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Spin Transfer Torque: a new method to excite or reverse a magnetization

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Abstract

The recent discovery that a spin polarized current can exert a large torque on a ferromagnet through a transfer of spin angular momentum, offers a new method to manipulate a magnetization without applying any external field. This additional spin transfer torque can generate oscillatory magnetic modes or even magnetization reversal, for a sufficiently large current. Although the nature of the magnetization dynamics induced by this new effect is not yet completely resolved, spin transfer is already a turning point in spintronics and is today the subject of an extensive research for applications in magnetic random access memory, fast programmable logic, high-density recording and in high frequency devices for telecommunications. ***To cite this article: V. Cros et al., C. R. Physique 6 (2005).***

Résumé

Le transfert de spin : un nouveau moyen pour exciter ou renverser une aimantation. La découverte récente qu'un courant polarisé en spin peut exercer, via un transfert de moment angulaire de spin, un fort couple sur un ferromagnétique offre un nouveau moyen pour manipuler une aimantation sans appliquer de champ externe. Ce couple dit de transfert de spin peut, pour un courant suffisament fort, générer des excitations magnétiques en hyperfréquence ou même provoquer le renversement de l'aimantation. Bien que la nature des modes magnétiques induits par le courant ne soit pas encore bien résolue, le transfert de spin représente d'ores et déjà une rupture en spintronique et fait l'objet de nombreuses recherches pour les applications dans les mémoires magnétiques non volatiles, la logique magnétique ultra-rapide, l'enregistrement haute densité ou encore dans les dispositifs hyperfréquences pour les télécommunications. ***Pour citer cet article : V. Cros et al., C. R. Physique 6 (2005).***

Keywords: Spintronics; Spin transfer; Microwave dynamics

Mots-clés : Spintronique ; Transfert de spin ; Dynamique hyperfréquence

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1. Introduction

Undoubtedly, 'spin transfer' is today a hot topic in spintronics. It takes roots in the long-standing problem of the interaction between the spin of the conduction electrons and a localized magnetic moment [1]. This transfer of spin is equivalent to a torque exerted on the magnetization which, at a sufficiently large current density, can stimulate magnetic excitations or even reverse the magnetization. Indeed it can be seen as a reverse effect of the Giant MagnetoResistance effect (GMR). In GMR, the spin polarized current in the structure is determined by the magnetic configuration contrary to the spin transfer, in which the spin current controls it. After the proposal of the spin transfer concept in 1996 [2,3], first evidences for spin transfer excitations came out quickly in the literature in point contacts [4] and nanowires [5] geometries. However, the first clear signature of spin transfer effect has been given by Katine and coworkers in 2000 on specially tailored spin valve nanopillars [6].

As described in the next section, in the spin transfer effect, a small transverse component of angular momentum is able, depending on the direction of propagation of the electrons, either to stabilize or destabilize the equilibrium position of the nanomagnet. In view of the very large number of works, both theoretical and experimental, done in the last five years, a puzzling question is: who did take care before about this small spin current when describing all the magnetoresistive transport properties of very similar devices? The spin transfer effect is indeed a very nice example of the usefulness of basic research. A tiny small component, until recently unknown or not considered, has opened a new interesting research field in solid state physics and, more specifically, a turning point of spintronics towards new problems of non linear physics. Moreover, this extensive research opens hopes for applications in non volatile magnetic memories, programmable fast magnetic logic, and in high frequency devices for telecommunications.

The manuscript is divided in four sections. First, in Section 2, we give a phenomenological description of the occurrence of the spin transfer in a magnetic trilayer spin valve structure. In Section 3, we present some of the key reflections of the most recent theoretical developments. The main features of the spin transfer torque in the presence of an external field are presented describing the stability conditions of the magnetic configuration of the device. Then in Section 4, we divide in three parts a brief review of the experimental results: the Current Induced Magnetization Switching (CIMS), the Current Induced Magnetic Excitations (CIME), and the Current induced Domain Wall Motion. Finally, before concluding, some of the very promising applications of the spin transfer are listed.

2. From the propagating electrons to the magnetic moment...

In 1996, Slonczewski [2] and Berger [3] have introduced almost simultaneously the concept of spin transfer. The basic device for the observation of magnetization excitations driven by a spin polarized current is a spin valve pillar as presented in Fig. 1. This structure contains two ferromagnetic layers F_1 and F_2 separated by a normal one NM. The layer F_1 is thick enough to be considered as fixed and serves as a spin polarizer in the device. On the other hand, the layer F_2 is thin and free to move under the action of the current. The electrons are injected perpendicularly to the plane of the layer. The direction of the spin polarization in the normal metal cannot be parallel to both M_1 and M_2. Thus it makes an angle with respect to M_2 when the two magnetizations are not collinear (see Fig. 1). When the electrons are passing through F_2, they align their spins by the

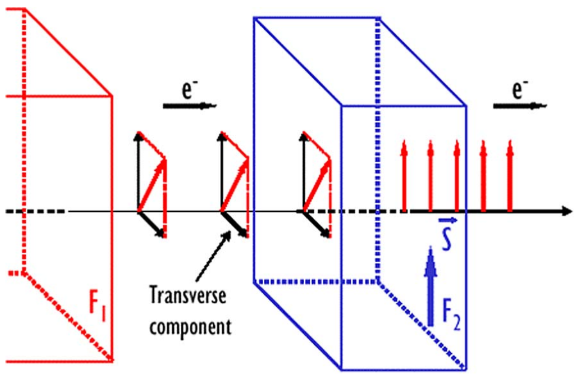

Fig. 1. Schematic diagram of the trilayer structure originally proposed by J. Slonczewski. The device is made of two magnetic layers F_1 and F_2 separated by a non magnetic layer. The layer F_1 is thick enough to be considered as a spin polarizer of the current and fixed upon the action of the current. The layer F_2 is thin and free to move under the action of the spin transfer torque. The transverse component of the spin current of the free layer moment will be absorbed and transferred to the local moment in F_2 when the electrons are passing through this layer. This results in a torque that can excite or reverse the magnetization M_2.

exchange interaction in the direction of M_2. Since the exchange interaction is spin conserving, this means that the transverse component of the spin current has been absorbed and transferred to M_2. This transfer of spin angular momentum is equivalent to the existence of a torque acting on M_2, now well known as Spin Transfer Torque (STT). In the framework of Slonczewski, the expression of the time variation of the magnetization M_2 of the thin layer due to the spin transfer is:

$$\frac{\mathbf{dM_2}}{\mathrm{d}t} = -\, P_{\mathrm{transv}}\mathbf{M_2} \times (\mathbf{M_2} \times \mathbf{M_1}) \tag{1}$$

where M_1, M_2 are the respective magnetic moments of the layers. The parameter P_{transv} is proportional to the magnitude of the transverse component of the spin current and is proportional to the current and the spin polarization. To describe the motion of magnetization, one has to add this new torque to the other torques in the equation of Landau–Lifschitz–Gilbert (LLG):

$$\frac{\mathbf{dM_2}}{\mathrm{d}t} = -\gamma_0\mathbf{M_2} \times \left[H_{\mathrm{eff}}\mathbf{u_x} + H_d(\mathbf{M_2}\cdot\mathbf{u_z})\mathbf{u_z}\right] + \alpha\mathbf{M_2} \times \frac{\mathbf{dM_2}}{\partial t} - P_{\mathrm{transv}}\mathbf{M_2} \times (\mathbf{M_2} \times \mathbf{M_1}) \tag{2}$$

where $\mathbf{u_z}$ is the out of plane unit vector, and $\mathbf{u_x}$ the in plane unit vector directed along the thick Co layer magnetization M_1. H_d is the demagnetizing field whereas H_{eff} represents the effective field, the sum of the applied field H_{app} and in plane anisotropy field H_{an} assumed to be oriented along the magnetization direction of the thick layer. In this approach, the torque due to the transfer of spin has therefore the same form as the second term i.e. a damping torque, except that it can dissipate or provide energy to the system depending on the sign of the current. Typical values of the critical current densities required to observe spin transfer effects (excitation and/or reversal of the magnetization) are about $10^7\ \mathrm{A\,cm^{-2}}$. In general, the GMR effect present in this device is used as a sensor to detect the motion of the thin free layer magnetization due to spin transfer.

3. Basics of the theoretical models

Following the approach of Slonczewski, in most theoretical models [7–9], the spin transfer torque is linked to the transverse spin polarization of the current transferred to the magnetic layer. Theoretical models were developed to answer two main questions. What is the microscopic origin of the transverse component of the spin current? And how is this component really absorbed by the magnetic layer?

With respect to the first question, Slonczewski has originally developed the concept of spin transfer in the ballistic regime [2,10]. As a consequence, the polarization of the current is defined only locally by the spin polarization of the density of states at the Fermi level. Following the experience of CPP-GMR (Current-Perpendicular-to-the-Plane GMR), the spin polarization of the current in multilayer metallic devices is known to be due not only to the spin dependent reflections at the interfaces but also to the spin dependent scattering in the bulk of the layer [11]. Thus all most recent theoretical developments [12–14] take into account the spin accumulation and the spin scattering both at interfaces and in the bulk. To treat correctly the transverse component of the spin current, they also integrate the quantum mechanically calculated values of the mixing conductance [15]. They represent indeed a kind of unified theory of CPP-GMR (collinear magnetic configuration) and spin transfer effect (non collinear magnetic configuration). This approach is the only one able to describe correctly recent experiments in which the sign of the current driven switching (normal or inverse CIMS) is controlled by the intentional doping of the magnetic layer with impurities of selected spin dependent scattering [16].

The second important question concerns the physical mechanisms originating the fate of a spin polarized current that enters a ferromagnetic layer (from a non magnetic layer). Two mechanisms have been mainly invoked [17,18]. The first is associated to a reduction of the transverse spin component of each electron because its reflection and transmission coefficients are spin dependent. The remaining part of the transverse spin component is then transferred to the free layer magnet because the spins precess around the local magnetization. When summing over all the electrons, a dephasing occurs and thus the transverse spin component averages to zero. Since the angular momentum is conserved, the moments of the magnetic layer gain what the electrons have lost. The characteristic length for the transfer of the transverse spin current has been estimated to a few atomic constants after the interface for most of the all-metallic ferromagnetic/non magnetic interfaces [17,18]. It would probably be much longer [19] in semiconductor magnetic heterostructures, in which some CIMS results have been recently obtained (see Section 4.1). In any case, it is much shorter than the characteristic length of the relaxation of the longitudinal spin current (the spin diffusion length). As a consequence, it signifies also that if the normal metal layer thickness is less than the electron mean path, then part of the transverse spin component at the NM/thin F_2 interfaces would come ballistically from the interface with the second ferromagnet (Thick F_1/NM). A final remark is that most of these models come from an oversimplified approach assuming that the free layer magnetization behaves like a macrospin. In this case, the only possible current-induced excitations are uniform precessions. Even if some of the key features of the Spin Transfer Torque (STT) are now well described by these models, there is still a long way to fully understand the current induced non linear dynamics of a nanomagnet integrated in micromagnetic simulations [20,21].

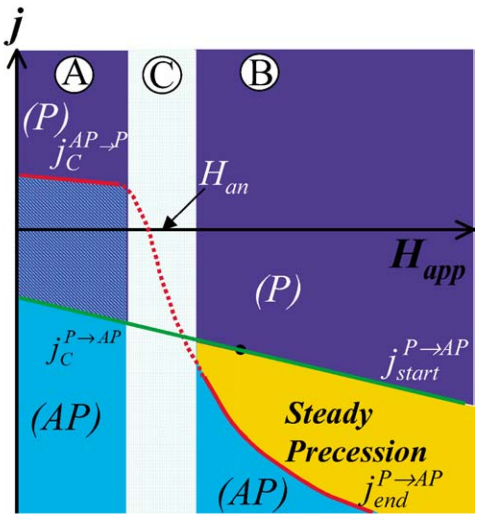

Fig. 2. Critical currents versus applied field stability diagram (schematic representation) showing the parallel (P in dark blue), antiparallel (AP in light blue), the bistable P/AP region (low field in zone A) and the yellow area in which both configurations are unstable (high field in zone B). The green line separates the region where the P configuration is stable (above the line) and unstable (below). The red line separates the regions where the AP configuration is stable (below the line) and unstable (above). Equations of the two lines are derived from the LLG equation of motion for a uniaxial magnetic anisotropy H_{an}.

3.1. Current-field stability diagram of the spin transfer effect

The uniqueness and novelty of the spin transfer effect is easily revealed in a diagram of the injected current versus the magnetic field (cf. Fig. 2). This kind of diagram is obtained by studying the stability/instability of the magnetic moment using a modified Landau–Lifschitz–Gilbert equation of motion taking into account the spin transfer torque of Slonczewski's model [22]. This oversimplified approach account nevertheless qualitatively for the experimental results presented in Section 4. The main feature in this diagram is the existence of two different regimes in presence of an external magnetic field for the action of the spin transfer torque on the magnetization. The crossover (zone C on Fig. 2) between these behaviors occurs for an applied magnetic field close to the in plane uniaxial anisotropy of the layer [23]. In the first regime (at low field, labeled zone A), one observes a direct and irreversible reversal of the magnetization (corresponding to transitions between the P and AP configuration of the magnetizations of the trilayer). This behavior is now considered as a fingerprint for the so called current induced magnetization switching (CIMS). In the second regime, at high field labeled zone B, the magnetization reverses in a progressive and reversible way between the P and AP configuration. This a rare example of a fully reversible transition in magnetism. This region (in yellow on Fig. 2) is associated with current induced magnetization excitation (CIME) [24]. These can be precessional states of the magnetization on different types and forms of orbits (depending on the field amplitude) and/or any other type of non uniform current induced excitations (i.e. spin waves in point contact devices). The main conclusion of this diagram is that the spin transfer torque is not of the same nature as the torque exerted by a field but is rather similar to a torque of negative friction. In the next two sections, we present more in detail some of the key experimental results obtained in the study of the spin transfer effect in each regime.

4. Spin Transfer Torque: experiments

4.1. Low field regime: Current Induced Magnetization Switching (CIMS)

Even if it was not the first observation, the measurement of a complete magnetization reversal induced by a spin polarized current without any magnetic field is probably one of the most striking example of spin transfer effect [25,26]. For sure, it has strongly contributed to the large and rapid growth of the domain in the last five years. In Fig. 3(a), we present an hysteresis cycle of the conductance in a Co(thick)/Cu/Co(thin) nanopillar in the absence of external magnetic field obtained at Cornell University [25]. The transfer of spin angular momentum to the thin layer magnetization (or nanomagnet) by the electrons flowing from the thick one forces the free nanomagnet to stay in the parallel configuration (low resistance state) above a critical current $I_c^{P\to AP}$. In their convention, it corresponds to a negative current of about -3 mA. On the other hand, when the electrons

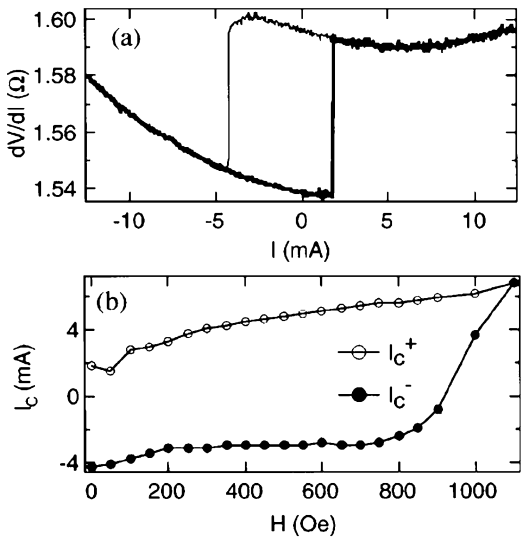

Fig. 3. (a) Differential resistance versus applied current at $H = 0$ measured on a nanopillar spin-transfer device. (b) Field dependence of the two critical currents $I_c^{P\to AP}$ and $I_c^{AP\to P}$, in the low field regime. Figure extracted from [25].

flow from the nanomagnet towards the thick Co layer (positive current), the spin transfer torque imposes, above a critical current $I_c^{AP\to P}$ (around 2 mA), an antiparallel alignment (high resistance state) with the thick Co layer magnetization. Both the sign and the order of magnitude of the critical current densities are in agreement with Slonczewski's predictions. The variation of the critical current with H is illustrated in Fig. 3(b) and is in full agreement with what is expected in the stability diagram presented in a previous section (red and green lines in zone A and C in Fig. 2). In low field hysteretic regime (zone A in Fig. 2), when H increases (reinforcing the P configuration), it is expected that $I_c^{P\to AP}$ decreases and $I_c^{AP\to P}$ increases. In fact, it has been recently observed that even in this hysteretic region, a reversible rounding of the hysteresis occurs just before the switching (around $I_c^{AP\to P}$ in Fig. 3(a)). This is attributed to current driven dynamical instabilities [27].

4.1.1. Temperature dependence of CIMS

The study of the temperature dependence of CIMS has given some important insights about the nature of the spin transfer effect. All the experiments have concluded that CIMS is thermally activated. However, depending on the authors, there have been some discrepancies in the conclusions about the switching mechanism. The question is whether the thermal dependence of CIMS is only governed by the sample temperature or do we have to introduce the concept of a spin dependent or magnetic temperature? In the first case, it means that the experimental results can be well understood only using a current dependent activation barrier and a spin transfer torque that coherently excites the moment [28–30]. In the latter case, the nature of the effect is fundamentally different, because in this approach, the electrons excite by transfer of spin some non uniform incoherent magnons which can increase or decrease the effective magnetic temperature [31,32]. This type of model was developed to understand how a DC current might excite a magnetization during very long time (seconds or more) without using the concept of coherent precession. However, a current induced increase of the magnetic temperature would never explain the experimental observation in the frequency domain of narrow peaks in the GHz range as presented later [33,34].

4.1.2. Tuning of the amplitude of the spin transfer torque

As mentioned before, both the sign and the amplitude of CIMS are directly related to the spin polarization of the current. In some recent experiments, a group at Michigan State University has succeeded in tuning the sign of CIMS by changing independently the sign of the scattering both at the interfaces and in the bulk of the layers [16]. They could control it by adding some Cr impurities in the ferromagnetic layers (Fe or Ni) which is known to scatter more strongly majorities electrons. Using mixing of ferromagnetic metals and Cr based alloys layers in the spin valve nanopillars, they could produce all possible combinations of normal or inverse GMR and also of normal or inverted CIMS. In an other study, they show that inserting sufficiently strong spin-flip-scattering (i.e. Pt) into the intermediate Cu layer eliminates hysteretic current-driven switching [35]. The consequence of these results is that one has to go beyond the original ballistic model to describe the CIMS. One must take into account the diffusion processes in the whole structure as it is done in the standard diffusive transport equations of the CPP-GMR theory. In fact, in a non collinear configuration of the magnetizations, as it occurs during the CIMS effect, the longitudinal and transverse component of the spin current are related one to the other and a global treatment of the longitudinal and transverse components of the spin current and the spin accumulation is required [9,13].

4.1.3. Reduction of critical current densities

Practical applications require to reduce substantially the critical current densities which are about 10^7 A cm^{-2}. Using some experimental data extracted from CPP-GMR experiments, one can calculate the spin polarization of the current and then the spin transfer torque. It was found that some reductions are possible compared to the existing values but not by more than one order of magnitude [7]. This reduction has been verified experimentally by inserting a thin layer of a strong scatterer material (FeMn or Ru) in the outside vicinity of the thin nanomagnet [36,37]. Therefore, the spin accumulation and thus the spin transfer torque is strongly increased at inner interface (normal metal/FM2 on Fig. 1) where the spin transfer effectively takes place. Another strategy to reduce the critical current densities is to observe CIMS in materials having a much weaker magnetization and a larger spin diffusion length than the common transition metals [38]. In this sense, the first example of CIMS in magnetic semiconductor GaMnAs based nanojunction has demonstrated the possibility to reverse (at low temperature) the moment of the nanomagnet with only a few 10^5 A cm^{-2} [39,40]. Another trail which is followed (and is very important for the possible applications) is to study the spin transfer in the tunnel regime with materials having a large spin polarization of the Density Of States at the Fermi level, like CoFe for example [41].

4.2. High field regime: Current Induced Microwave Excitation (CIME)

As mentioned in the paragraph presenting the stability diagram, the effect of the STT on the nanomagnet changes significantly when a magnetic field with an opposite action to the spin torque is applied. Typically, this crossover field is almost equal to the coercitive field of the nanomagnet. As shown in Fig. 4(a) and (b) extracted from [31], at H larger than this field, the hysteretic cycle of $\mathrm{d}V/\mathrm{d}I$ as a function of I (see Fig. 3) a reversible peak of $\mathrm{d}V/\mathrm{d}I$ at a threshold current I_t. (In general, this critical current I_t is equal to $I_c^{P\to AP}$ at low field.) Moreover, at higher I, there is reversible peak labeled (I_r) that shifts to higher current values when H increases. In addition to this reversible peak, one can generally observe several peaks for I between I_t and I_r. A room temperature, these intermediate peaks are replaced by a smeared peak. Both I_t and the series of peaks are weakly dependent with H. Let us now discuss the physical mechanism at the origin of these different sets of peaks in $\mathrm{d}V/\mathrm{d}I$. The threshold I_t has been identified as the onset of large amplitude excitations of the nanomagnet. At this critical current I_t, the energy led to the system by the spin transfer compensates the magnetic damping energy. This is represented by the green line in the high field regime on Fig. 2. Furthermore, these excitations are associated in the macrospin approximation to current induced steady precessional states (corresponding to the yellow area in Fig. 2). On the other hand, time resolved measurements have shown that the reversible peak at I_r is a consequence of the current induced telegraph noise between the P and AP configuration [31,42]. The peak position corresponds to the current at which, for H fixed, the dwell time in P and AP are equal.

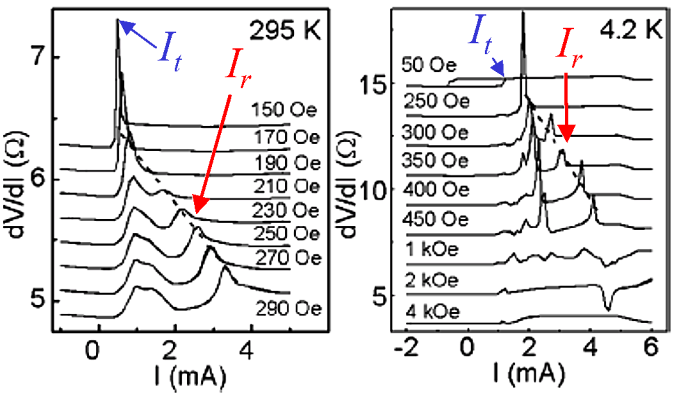

Fig. 4. High field regime: Differential resistance versus applied current in a NiFe/Cu/NiFe trilayer. The applied fields are the marked values at 295 K (left) and 4.2 K (right). Curves are offset for clarity. The peak labeled I_t indicates the onset of the steady precession regime. Dashed lines follow the reversible switching peak I_r that is a consequence of the current induced telegraph noise between the P and AP configuration. Figure extracted from [31].

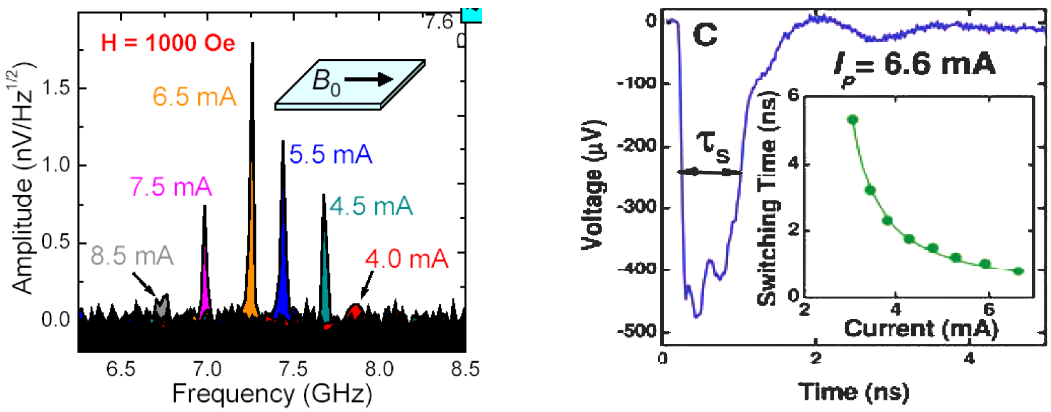

Fig. 5. (Left) High frequency power spectra at different values of applied current through the spin valve point contact. The peaks are associated to the large-angle precession of the magnetization of the free layer due to spin transfer. Figure extracted from [34]. (Right) Time resolved voltage signal due to spin transfer of the free magnet layer in NiFe/Cu/NiFe nanopillar at current $I = 6.6$ mA. The first voltage drop at $t = 0.3$ ns is due to the beginning of the pulse. After it, coherent oscillations are seen on the curve associated with onset of magnetization precession prior to the switching. Inset: dependence on the switching time versus the applied deduced from the experiments. Figure extracted from [47].

4.2.1. Measurements in frequency domain

Theoretical predictions suggest that for a certain range of H and I, the spin transfer may be able to generate oscillatory magnetic motions. As we have just seen before, measurements of $\mathrm{d}V/\mathrm{d}I$ versus I give indirect evidence (through the presence of peaks) of dynamical modes of the magnetization driven by the spin current. The first direct proofs have been provided recently by two American groups looking at the high frequency magnetization dynamics. The two studies differ only in the type of samples: spin valve nanopillars for the Cornell group [33] and spin valve point contacts for the NIST group [34]. In Fig. 5(a), we present the microwave power spectra measured by NIST resulting from current driven motion of the magnetization in a NiFe nanomagnet. One clearly sees above a critical current (of about 4 mA in this case), oscillations in the GHz frequency range. The onset of the dynamical peaks is not always directly related to the peak position in the $\mathrm{d}V/\mathrm{d}I$ characterization. As I further increases (for H applied in the film plane), the peak frequency decreases (redshift). An important point is that the magnitude of the emitted power does not increase linearly with I. This has been attributed to changes of precessional orbits. This behavior has also been observed in the nanopillars geometry. Some simulations for a single magnetic domain using the modified LLG equation of motion show two basic regimes of magnetization dynamics. First, at low current, the magnetization M precesses on small quasi elliptical orbits around H. As I increases, the trajectories become non elliptical and have a large angle excursion with respect to H direction. This kind of orbits called clam-shell orbits are the ones giving the largest microwave amplitude signals [43]. The second regime is reached as I is further increased when the magnetization M begins to oscillate out of the plane. In this case, the precession frequency increases with I (blueshift). In some other cases, some additional magnetic modes have been found and attributed to the motion of the thick magnetic layer [44]. Following the observation of reversible peaks in $\mathrm{d}V/\mathrm{d}I$ characteristic, it has been also proved that STT induces two-state transitions between P, AP and also intermediate magnetic states which results in a broadband power spectra at low frequency (up to 2 GHz) [45,46]. Finally, it has been shown that the precession frequency can be tuned from a few GHz to more than 40 GHz only by changing the magnetic field and the dc current. The excitation linewidths can be in some cases, extremely narrow (about a few megahertz) and lead to very high quality factors Q (around 18 000 [43]). Consequently, this device is a very effective current controlled microwave oscillator.

4.2.2. Time resolved experiments at the sub-nanosecond scale

Another way to directly probe the magnetic dynamics driven by spin transfer is to make time resolved measurements at the Gigahertz scale. This has been done recently on nanopillars by the Cornell University's group [47]. By measuring in time domain, they can observe as shown on Fig. 5(b), the steady precessional motion of the magnetization. In Fig. 5(b), they first observe a voltage drop at about 0.3 ns due to the onset of the current pulse. After this, one can clearly observe coherent oscillations equivalent to the peaks measured in microwave power spectra. Furthermore, this time resolved studies of the magnetic relaxation prove very directly that the effective damping parameter (Gilbert damping + STT) is fully electrically controllable using the spin polarized current.

4.3. Domain wall motion induced by spin transfer

Another form of current induced magnetic response without the use of any magnetic field is already known both theoretically and experimentally: the current driven motion of a Domain Wall (DW) in ferromagnetic materials [48,49]. When a spin-polarized current goes through a DW, the torque, resulting from the interaction of the conduction electron spins with the exchange field in the DW, progressively rotates the spin polarization of the current. Reciprocally, the spin-polarized current exerts an exchange torque on the magnetization within the DW. However, the details of the mechanism of current induced domain wall motion are not yet well identified. Indeed, the most recent theoretical models [50–53] based on spin transfer torque find much larger critical current densities (or DW velocities) than what is observed experimentally [54–58]. In particular, it has been found that the current-induced displacement of a DW in the permalloy (Py) layer of a Co(10 nm)/Cu(10 nm)/Py(5 nm) spin valve nanowire is obtained for critical current densities only of the order of $10^6\ \mathrm{A\,cm^{-2}}$ [54]. Similar behaviors are observed when current pulses as short as 0.4 ns are used to trigger the DW motion [59]. Thus this new approach to commute a magnet by DW motion is currently intensively studied for possible applications in MRAM or in fast novel magnetic logic based on DW motion [60,61].

5. Towards technological applications of spin transfer

As we have seen in the previous section, spin transfer effects can produce, depending on the field-current parameters, either a magnetic reconfiguration or other magnetic dynamics. This divides naturally in two branches the potential new applications.

First, in magnetic memories (MRAM) domain, spin transfer is generating much interest as an alternative to the use of current generated magnetic fields for the writing procedure in the magnetic element. Recent experiments [62] have proved that the magnetization reversal occurs for sub nanosecond current pulses (down to 200 ps). In particular, the concept of precharging strategy has been introduced both to accelerate the reversal and to reduce the critical current. This is promising for future application for MRAM based on spin transfer switching. By using specific design of spin valves (exchange bias layer, nano-oxide layer, annealing etc.), the critical current densities have been substantially lowered to about $5 \times 10^6\ \mathrm{A\,cm^{-2}}$ [63,64]. However, in the existing prototypes of MRAMs, the magnetic bit is a magnetic tunnel junction (MTJ) and not a spin valve. Up to now, only few results of CIMS have been obtained in such devices with critical current densities about $6\text{–}8 \times 10^6\ \mathrm{A\,cm^{-2}}$ [41,65,66]. In all cases, the switching has been measured in alumina based tunnel junctions with very low RA products (about $10\ \mu\Omega\,\mathrm{cm^{-2}}$). They are very difficult to produce due the thinness of the oxide layer and much hope relies in new low barrier height oxydes like MgO. For an other type of magnetoresistive devices, i.e. GMR read heads [67], STT can induce magnetization fluctuations that results in noise on timescales ranging from microseconds to nanoseconds. As the dimensions of all devices decreases, device size will soon reach the point where STT has really to be addressed. To conclude, in both cases (CIMS or current induced noise), a better understand of the physical mechanisms at the origin of the effect would help to decrease or increase the amplitude of the torque.

The second axis of applications for spin transfer effect deals with microwave spintronic devices. Even if many questions are still pending on the origin of the magnetic dynamics driven by spin current, this new class of microwave oscillators i.e. spin transfer nano-oscillator (STNO) has already a strong potential in telecommunication technologies such as mobile phones, chip-to-chip communications or radars. The need for new agile and cheap microwave synthesizers will increase as the frequency domain congestion increases. One of the big advantage of the STNO is that they directly emit in the microwave window contrary to the existing generation of oscillators. The current controlled agility of the STNO has been demonstrated to work from a few GHz up to 40 GHz. Furthermore they can present very narrow frequency linewidths with Q factor up to 18 000 with special angle condition for the applied field [43]. Real time measurements have shown that the turn-on time for magnetization precessions induced by spin transfer is very short (less than 1 ns). The main present drawback of the STNO is its very weak output microwave power. A solution to overcome this difficulty is to synchronize several oscillators, i.e. to force them to emit at a common frequency and phase in spite of the intrinsic dispersion of their individual frequencies. The synchronization of one STNO on a few hundred of MHz using an additional ac current has been recently observed by the NIST group. They show that over the locking frequency range, the device phase can be tuned by 180 deg [68]. More, it has also been shown that a mutual phase-locking is possible in close neighbor (a few 100 nm) double spin transfer devices [69,70]. These results are of interest for obtaining an enhanced microwave generation with networks of spin-transfer oscillators.

6. Conclusion

In classical magnetism, the ‘natural’ way to make magnetization changes is to apply an external magnetic field created either by an other magnet or by a current flowing in a wire. This is also the case in the forefront of spintronic technologies like magnetic memories MRAM, in which the writing process occurs by the manipulation of a *nanomagnet* on the *nanosecond* timescale. The research challenge is today the development of a new method to control the magnetization that can overcome the limits of classical magnetism (slow spatial decay and limited rise/decay time of a magnetic field). Such a breakthrough might be accomplished by the spin transfer effect. This new phenomena arises from the exchange of spin angular momentum between the propagating electrons and a local magnetic moment. All the non collinear part of the spin polarized current is transferred to the magnet and produces a net torque that results either in magnetization reversals or precessional dynamics for sufficiently large current densities. This creates much interest in the application of spin transfer as writing process in MRAM since this effect is local (this is a short range interaction) and at least able to work at a few of picoseconds. An other very promising application field for spin transfer concerns a new generation of microwave devices. Indeed the magnetic excitations driven by the spin polarized current are in the gigahertz scale. As the frequency of the emitted microwave power is controllable with the current, a new generation of agile oscillator is born with numbers of specific applications in future telecommunication equipment.

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