Spin amplification by controlled symmetry breaking for spin-based logic

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Abstract

Spin amplification is one of the most critical challenges for spintronics and spin-based logic in order to achieve spintronic circuits with fan-out. We propose a new concept for spin amplification that will allow a small spin current in a non-magnetic spin channel to control the magnetization of an attached ferromagnet. The key step is to bring the ferromagnet into an unstable symmetric state (USS), so that a small spin transfer torque from a small spin current can provide a magnetic bias to control the spontaneous symmetry breaking and select the final magnetization direction of the ferromagnet. Two proposed methods for achieving the USS configuration are voltage-controlled Curie temperature (VC-\(T_C\)) and voltage-controlled magnetic anisotropy (VC-MA). We believe the development of new 2D magnetic materials with greater tunability of VC-\(T_C\) and VC-MA will be needed for practical applications. A successful realization of spin amplification by controlled symmetry breaking will be important for the implementation of existing spin-logic proposals (e.g. ‘all spin logic’) and could inspire alternative ideas for spintronic circuits and devices.

The advent of spin channel materials with long spin diffusion lengths at room temperature (e.g. several microns for graphene [1–3]) enables prospects for spin-based logic relying on the flow of spin currents. The potential advantages of spin-based logic come from the integration of logic with nonvolatile ferromagnetic memory. This nonvolatility enables spintronic circuits with non-von-Neumann architectures, which may have enhanced performance beyond CMOS for data-intensive applications even if the speed or energy per operation of an individual device is not better than CMOS [4].

One of the primary challenges for spintronics and spin-based logic is to develop a process of spin amplification. Specifically, our usage of the term ‘spin amplification’ refers to the concept of a small number of spins controlling a large number of spins, which will ultimately enable fan-out in spintronic circuits. Here, we present a method of spin amplification based on the control of spontaneous symmetry breaking in ferromagnets, which could make existing proposals such as all spin logic (ASL) [5] more feasible and may inspire alternative ideas for spintronic circuits. We specifically discuss two physical mechanisms to achieve spin amplification by controlled symmetry breaking that are consistent with low power dissipation: (1) voltage control of Curie temperature (VC-\(T_C\)) [6, 7] and (2) voltage control of magnetic anisotropy (VC-MA) [8]. 2D materials are particularly well suited for this purpose because electrostatic gates can strongly tune the carrier density and thus control the magnetic properties in proposed magnetic transition metal dichalcogenides (TMDs) [9–12].

For concreteness about our concept of spin amplification, it is worthwhile to discuss relevant parts of the ASL proposal. We consider a non-magnetic spin channel with an input ferromagnet and an output ferromagnet as shown in figure 1. By driving electric current from the input ferromagnet to the spin channel and exiting through a ground point, this generates electron spin polarization inside the spin channel (i.e. spin injection). Subsequently, the spin polarization diffuses through the spin channel via electron diffusion and reaches the output ferromagnet. These processes of spin injection and spin diffusion are well established in various spin channel materials including metals, semiconductors, and graphene [13–16]. The final and most critical step for ASL is to have the
electron spin polarization in the channel write the magnetization state of the output ferromagnet via spin transfer torque (STT). This is the step that defines our sense of spin amplification. Consider the electron spins in the channel as the ‘small number of spins’ and the ferromagnet as the ‘large number of spins’. Then this step of writing the magnetization of the output ferromagnet is a situation where a small number of spins is controlling a large number of spins. Our goal of spin amplification is to have a smaller number of spins in the channel control an increasingly larger number of spins in the output ferromagnet.

The key idea is to write the output magnetization by controlling the ‘spontaneous symmetry breaking,’ the process by which a ferromagnet acquires its magnetization direction when it undergoes a phase transition from the paramagnetic state \((T > T_C)\) to the ferromagnetic state \((T < T_C)\). As illustrated in figure 2, the free energy \((F)\) versus magnetization \((M)\) in the paramagnetic state has a minima at \(M = 0\) (figure 2(a)). As the temperature is lowered to below \(T_C\), the \(F\) versus \(M\) curve has a local maximum at \(M = 0\) and local minima at \(M \neq 0\) (figure 2(b)). With the magnetization still at zero, the system is in the unstable symmetric state (USS). Due to this instability, the system will ‘spontaneously’ choose a direction for the magnetization in order to lower the free energy (figure 2(c)). Theoretically, the choice only requires an infinitesimal magnetic bias, such as the Earth’s magnetic field, stray magnetic fields, or random fluctuating magnetic fields. In principle, the magnetic bias could also come from spintronic effects such as STT, which we will use for the basis of spin amplification. In terms of the ASL device (figure 1), we first get the output magnet into the USS in figure 2(b). Then we utilize STT from the spin channel to provide the magnetic bias that will select the final magnetization state. In theory, the STT could be infinitesimally small, but in practice it needs be large enough to overcome any stray magnetic fields in the device. In any case, the amount of STT needed should be orders of magnitude smaller than required in the original ASL proposal. Thus, by using a small STT to provide the magnetic bias to control the spontaneous symmetry breaking and write the output magnet, we are able to achieve our notion of spin amplification.

The method for getting the system into the USS configuration is important. Heating the output magnet to increase its temperature above \(T_C\) is not a practical solution. This is likely to require too much power
and the thermal process would be slow. A better option is to use electrostatic gates to control magnetic properties such as VC-\(T_C\) and VC-MA. In benchmarking studies, spin-logic devices based on voltage controlled switching tend to rate very well in terms of the energy per operation [17], so we anticipate that the use of VC-\(T_C\) and VC-MA for spin amplification could also rate well for this metric.

The VC-\(T_C\) was first observed in \(\text{In}_{1-x}\text{Mn}_x\text{As}\), a dilute magnetic semiconductor where Mn ions are coupled ferromagnetically by a hole-mediated exchange interaction [6]. By using a positive gate voltage to reduce the hole density, the exchange coupling between Mn ions is weakened and \(T_C\) goes down. More recently, the VC-\(T_C\) was achieved at room temperature in ultrathin cobalt films, where an increase in the electron density increases \(T_C\) [7]. The likely explanation for the effect is a modulation of the magnetocrystalline anisotropy, which has a strong effect on \(T_C\) in 2D ferromagnets [18]. In this regard, proposed 2D ferromagnetic TMDs are ideally suited for VC-\(T_C\) due to the strong gate tunability of carrier density and highly anisotropic crystal structure [9–12].

The geometry for the VC-\(T_C\) approach is shown in figure 3(a), with a gate dielectric and metal gate located on top of the output magnet. To write the magnetization state, the magnet is first brought into the paramagnetic state by applying the appropriate gate voltage (‘ON’), which causes the magnetization to go to zero (figure 3(b)). Next, spin current in the non-magnetic spin channel is generated by electrical spin injection (or possibly spin pumping) from the input ferromagnet, which produces a magnetic bias on the output magnet via STT. The gate voltage is then released (‘OFF’) to place the output magnet in the USS configuration (see figure 2(b)), and the STT magnetic bias can determine the direction in which the magnetization will align to break symmetry. Figure 3(c) shows the final state of the output magnet in its ferromagnetic ground state, where the magnetization direction is determined by the STT magnetic bias controlling the spontaneous symmetry breaking.

The use of VC-MA provides an alternative method of reaching the USS configuration. The experimental demonstration of VC-MA in a solid state device was achieved in a (metal gate)/MgO/Fe structure, where a positive gate voltage reduces the strength of the perpendicular magnetic anisotropy of the Fe film [8]. Possible explanations for the change in magnetocrystalline anisotropy include (1) a change in the occupancy of d-orbitals [19] and (2) electric-field-induced modifications to the electronic band structure [20]. To illustrate the VC-MA writing process, we consider an output ferromagnet with an out-of-plane (\(z\)-axis) easy axis. To begin, a gate voltage is applied to turn the \(z\)-axis into the hard axis (i.e. \(x\)-\(y\) easy plane) and bring the magnetization in-plane (\(M_z = 0\)). Next, the gate voltage is released to turn the \(z\)-axis back into the easy axis and the system goes into a USS configuration with \(M_z = 0\). From this configuration, the STT magnetic bias will push the system to the ferromagnetic ground state and determine the final direction of the output magnetization.

We also note that using the voltage controlled spin amplification (both VC-\(T_C\) and VC-MA) has an inherent advantage of ensuring the directionality of information flow. For example, in a system consisting of multiple ferromagnets connected by a spin channel, each magnet has the ability to act as an input or an output. Operating as an input, the magnet generates spin polarization in the spin channel according to its magnetization direction through electrical spin injection (or possibly other methods such as microwave spin pumping or thermal spin injection). For electrical spin injection, a magnet is selected for this function simply by applying a current from the ferromagnet to the spin channel. However, once the spin polarization is inside the spin channel, it can diffuse in any direction and, in principle, write the magnetization of any of the other magnets. In such a situation, there is no control over

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directionality of the information flow. One approach to overcome this problem is to control the spin diffusion, such as in ASL where the contact resistances between the ferromagnet and spin channel are adjusted to promote directionality of the spin current. The beauty of our spin amplification method is that the spin diffusion does not have to be controlled because the output magnet is selected by applying a gate voltage. Thus, the directionality between an input magnet (selected by electrical spin injection current) and an output magnet (selected by gate voltage) is strictly enforced. This flexibility in the selection of input and output magnets to control the flow of information could potentially lead to completely new approaches for spin-based logic.

Finally, we discuss the feasibility of this approach by (1) considering experimental results on STT in lateral and vertical geometries, (2) estimating the requirements for non-local spin torque switching for graphene spin channels, and (3) considering experimental results on VC-MA. Currently, two groups have demonstrated non-local spin torque switching in zero magnetic field for a lateral geometry with metal spin channel. Otani and co-workers switched permalloy (Py) nanomagnets with 75 × 170 nm² area and 20 nm thickness using a pure spin diffusion current in a Cu channel [21]. The critical excitation current at a temperature of 10 K was 5 mA (current density of 3.6 × 10¹¹ A m⁻²) at the injector, and the corresponding spin current at the Py detector was calculated to be 317 μA (critical spin current density of 2.5 × 10¹⁰ A m⁻²). Ji and co-workers obtained similar results for non-local switching of Py nanomagnets with a critical excitation current of 3.5 mA (current density of 3.3 × 10¹¹ A m⁻²) at the injector for 4.5 K, and 1.7 mA (1.6 × 10¹¹ A m⁻²) for 190 K [22]. In a graphene spin valve, non-local spin torque switching of a Py electrode (100 nm × 4 μm area, 5 nm thickness) has been observed experimentally but switching could only be achieved with a considerable applied magnetic field (2.5 mT for an electrode with coercivity of 3.5 mT), which suggests that the important spin-torque is from the ‘field-like’ term instead of the more typical ‘Slonczewski’ term [23, 24]. The observed critical current for excitation was 4 mA (corresponding to a current density of 3.3 × 10¹⁰ A m⁻²). In vertical magnetic tunnel junction structures, a low critical current density for spin-torque switching in zero field and at room temperature was achieved for perpendicularly magnetized CoFeB across an MgO barrier [25]. With cylindrical CoFeB nanomagnet of diameter 40 nm and thickness 1.3 nm, the spin-torque switching was achieved with a critical current of 49 μA (critical current density of 3.9 × 10¹⁰ A m⁻²). If we assume that MgO symmetry spin filtering produces a large spin polarization, then the critical spin current density is of the same order of magnitude (10⁷ A m⁻²). Interestingly, the perpendicular magnetic anisotropy KP, which includes both the surface anisotropy (Ks) and shape anisotropy (i.e. \( K_p = \left( \frac{K_s - \mu_0 M^2}{2} \right) \)), where \( t \) is the thickness of the magnet, \( \mu_0 \) is the permeability of free space, and \( M \) is the magnetization), was large enough to be thermally stable at room temperature: \( K_p \) is 400 T at 300 K.

To estimate the requirements for non-local spin torque switching in graphene spin valves, we consider the theoretical critical current for both in-plane and out-of-plane magnetized nanomagnets. For concreteness, we consider a graphene channel of width 200 nm and a nanomagnet of area 50 × 200 nm². For in-plane magnetization, we amend the macrospin model of Sun [26] to include a surface magnetic anisotropy (Ks, with positive values favoring out-of-plane magnetization) that could be controlled by gate voltage. In zero applied field, the critical spin current for in-plane magnetization becomes

\[
I_c = \frac{2\alpha e\mu_0 MV}{\hbar}\left( H_K - \frac{1}{2} H_S + \frac{1}{2} M \right),
\]

where \( \alpha \) is the Gilbert damping parameter, \( e \) is the electron charge, \( h \) is the reduced Planck’s constant, \( V \) is the volume, \( H_K = 2K/\mu_0 M \) is the anisotropy field associated with the in-plane uniaxial anisotropy \( K \), and \( H_S = 2K_S/\mu_0 M \) is the anisotropy field associated with the surface anisotropy. For in-plane magnetized materials, the shape anisotropy term usually dominates so the critical spin current reduces to \( I_c = \alpha e\mu_0 M^2V/h \). For a 5 nm thick Py nanomagnet with area 50 × 200 nm², we obtain a critical spin current in the range of \( I_c = 120–400 \mu A \) (using \( \alpha = 0.002–0.007, M = 7.8 \times 10^5 A m^{-1} \) from [21]). For the case of out-of-plane magnetization, the in-plane anisotropy is neglected and the critical spin current in zero applied field is

\[
I_c = \frac{2\alpha e\mu_0 MV}{\hbar}\left( \frac{1}{2} H_S - \frac{1}{2} M \right) = \frac{2\alpha eK_S V}{h}. \quad (2)
\]

For a CoFeB nanomagnet with area of 50 × 200 nm² and thickness of 1.3 nm based on parameters from [25] (\( \alpha = 0.02, M = 1.26 \times 10^6 A m^{-1}, K_p = 2.1 \times 10^5 J m^{-3} \)), the critical spin current is \( I_c = 166 \mu A \). Therefore, the analysis of both in-plane and out-of-plane magnetization shows that it is necessary to have spin current on the order of 200 μA (critical spin current density of \( \sim 2 \times 10^{10} A m^{-2} \)) to induce spin-torque switching.

To understand whether this could be achieved with a graphene spin channel, we need to consider the current carrying capacity of graphene, the robustness of the tunnel barrier for injection, and the efficiency of spin absorption into the detector. We consider a device geometry as shown in figure 1, with the output magnet having transparent contact to graphene, and all other contacts having tunnel barriers to minimize the spin absorption. In addition, the long spin diffusion length of graphene (several microns) makes it possible to achieve the ‘confined geometry’ with device size much smaller than spin diffusion length
Under such conditions, the conversion of charge current to spin current can be much more efficient and the resulting spin currents could be more similar to that found in magnetic tunnel junctions. In addition, the confinement of spin current and the suppression of spin absorption through the tunnel barriers should cause most of the injected spins to be absorbed into the output magnet. Achieving this will require substantial improvements to the quality of the materials and interfaces. The issue then becomes whether it is possible to inject spin current on the order of 200 μA into a 200 nm wide strip of graphene. Based on a maximum current density of 10^{12} \text{A m}^{-2}[29], a 3 nm thick multilayer graphene (~9 monolayers) of width 200 nm could carry a maximum current of 600 μA. With a spin injection efficiency of 30%, the corresponding spin current would be 180 μA. To gauge the limitations of spin current due to the tunnel barrier, we consider that spin injection into graphene with a current density of 5.0 \times 10^{10} \text{A m}^{-2} across Al_{2}O_{3} tunnel barriers has been achieved [23]. For an area of 50 \times 200 \text{nm}^{2} the current would be ~500 μA, so a 30% spin injection efficiency would produce a spin current of ~150 μA. Alternative barriers such as amorphous carbon, which has led to the highest observed spin accumulation are also promising [30]. This analysis indicates that it could be possible to achieve non-local spin torque switching in zero field in graphene without the spin amplification, but it would be challenging because the materials have to maintain ideal spin transport properties at high bias. Moreover, the materials are at the borderline of their physical limits and Joule heating could become an issue. But the outlook may be better because the above analysis is based on the more prevalent Slonczewski-type spin-torque, while experiments on graphene suggest that the field-like spin-torque may be stronger [23, 24]. More experiments will be needed to clarify this interesting issue.

Next, turning to the concept of spin amplification based on VC-MA, we can see in equations (1) and (2) that if the surface anisotropy (K_{S} or equivalently H_{S}) were tuned by an electrostatic gate, then the critical spin current could be reduced substantially. For in-plane magnetization, equation (1) shows that increasing K_{S} will counteract the shape anisotropy to reduce the critical spin current even if the easy axis remains in-plane. If the increase of K_{S} is large enough, the critical current approaches zero as the easy axis switches to out-of-plane, which is the realization of the USS configuration (relative to the in-plane configuration). Similarly for out-of-plane magnetization, equation (2) shows that decreasing K_{S} will lower the critical spin current even if the easy axis remains out-of-plane. If K_{S} is reduced to be weaker than the shape anisotropy, the critical current approaches zero as the easy axis switches to in-plane, which is the realization of the USS configuration (relative to the out-of-plane configuration). Thus, by tuning the surface magnetic anisotropy, it becomes possible for smaller spin currents to provide sufficient spin torque to switch the magnetization.

The relevant question then becomes whether the voltage tuning of K_{S} is sufficient to provide a transition from a USS configuration to a thermally stable state. This is best considered for the case of out-of-plane magnetization because the thermal stability is directly related to the total perpendicular anisotropy K_{P}. A relevant study was performed on ~0.60 nm Fe_{80}Co_{20} films, where changing the voltage applied across a 1.7 nm MgO layer by 1 V (i.e. change in E field of 6 \times 10^{3} \text{V m}^{-1}) caused K_{S} to vary by 1.9 \times 10^{-3} \text{J m}^{-2} [31]. This changes K_{P} by 3.2 \times 10^{3} \text{J m}^{-3}, and for a nanomagnet with area 50 \times 200 \text{nm}^{2}, the change in the energy barrier K_{P}V is 1.9 \times 10^{-19} J = 1.2 \text{eV} = 48 k_{B}T at 300 K. Thus, if we take 40 k_{B}T as the criteria for thermal stability, then it is possible to tune from the USS configuration to a thermally stable state with an applied gate voltage. This study used an ultrathin MgO layer of 1.7 nm thickness; for a gate dielectric, it would be preferable to use a 10 nm MgO layer for less leakage current (exponentially suppressed), while applying ±3 V to achieve the equivalent electric fields. This validates the feasibility, at least in principle, of the proposed spin amplification method based on parameters from existing materials and established models.

In conclusion, we propose a new method for spin amplification based on controlled symmetry breaking that allows a spin current in a non-magnetic spin channel to write the magnetization of an attached output magnet. This concept could be applied to many material systems and is particularly well-suited for spintronic devices based on 2D materials. Graphene is an ideal material for the spin channel because it has the longest spin diffusion length at room temperature of any material. Proposed magnetic TMDs appear to have the desired characteristics needed to achieve stronger electric field tuning of Curie temperature and magnetic anisotropy. Developing such materials and achieving spin amplification will be an important advance for spin-based logic and 2D spintronics.

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