnet will be disadvantageous to realize with simple magnetometry procedure [73]. MPE has been understood in vdW heterostructure constructed by graphene monolayer in close proximity with 2D ferromagnetic semiconductor CrBr₃ with interlayer separation of 3.77 Å. The atomic configuration of Gr–CrBr₃ heterostructure is shown in figure 3(i). Moreover, the percentage of spin-polarization is understood by the partial density of states (PDOS) for individual atomic orbitals of carbon (C), chromium (Cr) and bromine (Br) was found to be 1.5%, 71.2% and 0.8%, respectively, shown in figures 3(a)–(c). It is quite evident that the percentage of spin-polarization for Cr will be considerably higher compared to C and Br due to inherent magnetic nature of Cr. Also, the coupling between C p-orbitals and Cr d-orbitals effectively engage in connecting Gr–CrBr₃ heterostructure and can be calibrated when they come in close proximity. Thereafter, in figure 3(d) the spin-polarization for Gr–CrBr₃ heterostructure is found to be 63.6%, which transparently suggests the active behaviour of all atomic orbital spins because of proximity coupling among graphene and CrBr₃. The charge density profile as shown in figure 3(e) depicts no appropriate charge transfer due to vdW nature of the interaction, but the alignment of electronic charge was observed superficially on Gr–CrBr₃ heterolayer system. The exchange coupling via MPE in heterostructure system is majorly depends upon orbital hybridization near the interface. The spin density distribution in the 3D mapping (shown in figure 3(f)) yellow colour signifies highly concentrated spin-polarized states of Cr atom and cyan colour represents less concentrated spin-polarized states of Br atom. In 2D spin density mapping, the potent red colour represents the highly condense spin-polarized states whereas the cyan colour depicts less condense spin-polarized states. Therefore, the spin density distribution can be corroborated with PDOS patterns signifying the percentage of spin-polarized individual orbital C, Cr and Br. Figure 3(h) depicts the electronic charge density distribution, where red and yellow colour signifies electron amalgamation and disappearance. It is quite evident no continuous charges transfer between the layers whereas rearrangement of charge is observed in the surface of Gr–CrBr₃ heterostructure. Moreover, the moment of a monolayer CrBr₃ magnet was observed as 3.39 µB per cell with significant enhancement of 39%, which is analogous to bulk architecture. Thereafter, the magnetic moment in heterostructure system was found to be 3.47 µB per cell which shows 8% notable increment of the magnetic moment in the heterostructure system then the monolayer CrBr₃ at zero biasing specifying the MPE and electrical control in the Gr–CrBr₃ heterostructure leads to miniband splitting [74].

Moreover, the aforementioned theoretical simulation work on Gr–CrBr₃ heterostructure is the first report in pristine Gr–CrBr₃ heterolayer system, which later has been proved by fabricating Gr–CrBr₃ heterostructure experimentally as shown in figures 3(j) and (k). Figure 3(l) depicts the MPE in Gr–CrBr₃...
heterostructure is realized by Zeeman spin Hall effect (ZSHE), which is induced by splitting of Dirac cone in graphene initiated from electron and hole-like carriers having dissimilar spins near the Dirac point. MPE in Gr–CrBr$_3$ heterostructure can be understood by measuring non-local resistances $R_{nl}$ and voltage $V_{nl}$ shown in figure 3(m). With the increase in an applied magnetic field the non-local resistance $R_{nl,LD}$ (peak of $R_{nl}$ at Dirac point), there is a sharp growth of $R_{nl,LD}$ which signifies a prominent amplification in Zeeman splitting energy. The emergence of Zeeman splitting energy enhancement via MPE is shown in figure 3(n), where temperature dependence non-local resistance measurement in Gr–CrBr$_3$ heterostructure encounter rapid drop-off, as the temperature outreach about 37 K, which indicates the transition temperature $T_C$ of CrBr$_3$. The $T_C$ represents the transformation of phase from ferromagnetic state to paramagnetic. In contrary, pristine graphene manifest very weak temporal nature which differs from Gr–CrBr$_3$ heterostructure. Therefore, MPE is the prime contribution for the induction of non-local resistance in Gr–CrBr$_3$ heterostructure at a lower temperature than $T_C$ of CrBr$_3$ [75]. However, for interfacial engineering via MPE could be described in two different mechanisms [76]: firstly, the penetration of wave function from non-magnetic layered material to a ferromagnet as evanescent states as no state persists at Fermi level, when they obtain spin splitting from the neighbour ferromagnetic layer. Secondly, the penetration takes place from the ferromagnetic layer into the non-magnetic layer, by the polarization of electronic structure at the $E_F$. Therefore, interfacial engineering via MPE opens a new paradigm to tailor 2D magnetic properties for the creation of synthetic spin switches develop in close proximity with a 2D nonmagnetic material.
5. Applications in designing novel spin mediated device

With an overview, on altering spin-related phenomena of materials utilizing MPE the evolving applications can mostly scrutinize based on spintronics, valleytronics, magnonics, spin-orbitronics but not essentially restricted to magnetic memory devices in which employment of MPE via exchange bias effect is already been established and commercialized. However, MPE obeys two important motivations i.e. one is to scrutinize the opportunities which can accompany or restore other strategies for designing the nanoelectronic device and other is to explore different systems, where the presence of inherent properties utilizing proximity effect could validate novel applications. Moreover, MPE allows us to reimagine process information as well as introduce low-power spintronics but also how to combine tactfully non-labile memory and logic devices. Thereafter, penetration of spin current can be improved by proximity effects comprising a novel range of spin-based switching devices.

5.1. Magnetic tunnel junctions

The magnetic tunnel junction (MTJ) is the most important architecture for designing novel spin-electronic device [77, 78]. The most prominent advantage in all type of vdW MTJs is the breadth of the barrier which enables the whole area tunnelling. In contrary, non-uniform MTJs realize the tunnelling current preferentially through thinner barrier regions because of tunnelling current, which is an exponential parameter across the breadth of the barrier. However, various vdW MTJs has been realized on the basis of Fe0.25Ta2S2-Ta2O5-Fe0.25Ta2S2 [77], graphite-CrI3-graphite [79], Fe2GeTe2-BN-Fe2GeTe2 [80], and graphite-CrBr3-graphite [81]. A huge tunneling magnetoresistance has been observed on graphite-CrI3-graphite heterostructure with maximum magnetoresistance representing 19 000% at 2 K [82], 550% at 300 mK [83], 10 000% at 10 K [79] and 1000 000% at 1.4 K [84]. The importance of this kind of MTJ was considered to utilize various scattering mechanisms for tunnelling of electrons over the alternate polarization of spin in CrI3 layers. Moreover, those MTJs were understood from magnon-assisted tunnelling procedure, where magnons can excite over the magnetic substrates logically by microwave. The excited magnons can propagate into the adjacent 2D materials which differ from traditional electron- or phonon-assisted tunnelling procedure without necessarily considering the conducting electron. A prominent spin-valve effect has been realized in Fe2GeTe2/h-BN/Fe2GeTe2 junctions because of the variation in coercive field from the two electrodes acquiring non-consistent demagnetization factor having a different structure. The obtained 160% magnetoresistance at 4.2 K complements spin polarization percentage up to 66% at the Fermi energy, which signifies the presence of 83% and 17% of dominant and recessive spins, respectively. These experimental findings confirm the corresponding magnetic behaviour at the surface of Fe2GeTe2 crystals, which were analogous to those of the bulk counterparts. The basic proof-of-concept shows a promising focus towards proximitzed materials for high-efficacy in spin-electronics or magnonics.

While developing vdW MTJs it has a major concern in experimental realization in room temperature, non-liability and low-power switching phenomena. However, for the experimental establishment of Cr-halide MTJs preferably operates at liquid helium temperature, labile and acquires high magnetic fields for triggering between particular regions. For experimentally fabricating vdW MTJs, huge endeavour needs to be focused on highlighting the major points such as high-temperature vdW magnetic material, magnetic anisotropy, high remnant magnetization, moderate strength of the coercive field and robust proximity effect with the neighbouring layer. However, it is expected that better electrical manipulation and notable thermal perturbations in proximitized material could permit a lower analytical current for realizing spin torque magnetization behaviour compared to conventional non-vdW MTJs. This low value of the analytical current is the important factor for the realization of spin-transfer torque (STT) mediated magneto-resistive memory device.

STT assisted quantum magnetotransport phenomena have been studied in MoS2-Phosphorene vdW heterostructure using magnetization density switching. The time-dependent spin current tunes the behaviour of STT with rotational variation in the magnetization angle of the heterojunction. The magnetotransport behaviour has been realized in phosphorene and MoS2 heterostructure system for a spin-valve structure known for relative difference for conduction of charge in a parallel arrangement. Figures 4(a) and (b) show the optimized atomic structure of the modelled MoS2-P heterostructure system. The scheme of typical MTJ modelled by Fe/MoS2-P/Pt, where the scattering region consists of MoS2-P heterostructure connected with two leads Fe and Pt as shown in figure 4(d). Figure 4(c) shows the puckered structure of individual monolayers MoS2 and phosphorene, which acts as a transmission channel for the heterojunction leading to two interplanar spacing with widths D and d, respectively. The electrons penetrate from left region tunnelling through the scattering region towards the right region magnetization orientation gyrates by a finite angle resulting in spin angular momentum. The difference between entering and exiting of polarized spin current at the right electrode, suffer a torque on the right ferromagnetic lead. Such torque
results the transmission of angular momentum of spin from left to the right region by polarized spin current, without any absorbance near the interface of the heterojunction.

Figures 4(e) and (f) show the magnetoresistance behaviour at higher and lower energy for MoS\textsubscript{2}-P heterojunction, where the torque module mostly represents the damped-oscillatory behaviour. This damped oscillatory behaviour was observed by calculating by time-dependent spin-current and current-mediated STT introduced by an extrinsically applied field as observed in figure 4(g). The current-mediated STT in MoS\textsubscript{2}-P heterostructure system is visualized at three different direct currents (DC) biases 10, 20 and 30 mV respectively, with three different rotatory angle of magnetization direction for right region. For $\theta = 30^\circ$, symmetricity is seen equally for both the spin for left and right region, for $\theta = 90^\circ$ the system shows asymmetric nature while at $\theta = 60^\circ$ shows an intermediate state. However, for confirming the temporal sinusoidal oscillatory nature STT, the Fourier transform of spin-up current at revolving angle $\theta = 90^\circ$ with a frequency of 10 mV signifies the resonant states, confers the oscillation nature of temporal current mediated STT (as observed in figure 4(h)). The Fourier transformed current shows oscillatory behaviour with an intense peak at a low frequency of 150 meV. The oscillatory trend has been realized at frequency 150 meV of evanescent spin-up current. However, the other two points at 0.25 and 0.295 eV at the range of 0.405–0.420 eV gain comparatively high frequency. Therefore, evanescent STT exhibits continuous oscillatory nature because of the existence of such interface-localized resonant states [85].

Thereafter, four-layer CrI\textsubscript{3} heterostructure in close proximity with graphene contacts in a dual gate type structures as seen in figure 4(i). Figure 4(j) shows the variation in gate voltages at the constant magnetic field the device can be reversibly switched between two stable magnetic states with different resistance meanwhile RMCD value is almost persistent. Therefore, the TMR can easily tune between 17 000% and 57 000% due to amalgamation of spin-varying tunnel barrier with the change in barrier distribution in graphene contacts [86].

5.2. Spin-lasers

Lasers are predominant in day-to-day life with their applications in optical storage, printing, optical sensor, display systems [87]. However, to attain population inversion for lasing, a huge mobility of electron is required, which guides to realize shorter spin relaxation times along with a shorter spin diffusion length [88]. With the incorporation of magnetic species in spin lasers, MPE could be introduced as electrically toggle sources of spin-polarized carrier [76] as well as to overcome the utmost need for inducing magnetization via
Figure 5. (a) Displaying the scheme of vdW heterostructure formed by monolayer WSe$_2$ and magnetic-layered semiconductor CrI$_3$ and encapsulated layered h-BN and bulk h-BN. (b) Atomic representation of top and side view of CrI$_3$ crystal structure. (c) Optical micrography picture of fabricated device. The WSe$_2$-CrI$_3$ heterostructure is sandwiched by optically translucent h-BN with scale bar 5 µm. (d) Spin-valley connection and valley-mediated optical selection rules in monolayer WSe$_2$ due to CrI$_3$. Dotted (solid) lines visualize the edges of band before (after) proximitized coupling. Black arrows signify the spin. Position selective dynamics of ferromagnetic domains (e) spatial map of $\rho$ at selected applied magnetic field of $\approx 0.5$ T with the selected spots of magnetic field sweeps of $\rho$ denoted by blue, grey, brown and black in (f), (g), (h) and (i). From [94]. Reprinted with permission from AAAS.

spin pumping on nonmagnet. The feasibility in vdW-based spin lasers with prudent spin-dependent properties has been realized by experimental evidence of lasing identical structures, which permit a very low lasing threshold [89]. Moreover, for realizing MPE in vertical geometric lasers could be advantageous for vdW heterojunction for elucidating modified properties analogous to lateral counterparts [90].

The first investigation demonstrates pronounced magnetic phenomena at vdW interfaces basically focused on CrI$_3$/WSe$_2$ structures. Figure 5(a) depicts the architecture of the heterostructure system in close proximity between WSe$_2$ monolayer and 10 nm thick CrI$_3$ layer are encapsulated by 10–20 nm thin h-BN for prevention of sample degradation with the optical microscopy image as shown in figure 5(c) of the fabricated heterostructure. The monolayer semiconducting WSe$_2$ due to its manifestation in spin and valley pseudospin degrees of freedom comprehending circularly polarized valley optical selection rules [91], spin-valley combined effect [92] and valley Zeeman splitting [14, 93], which improves the energy degeneracy by breaking time-reversal symmetry. In such devices, when the laser is pivoted on a feeble domain as shown in figure 5(e) the magnetization value can invert without manually changing the direction of an applied magnetic field as observed in figures 5(g) and (h). However, in case of the strong magnetic domain as shown in figure 5(i) only one hysteresis loop is observed at lower temperature photoluminescence of WSe$_2$, which reveals zero-field Zeeman splitting of excitonic resonances. The effect is due to an interfacial exchange energy which is equal to the presence of an effective 13 T magnetic field. Initially, the observation is a replica of the Barkhausen effect due to the quick swap of the domain size in ferromagnetic material. Moreover, the laser spot is focused on the central region of the weak domain, which is less affected by changes in domain size. Thereafter, the $\mu$-B graph near the domain boundary does not exhibit the fine steps as observed in figure 5(i). The fact that the Zeeman effect disappears above the bulk Curie temperature of CrI$_3$ confirms the origin of the phenomena. These first experiments also probed the evolution of the exchange field with an applied perpendicular magnetic field, which was found to be more complex than expected for a conventional magnet. One of the most pronounced features in the photoluminescence measurements is a sharp jump at $B \approx 0.85$ T, indicative of a field-induced change in the magnetic state of the system. The underlying mechanism and integration of optically control of valley pseudospins in proximitized vdW heterostructure will acquire additional knowledge to illustrate exchange interactions and interfacial effects to inspect novel physical phenomena in spintronics and valleytronics [94].

5.3. Spin-logics
Spin logic is a device that mostly employs magnetoresistive properties in which lower or higher electrical resistance states can be modified by orienting the magnetization value of each layer in parallel or antiparallel, respectively. The feasible utilization of spin instead of charge as an internal variable in developing devices for processing and storing information has been discussed broadly [95, 96] because it has the ability to permit
low-power spintronic device. However, beyond the development of magnetic hard drives, a fundamental challenge remains to incorporate such non-labile ferromagnetic material as a purpose of ordered amalgamation of built-in memory and spin logic [97]. This interesting anticipation provides a focus to conquer the intrinsic restrictions on widely engage logic circuits on the basis of von Neumann architecture. The plan of such a logic circuit depends on the development of central processing units integrated via a transmission channel to memory. The conventional example such as network routers generally the internet protocol addresses are analogous with a list of patterns for finding a match. Introduction of such conventional logic devices may restrict due to scalability issues, making them problematic for large search issues that are essential for fulfilling contemporary tasks [98]. However, the spin in lateral spin-valves introduce magnetologic gates (MLGs) [99] which has been successively expanded it to ferromagnet-graphene heterojunctions [100], for smooth incorporation of memory and logic utilizing assembly.

The possibility for realizing spin logic has given thrust during the demonstration at an ambient temperature of the MLG built on graphene [101]. However, graphene-based lateral spintronics application particularly spin-logic devices, acquire large SOC tunability along with electric field [102]. The tunability of large SOC is not possible in pristine graphene materials, but can be realized by stacking graphene in close proximity with materials exhibiting spin–orbit phenomena. The spin transport in graphene-based lateral spin logic consists of four electrodes lithographically motif above graphene as seen in figure 6(a). In non-local measurements, the current I is applied externally in the electrode F1 and M1. Due to the spin-splitting of electronic bands in electrode F1, the spin-injection via current applied creates a spin accumulation below the contact. This non-uniform spin density penetrates along the spin channel towards electrode F2. Figure 6(b) depicts a sharp transition that replaces from parallel to antiparallel ordering of F1 and F2 magnetizations. Spin precession measurements describe the parallel and antiparallel configurations were observed in figure 6(c). The indication of spin is maximum at B = 0, and its thorough value decreases
with increasing $B$ and disappears at large applied magnetic fields because of spin dephasing. Their development has prompted a growing interest in MPE among the scientific community for evaluating anisotropic spin dynamics [103], by theoretical modelling as well as experimental fabrication, as a purpose of assembling details about intrinsic graphene SOC and proximitized SOC in vdW heterostructure. TMDC in proximity with graphene Indent a rich pattern of spin in graphene and corroborates high-quality charge/spin transmission by incorporating SOC. The realization of Rashba type spin–orbit phenomena in graphene is generated from disintegrating out-of-plane symmetry in close vicinity with TMDC [104].

The effective electric field is applied perpendicular to the momentum of the electrons in an out-of-plane symmetry, which creates an in-plane Rashba SOC within the Dirac cone and generates a tangential winding pattern of spin in momentum space. The winding nature of Rashba SOC in graphene changes the mark among the spin-split Dirac cones of conduction and valence band as shown in figure 6(d). Moreover, the current-mediated spin splitting with opposite sign minimizes the total spin density at the Fermi level. The energy difference in the middle of the spin-split at Dirac cone is increased due to the presence of valley-Zeeman field. The clear manifestation of converting charge-to-spin in TMDC-graphene heterostructure is observed because of Rashba–Edelstein effect followed by the spin hall effect (SHE). The SHE has currently been realized in multilayer MoS$_2$-multilayer graphene [105], where the signal of SHE in graphene is overlapped by incorporating spin-to-charge conversion, which is primarily linked with SHE in bulk MoS$_2$. Thereafter, bulk TMDC is highly suppressed due to the contribution of SHE in the heterostructure system. Figure 6(e) displays the geometry comprising monolayer WSe$_2$-monolayer graphene which is encapsulated between monolayer h-BN and bulk h-BN. The optical image of the experimental fabrication is shown in figure 6(f), represented by white dashed line showing the graphene region into Hall bar which permits the nonlocal detection of induced spin density [106]. Therefore, it is necessary to engineer high-quality interface of graphene with other layered material comprising spin–orbit phenomena which is necessary for the ultimate control of the magnitude of the induced SOC by the effort of an extrinsically applied electric field. These measurements and realizations have a substantial importance in the field of spintronics, contributing towards all-electrical spin generation and manipulation in proximitized vdW heterostructures.

5.4. Spin field-effect transistors (FETs)
The transistor application related to spin instead of charge is known as spin transistors which could unveil high potentiality in nonlabile device applications. However, the realization is still a fundamental challenge. The external perturbative control on 2D vdW heterostructure is of gaining enormous attention for fundamental key reasons and its potential device application like field-effect transistor [58]. In the past two decades, thin films comprising of conducting materials, gate manipulated magnetism has been established, firstly by magnetic doping or defects created in semiconductor and later followed by traditional ferromagnetic substrates [107]. Moreover, the electric field manipulation has been recently realized in bilayer CrI$_3$, the external perturbation like electric field and doping can tune the spin-flipping magnetic field [8, 108]. One outstanding phenomenon is to realize the complete conversion of interlayer antiferromagnetism to ferromagnetism in graphene-encapsulated bilayer CrI$_3$ via electrostatic doping [109]. Moreover, 8% significant enhancement of magnetic moment is observed via MPE in Gr–CrBr$_3$ heterostructure whereas the enhanced magnetic moment can be tuned in the presence of electric field which has a potential application in modelling single gate FET. The introduction of nonmagnetic graphene layer over CrBr$_3$ exerts a staggering potential at the interface with fixed distance because of which density of electron and charge were tuned in the heterostructure system. To visualize the clear understanding on polarization at the interface and Fermi energy difference has been displayed schematically in figures 7(a) and (b). An externally applied perpendicular electric field to the hetero system in both forward and reverse directions of the $z$-axis which follows the ferromagnetic ordering, field variation is calculated in V/Å as observed in figures 7(c) and (d). Thereof, the perpendicular external electric field generates rearrangement of electrons, which does not lead to any structural changes in the atomic surface of the heterostructure system. Figure 7(e) displays the single gate field effect transistor device prototype from Gr–CrBr$_3$ heterostructure is observed. Gr–CrBr$_3$ is in close proximity with each other encapsulated among the two leads (source and drain) in the middle region. The gate is located above the middle region for the smooth passage of electrons across the channel from one lead (source) to another lead (drain) when applying an electric field. Subsequently, extrinsically applied electric perpendicularly in Gr–CrBr$_3$ heterostructure tunes the miniband spin splitting and transport phenomena. The interfacial polarization effect also exists because of the presence of two varied ingredient which enhances the conductivity by electrostatic screening in the heterostructure system [74].

Bilayer graphene (BLG) is proximitized with monolayer WSe$_2$ for realizing the prototype of spin FET theoretically. The proximitized spin FET device manages by tuning gate voltage for calculating spin
6. Future perspectives and concluding remarks

Detailed understanding on MPE in vdW heterostructure is one of the important steps for full exploitation on resembling the properties from one layer to adjacent layer, which has been widely accessed for possible application in spintronics and valleytronics. MPE is commonly seen as peculiar and disarticulate phenomena which instead contemplate as a flexible platform to convert a wide range of materials with enhanced functionalities. With the advent in developing heterostructures of low dimensions and modified interfacial phenomena, we believe that the zeal behind developing unusual heterostructure via proximity effect can only adopt new and unique physical properties which generally vary from their pristine form. This trend is epitomized by van der Waals heterostructures in which their individual component displays the superiority of interface compared to the bulk counterpart, provide a versatile medium to investigate and explore proximitized materials. In pristine form of 2D materials the long-range spin correlation is suppressed by thermal fluctuations, however, these thermal fluctuations can be prevented by anisotropy spin dynamics.
However, in recent past, the extrinsically local magnetic moments were induced by doping, chemical functionalization of surface or non-magnetic material in proximity with magnetic substrates which has a huge limitation in realizing and modelling spin-related device. Existence of long-range magnetic correlation in pristine 2D material is challenging because of strong thermal perturbation which has the possibility of destroying the magnetic behaviour in pristine 2D material. The fundamental challenge lies in developing improved interface quality with intrinsic physical properties such as magnetic property in proximitized vdW heterostructure so as to create long-range correlation which is a tough task to realize by extrinsically doping or inducing local magnetic moment via robust exchange coupling or coupling with the magnetic substrate [5]. Moreover, it will be very much instructive, for instance, to explore more vdW heterostructure which are intrinsically ferromagnets, antiferromagnets or having spin–orbit phenomena, which has become possible to now contemplate previously unidentified implications of proximity effects in atomically thin vdW materials which also includes intrinsic magnetism and nontrivial topological phases for overcoming the previous limitations of spin-devices. Here, we provide a detailed understanding on modified functionalities of proximitized vdW heterostructure for obtaining intrinsic magnetic nature unlike the extrinsically induced phenomena which has the capability of creating and tuning long-range magnetic ordering via robust exchange interaction. We highlighted how MPE along with external perturbation such as light, electric field, gating tunes the electronic structure, magnetic ordering and optical response in vdW heterostructure system. Meanwhile we reviewed few recent studies from the literature, for obtaining long rang magnetic order and valley Zeeman splitting in proximitized vdW heterostructure. Furthermore, broadening of experimental realizations of proximitized vdW hetero system to a much wider prospect is the utmost requirement, where many materials are present with quite clear evidence of layered vdW semiconducting system with intrinsic physical properties along with the interfacial phenomena. Therefore, proximitized vdW heterostructure with sharp atomic thickness can be designed by composing semiconducting layered material and 2D magnets for exploring the interaction effect, necessary for fabricating high-performance spin-electronic and valleytronics device such as spin FET, spin-logics, magnetic tunnel junction realizing magnetoresistive effect and spin-lasers. This perspective of MPE here opens various directions for future work in a broader prospect with the motivation in synthesizing, fabricating and theoretical modelling of proximitized vdW heterostructures for possible technological interest.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

M B would like to acknowledge Department of Science and Technology (DST), Govt. of India for providing INSPIRE Fellowship (IF180514). The authors acknowledge Tezpur University for providing High Performing Cluster Computing (HPCC) facility. The authors would like to acknowledge NBIOs award project, Department of Biotechnology (DBT), Govt. of India, vide Grant No. 102/IFD/SAN/5142/2018-19.

Conflicts of interest

There are no conflicts to declare.

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