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Theory of spin current in magnetic nanopillars for zero-field microwave generation

D M Edwards[1] **and J Mathon**[2]

[1] Department of Mathematics, Imperial College, London SW7 2BZ, UK
[2] Department of Mathematics, City University, London EC1V 0HB, UK

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Abstract
In a magnetic nanopillar, microwave oscillations of the magnetization of one magnetic layer can be driven by spin-polarized current emitted from another magnetic layer. The conditions for this to occur in zero applied field are formulated in terms of the two components of the spin-transfer torque. One simple route to achieve microwave generation is to ensure that these components have opposite sign. Quantum-mechanical calculations are presented that show how this may be achieved by a suitable choice of the oscillating magnet thickness.

1. Introduction

A typical magnetic nanopillar is essentially a trilayer system, with two magnetic layers separated by a non-magnetic spacer layer. One magnetic layer (the polarizing layer) is thick and its magnetization direction is assumed to be fixed. The second (switching) layer is thin and its magnetization is free to rotate under the influence of various torques. The trilayer is attached to external non-magnetic leads. We assume in this paper that the nanopillar cross-section is small enough for the magnetic layers to be considered as single-domain, but large enough for them to be treated as extended thin films. The torques acting on the switching layer arise from an external magnetic field, anisotropy fields and the two components of spin transfer torque which appear when a current passes through the trilayer [1]. We shall consider the most common experimental situation, in which the magnetization of the polarizing magnet, the in-plane uniaxial anisotropy axis in the switching magnet and the external field are all collinear. The spin-transfer torque can be used to switch the magnetization of the switching magnet between the parallel (P) and antiparallel (AP) orientations relative to the magnetization of the polarizing magnet. The switching process relies on the scenario that when one of the configurations (P or AP) becomes unstable, at a critical current, the other configuration is stable and therefore available for switching into it. However, in the presence of an external field larger than the coercive field of the switching magnet, it is found experimentally [2–5] that, for a current greater than a critical value and with the correct sense, neither the P nor the AP

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configuration is stable. The magnetization of the switching magnet is then in continual motion and becomes a source of microwave generation. Bertotti *et al* [6] have shown that the motion is periodic, and that, near the instability, the frequency is just that of ferromagnetic resonance in the given anisotropy and external fields. These authors consider only one component of spin-transfer torque and an applied field is essential, in their model, for the precessional motion. Edwards *et al* [1] predicted that a similar instability of both the P and AP configurations can also appear in zero applied field when the two components of spin-transfer torque have opposite signs. A nanoscale source of microwaves in zero applied field would certainly find important applications. In section 2 of this paper we review the phenomenological theory of this process [7] and in section 3 we show how detailed quantum-mechanical calculation of spin-transfer torque may be used to design real systems with the desired behaviour.

2. Phenomenological theory

The equation of motion for the magnetization of the switching magnet is the Landau–Lifshitz–Gilbert (LLG) equation,

$$\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} + \gamma \boldsymbol{m} \times \frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} = \boldsymbol{\Gamma}, \tag{1}$$

where $\boldsymbol{m}$ is a unit vector in the direction of the switching magnet moment, γ is the Gilbert damping parameter and $\boldsymbol{\Gamma}$ is the reduced total torque. In describing the switching magnet by a unique unit vector $\boldsymbol{m}$, we assume that it remains a uniformly magnetized single domain, and this seems to be the case in many experiments [2–5]. To specify the torque $\boldsymbol{\Gamma}$ we introduce a unit vector $\boldsymbol{e}_z$ in the direction of the in-plane uniaxial anisotropy field $\boldsymbol{H}_u = H_{u0}(\boldsymbol{m} \cdot \boldsymbol{e}_z)\boldsymbol{e}_z$ and a unit vector $\boldsymbol{e}_y$ perpendicular to the layer planes. The reduced torque takes the form

$$\boldsymbol{\Gamma} = H_{u0}\{(\boldsymbol{m} \cdot \boldsymbol{e}_z)\boldsymbol{m} \times \boldsymbol{e}_z - h_p(\boldsymbol{m} \cdot \boldsymbol{e}_y)\boldsymbol{m} \times \boldsymbol{e}_y + v g_{\parallel}(\psi)\boldsymbol{m} \times (\boldsymbol{p} \times \boldsymbol{m}) + v g_{\perp}(\psi)(\boldsymbol{m} \times \boldsymbol{p})\}, \tag{2}$$

where the relative strength of the easy plane anisotropy $h_p = H_{p0}/H_{u0}$ and $vg_{\parallel}(\psi)$, $vg_{\perp}(\psi)$ measure the strengths of the in-plane (Slonczewski) torque and the out-of-plane (effective field) torque, respectively. $\boldsymbol{p}$ is a unit vector in the direction of the magnetization of the polarizing magnet and ψ is the angle between $\boldsymbol{m}$ and $\boldsymbol{p}$. The reduced bias voltage is defined by $v = eV_b/(|\langle \boldsymbol{S}_{\mathrm{tot}} \rangle| H_{u0})$, where $\langle \boldsymbol{S}_{\mathrm{tot}} \rangle$ is the total spin angular momentum of the switching magnet. The applied field has been taken as zero. The anisotropy field is in units of angular frequency and must be multiplied by $\hbar/2\mu_{\mathrm{B}} = 5.69 \times 10^{-12}$ to obtain the field in tesla. It is convenient to define the magnitudes $T_{\parallel}$ and $T_{\perp}$ of the in-plane and out-of-plane spin-transfer torques which appear in equation (2), expressed in units of eV_b. Thus

$$T_{\perp} = g_{\perp}(\psi) \sin \psi, \qquad T_{\parallel} = g_{\parallel}(\psi) \sin \psi. \tag{3}$$

In the situation considered here, with the polarizing magnet magnetized in the direction of the in-plane uniaxial anisotropy axis in the switching magnet ($\boldsymbol{p} = \boldsymbol{e}_z$), steady-state solutions of equation (1) (given by $\boldsymbol{\Gamma} = 0$) exist for $\boldsymbol{m} = \pm \boldsymbol{p}$, correponding to the P and AP configurations discussed in section 1. The stability of these states is easily investigated by linearizing equation (1) about the steady state [7]. The stability conditions simplify when we recognize that the Gibert damping parameter $\gamma \ll 1$ and that the easy plane anisotropy is much larger than the uniaxial anisotropy (typically $h_p \approx 100$). The stability conditions for the P state are

$$v g_{\perp}(0) > -1, \qquad v g_{\parallel}(0) > -\tfrac{1}{2}\gamma h_p \tag{4}$$

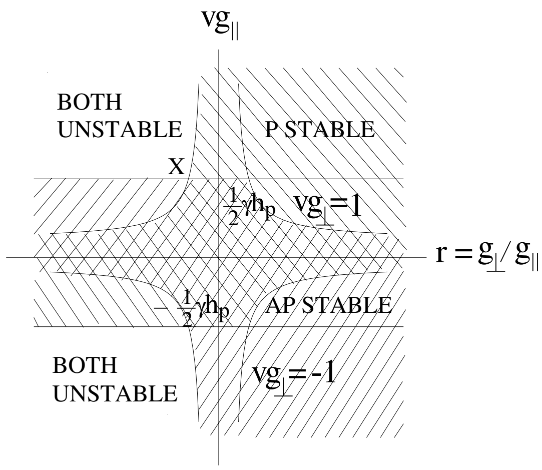

Figure 1. Stability diagram for $h_{\text{ext}} = 0$.

and for the AP state they are

$$vg_\perp(\pi) < 1, \qquad vg_\parallel(\pi) < \tfrac{1}{2}\gamma h_p. \tag{5}$$

From equation (3) we note that

$$g_i(0) = [\mathrm{d}T_i/\mathrm{d}\psi]_{\psi=0}, \qquad g_i(\pi) = -[\mathrm{d}T_i/\mathrm{d}\psi]_{\psi=\pi}, \qquad i = \perp, \parallel. \tag{6}$$

Quantum-mechanical calculations (see section 3) show that both components of the spin-transfer torque defined by equation (3) frequently have a sine-like dependence on angle ψ. Hence $g_\parallel$ and $g_\perp$ are approximately constant and, in particular, we may assume that the equations

$$g_\perp(0) = g_\perp(\pi) = g_\perp, \qquad g_\parallel(0) = g_\parallel(\pi) = g_\parallel \tag{7}$$

are approximately satisfied. In figure 1 we plot the regions of P and AP stability, assuming that equation (7) holds. We also put $r = g_\perp/g_\parallel$. It is in the 'both unstable' regions that persistent oscillations of the magnetization occur. A necessary condition for this behaviour, with microwave generation in zero field, is clearly $r < 0$. This was first predicted by Edwards *et al* [1] and found to occur for a Co/Cu/Co(111) system with the switching magnet consisting of a Co monolayer. In that case the assumptions $g_\perp(0) = g_\perp(\pi)$ and $g_\parallel(0) = g_\parallel(\pi)$ are satisfied quite well. Strong deviations from these relations will result in equations (4) and (5), leading to different criteria. This zero-field behaviour can also be obtained in the absence of the out-of-plane torque with a rather unusual angle dependence of the torque [8]. However, it is not clear in general how this can be achieved. On the other hand, the conditions for obtaining $r < 0$ are more easily investigated and, when this criterion, together with equation (7), is satisfied, zero-field microwave generation can occur. In the next section we carry out such an investigation by means of new quantum-mechanical calculations which, therefore, shed light on the design of suitable structures for microwave generation in zero field.

3. Nanoscale engineering of the spin-transfer torque

In order to obtain the instability discussed at the end of section 2, we require that the components $T_\parallel$ and $T_\perp$ of the spin-transfer torque have opposite signs. To engineer this

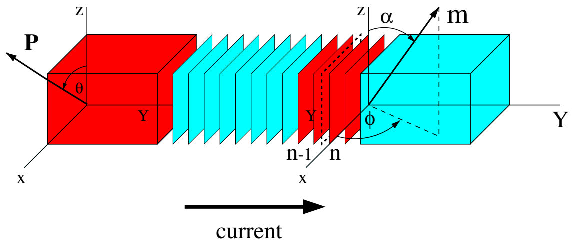

Figure 2. Schematic picture of the magnetic layer structure. (This figure is in colour only in the electronic version)

situation we need to investigate the factors that control the relative sign of $T_{\parallel}$ and $T_{\perp}$. The spin-transfer torque is the difference between the spin current in the spacer, separating the polarizing and switching magnets, and the spin current in the non-magnetic lead which is attached to to the switching magnet. Here we shall focus our attention on the behaviour of the spin current in the switching magnet, since it will be seen that this is the most important factor governing the sign of $T_{\perp}$. We have shown [1] that the local spin current in any part of the layer structure shown schematically in figure 2 can be calculated rigorously using the non-equilibrium Keldysh formalism. In particular, the Keldysh formalism [1] gives the spin current between any two atomic planes n, $n-1$ in the switching magnet (see figure 2) in terms of local one-electron Green's functions. We have also demonstrated [1] that the so-called standard model approximation to the rigorous Keldysh formalism is a very good approximation for real systems. Using the standard model [1], we have investigated the spin current in the switching magnet for a single-orbital sc tight-binding band structure, assuming that the layers are parallel to the (001) plane. A single-orbital tight-binding band allows us to vary the parameters of the model and thus gain an insight into the behaviour of the spin current in the switching magnet.

The main role of the polarizing magnet is to produce a stream of spin-polarized electrons. We have chosen the polarizing magnet to be just half metallic with the top of the majority-spin band coinciding with the Fermi level. This results in 100% spin polarization and the situation with only one spin-band occupied by holes is a reasonable approximation to cobalt. Strictly, of course, cobalt is not a half metal, having a small but non-zero density of states at the Fermi level in the majority-spin band. In all our calculations the polarizing magnet was taken to be semi-infinite. The non-magnetic spacer layer and the semi-infinite non-magnetic lead attached to the switching magnet were assumed to be made of the same material. We have taken the spacer layer to contain 20 atomic planes since, for such thicknesses, the spin current becomes essentially independent of the spacer thickness (in the ballistic limit that we consider).

There are two main parameters of the switching magnet that govern the behaviour of the transverse spin current with components J_x, J_y, which determine the parallel and perpendicular spin-transfer torques, respectively. The first parameter is the exchange splitting Δ between the majority- and minority-spin bands. The second is the thickness of the switching magnet N measured in atomic planes. We first show in figure 3(a) the dependence of the parallel component (x-component in the notation of figure 2) of the local spin current on the position in the layer structure for a switching magnet of 50 atomic planes (circles) and of 20 atomic planes (squares). The angle between the magnetizations is taken as $\pi/2$. The Fermi level in the switching magnet was chosen in this case to intersect both the majority- and minority-spin bands, which models, for example, the situation in iron or permalloy. The spin current for the first 20 atomic planes is that in the spacer where all the components of the spin current are

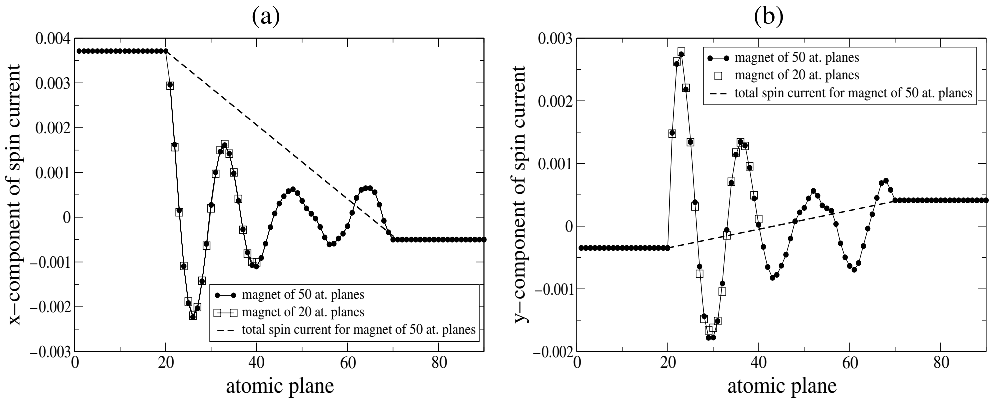

Figure 3. Spatial dependence of the parallel (x) component of spin current (a) and perpendicular (y) component (b) for a magnet with carriers of both spins.

naturally conserved. The results for the last 20 atomic planes correspond to the spin current in the lead (in the case of the switching magnet of 50 atomic planes), which is also conserved. Finally, the broken line connecting the values of the spin current in the spacer and in the lead refers to the total spin current in the switching magnet. The significance of the total spin current in the switching magnet will be discussed later. The corresponding position dependence of the perpendicular spin current (y-component) is shown in figure 3(b).

A number of interesting features of the spin current in the switching magnet can be deduced from figure 3. Firstly, both components of the spin current oscillate about zero as a function of the position in the switching magnet. The oscillations of the parallel and perpendicular components have approximately the same amplitude. In fact, a comparison of figures 3(a) and (b) shows that the two oscillations are essentially just shifted in phase. The oscillations decay very slowly with the distance from the spacer/switching magnet interface. The profile of the oscillations is independent of the switching magnet thickness, i.e. the variation of the spin current within the magnet of 20 atomic planes is virtually identical to that in the first 20 planes of the magnet containing 50 atomic planes. Of equal importance is the fact that the amplitude of spin current oscillations in the switching magnet is comparable to the value of the spin current in the spacer layer itself. We recall that the spin-transfer torque is the difference between the incoming and outgoing spin currents. Therefore, it can be seen from figure 3(b) that, simply by selecting the appropriate thickness of the switching magnet, we can engineer the sign of the perpendicular component of the spin-transfer torque. Similarly, it can be seen from figure 3(a) that the magnitude, but not the sign, of the parallel component of the torque can be strongly influenced by the choice of the switching magnet thickness.

The profile of the spin current across the layer structure we have determined should be contrasted with the results of earlier calculations of Stiles and Zangwill [9] for a parabolic band model and for a Cu/Co interface. They argue that in all cases there is a large discontinuity in the spin current at the spacer/switching magnet interface and the amplitude of their calculated oscillations of the spin current in the switching magnet is, therefore, only some 10% of the spin current in the spacer. That means that in their model such oscillations can influence neither the sign nor the magnitude of the spin-transfer torque. However, any discontinuity of the spin current is unphysical, since the continuity of the wave functions and of their spatial derivatives guarantees automatically the continuity of all the components of the spin current everywhere in the layer structure. We thus conclude on the basis of our rigorous Keldysh formalism [1], which naturally has the property that the spin current is continuous everywhere, that engineering of

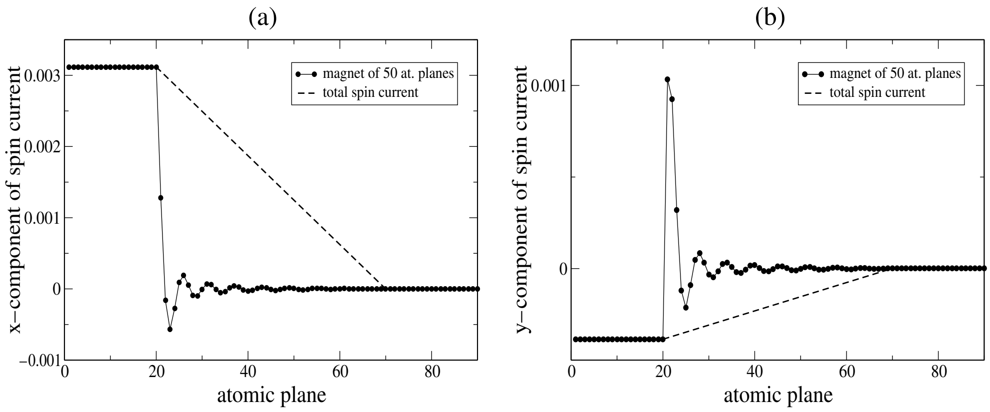

Figure 4. Spatial dependence of the parallel (x) component of spin current (a) and perpendicular (y) component (b) for a half-metallic magnet.

the sign and magnitude of the spin-transfer torque components by the choice of the switching magnet thickness is perfectly feasible.

There is, however, one case when the amplitude of spin current oscillations in the switching magnet is small and the oscillations decay exponentially with the distance from the spacer/switching magnet interface. This occurs when the exchange splitting Δ in the switching magnet is so large that it becomes a half-metallic ferromagnet. The results for the profiles of the parallel and perpendicular components of the spin current in a half-metallic switching magnet are reproduced in figures 4(a) and (b).

It is clear that, in the case of a half-metallic switching magnet, no engineering of the spin-transfer torque by varying the thickness of the magnet is possible. However, one should bear in mind that transition metal magnets that are used in all experimental pillar structures are not half-metallic and that the above special case is thus not applicable to real systems.

There are three points that remain to be clarified. The first is the physical interpretation of our calculated oscillations of the spin current. Within the so-called standard model, it can be shown [1] that the spin-transfer torque on any given atomic plane of the switching magnet is proportional to the transverse spin induced by electrons incident from the spacer at an angle ψ to the exchange field of the switching magnet, which is taken to be parallel to the z-direction. The proportionality factor is the exchange splitting Δ. Within the standard model it follows that electrons incident from the spacer precess in the exchange field of the switching magnet. The x- and y-components of the transverse spin thus oscillate periodically as a function of the distance from the spacer/switching magnet interface. Naturally, the oscillations of the two transverse components of the precessing spin are just shifted in phase. The aforementioned proportionality of the local spin-transfer torque to the local transverse spin thus implies that the spin current also oscillates in the same manner. This interpretation is qualitatively the same as that given earlier by the proponents of the standard model (see, e.g., [9]).

In section 2 we assumed in the discussion of the stability of steady states that the dependence of the spin-transfer torque on the angle ψ between the magnetizations of the switching and polarizing magnets is approximately sinusoidal. The angular dependences of the two components of the torque, determined for the same set of parameters as in figure 3, are shown in figure 5.

It can be seen that both torque components obey quite well a sinusoidal dependence on ψ and, hence, the relations specified in equation (7) of section 2 are satisfied for our single-orbital

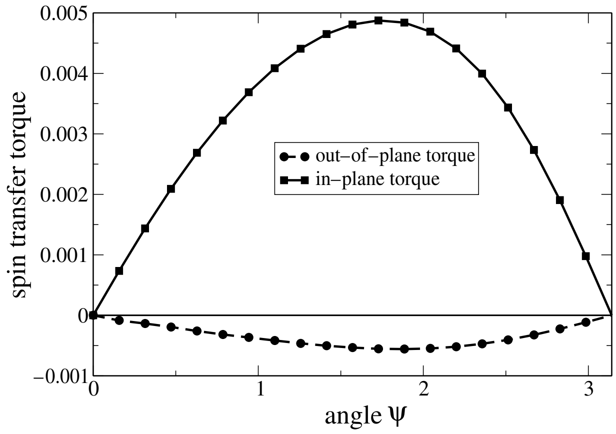

Figure 5. The angle dependence of the two components of the spin-transfer torque for the same parameters as in figure 3 and for a switching magnet of 20 atomic planes.

tight-binding model to a good approximation. Hence our insistence on the importance of the negative sign of the ratio of the two torque components is highly relevant to the search for zero-field microwave generation.

Finally, we have to clarify the significance of the total spin current, which is denoted in figures 3 and 4 by broken lines. In a steady state the total torque acting on any atomic plane of the switching magnet has to be zero. Since we assume that a uniaxial anisotropy in the switching magnet is uniform across the thickness of the magnet, the anisotropy torque acting on each atomic plane of the magnet must be constant. Since the anisotropy torque must be compensated by a spin-transfer torque, the spin current in the switching magnet should drop linearly across the magnet, as indicated by the broken lines in figures 3 and 4. However, it is clear that this condition is far from being satisfied in the standard model adopted here. There is, however, a simple explanation of this 'paradox'. In order to bring the oscillatory spin current into coincidence with the broken line, one needs to consider an additional internal spin current arising from a slight twist of the magnetization in the switching magnet [1]. This internal spin current corresponds to exchange coupling between neighbouring atomic planes. Since the exchange stiffness of a typical magnet is large, only very small twists of magnetization between neighbouring atomic planes are required to make up the difference between the oscillatory spin current obtained in the standard model and the required straight line. Such a small twist has a negligible influence on the spin current calculated in the standard model, i.e. the curves presented in figures 3 and 4 can be taken as including the effect of a small twist of magnetization. The sum of the current-induced spin current and the spin current due to a small twist of the magnetization is then the total spin current, denoted by broken lines in figures 3 and 4.

4. Conclusions

There is considerable interest in designing devices for microwave generation which are based on the oscillations of a magnetic layer driven by a spin-polarized current. It would be important to obtain this effect in the absence of an applied magnetic field. The spin-transfer torque which drives the magnet has two components, and it is shown that one simple route to achieve microwave generation is to ensure that these components have opposite sign. Quantum-mechanical calculations are presented that show how this may be achieved by a suitable choice of the oscillating magnet thickness.

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